Monte Carlo Analysis of Arsenic Concentrations in Kenogamisis Lake, Geraldton, Ontario

Final Report

June 28, 2018

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Sign-off Sheet

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Executive Summary

The Hardrock Project includes development of an open pit mine in an area presently occupied in part by portions of the historical MacLeod and Hardrock tailings. Enhanced reclamation of the historical MacLeod and Hardrock tailings as part of the Project plan, in combination with the changes in groundwater flow due to dewatering of the open pit, will substantially reduce groundwater arsenic loadings to Kenogamisis Lake, and in particular to Barton Bay.

A deterministic mass balance model of lake water and sediment (Stantec 2018) was previously developed to support prediction of arsenic concentrations in water and sediment of Kenogamisis Lake. The deterministic model reproduced the main features of the seasonal cycle of arsenic concentrations in water, as well as historical accumulation of arsenic in sediment. The expected future reductions in arsenic loading to Kenogamisis Lake were of sufficient magnitude that the deterministic model predictions are reliable indicators of the relative change of future arsenic concentrations in water and sediment. Without changes due to the Project, arsenic concentrations in water and sediment would be expected to remain similar to concentrations that have been observed over the past decade.

Following review by MOECC staff (MOECC 2018a) it was confirmed that Stantec had satisfied most of the MOECC technical comments on the deterministic modelling of arsenic in Kenogamisis Lake. However, it was noted that a comment remained outstanding, that “appropriate confidence intervals for the STELLA™ modelling tool are needed” with respect to arsenic concentrations in the lake water. The memorandum outlined a suggested Monte Carlo approach to further evaluating the uncertainty in STELLA™ model predictions of arsenic concentrations in the water of Kenogamisis Lake.

The present report describes the work carried out to complete the Monte Carlo modelling, and the results of the modelling. The Monte Carlo input parameters were developed by Stantec and reviewed by a team of five external technical experts retained by Greenstone Gold Mines GP Inc., as well as by MOECC staff. The Monte Carlo model results are consistent with and support the results of the deterministic modelling. Importantly, it is shown through the Monte Carlo uncertainty analysis that the projected future reductions in arsenic concentrations in Kenogamisis Lake will be significant.

The significant net positive effects that are predicted can be attributed to Project design measures addressing historical tailings within the Project Development Area.

1.0 INTRODUCTION

1.1 BACKGROUND

Greenstone Gold Mines GP Inc. (GGM) proposes the construction, operation, and closure of an open pit gold mine, process plant and associated ancillary facilities, collectively known as the Hardrock Project (the Project). The Project is located in northwestern Ontario, approximately 275 km northeast of Thunder Bay, in the Municipality of Greenstone, Ward of Geraldton. The Project is generally centred at the intersection of Highway 11 and Michael Power Boulevard. Highway 11 currently traverses the Project property in an east-west direction.

The Project is partially situated within an area of historical mine sites that were actively mined between the 1930s and 1970s, and in later years was known as the MacLeod-Mosher complex. The historical underground operations include the MacLeod-Mosher Mine and the Hardrock Mine. Premier (2011) reported that historical mining activities associated with the Project affected approximately 100 hectares (ha) of land, including tailings facilities referred to as the historical MacLeod high tailings and MacLeod low tailings. The historical MacLeod tailings are mostly situated north of Highway 11 near Barton Bay East (BBE, Figure 1-1), part of Kenogamisis Lake. Historical tailings associated with the former Hardrock Mine (the Hardrock tailings) are located south of Highway 11.

As a result of the presence of these historical tailings areas, as well as the continuing effects of other historical mining activities within its watershed, loadings of arsenic (as well as iron and other metals) to Kenogamisis Lake are elevated relative to background or natural loadings. Arsenic, iron and phosphorus in Kenogamisis Lake have been identified by the Ontario Ministry of the Environment and Climate Change (MOECC) as being subject to Policy 2 under the provincial Water Management approach (Ontario Ministry of the Environment and Energy 1994). Under Policy 2, water quality which does not meet the Provincial Water Quality Objective (PWQO) shall not be further degraded and all practical measures shall be undertaken to upgrade the water quality to the Objectives.

Stantec (2018) has previously developed a deterministic model of arsenic concentrations in the water and sediments of Kenogamisis Lake. The model was implemented using a commercially available software system known as "STELLA^{TM}", and the model of arsenic in the water and sediments of Kenogamisis Lake is often referred to as "the STELLA^{TM} model". The purpose of that modelling was to provide further understanding and detail to simpler modelling of water quality that was presented in Chapter 10 of the Environmental Impact Statement (the EIS, Stantec 2017) for the Hardrock Project (the Project).

A recent memorandum (MOECC 2018a) confirms that Stantec has satisfied the MOECC technical comments on the deterministic modelling of arsenic in Kenogamisis Lake. However, the memorandum notes that there remains an outstanding comment, that "appropriate confidence intervals for the STELLA^{TM} modelling tool are needed". The memorandum outlines a suggested stochastic or "Monte Carlo" approach to evaluating the uncertainty in STELLA^{TM} model predictions of arsenic concentrations in the water of Kenogamisis Lake. The memorandum notes that the Monte Carlo simulations may be used to derive 95% confidence intervals for the predicted results (i.e., arsenic concentrations in the water of the various sub-basins of Kenogamisis Lake during specific future phases of the Project).

1.2 DETERMINISTIC AND STOCHASTIC MODELLING

1.2.1 Introduction to Deterministic and Stochastic Modelling

Numerical models may be deterministic (as is the case with the existing STELLA™ model), where key variables are assigned uniquely determined values, and the model generates a unique solution which may represent a "most likely" or "worst case" output according to the intent of the modeller or specific simulation. Alternatively, models may be stochastic, in which case key variables are assigned statistical distributions, with many simulations being performed with individual parameter values being assigned values drawn from their statistical properties. Stochastic (or Monte Carlo) models generate a manifold of results which allow the modeller to evaluate the uncertainty inherent in the system being modelled (Renard et al. 2013).

While deterministic and stochastic modelling approaches have often been viewed as rivals, Renard et al. (2013) stress that they may be best deployed as complementary approaches, and that synergy can arise from this approach. However, the choice of a model must be based on the needs and constraints for a given project, as well as the current level of knowledge and resources. The choice should not be dogmatic, but rather driven by the principle of maximum efficiency to solve a given problem (Renard et al. 2013). Mishra (2009) notes that although Monte Carlo simulation provides versatility in uncertainty propagation studies, it may not be the most efficient approach and could be an "overkill" solution when parameter uncertainty is poorly defined, when models are computationally intensive, or when outcomes of interest are limited in number.

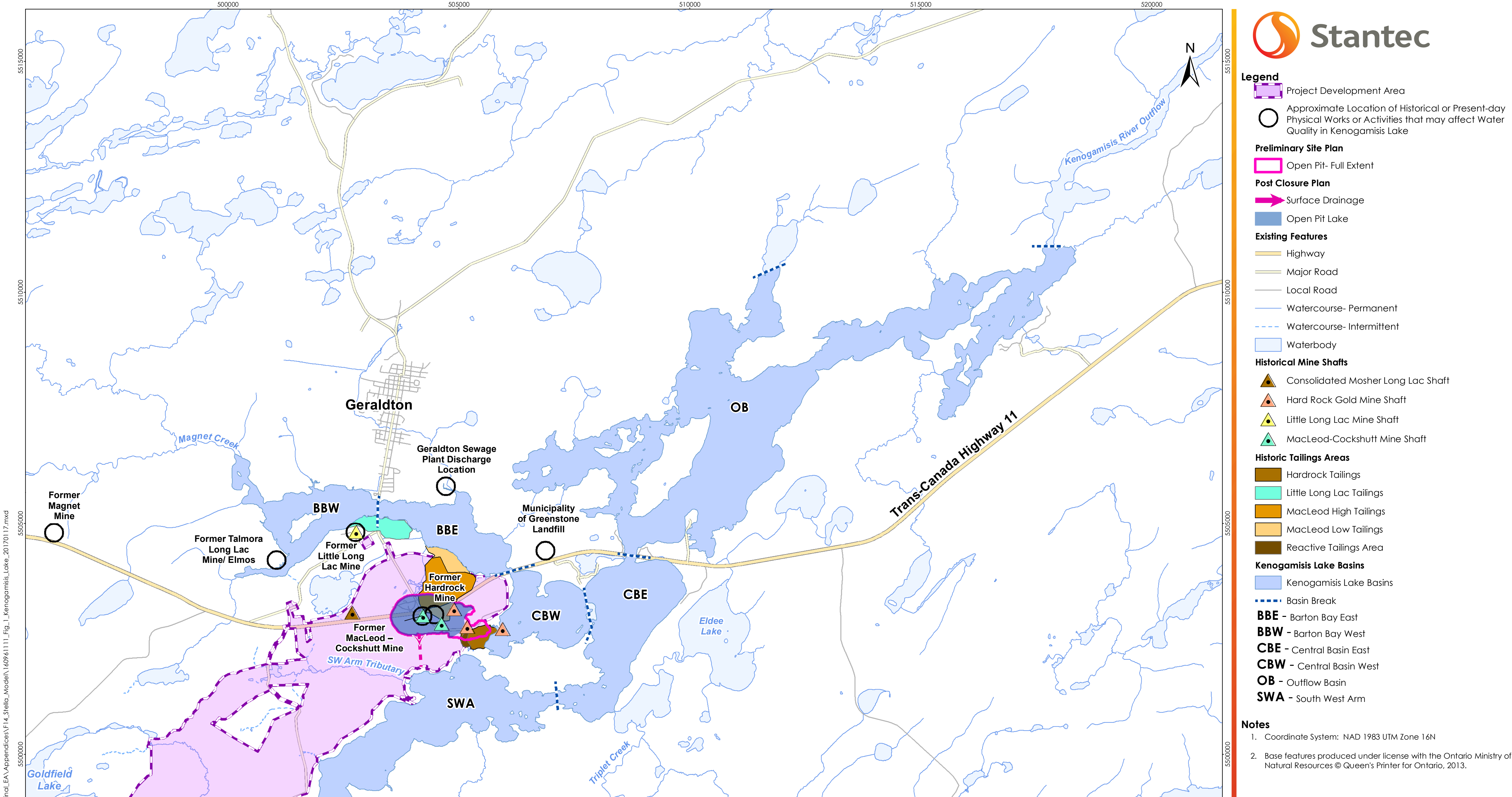
1.2.2 Stochastic Modelling – Possible Constraints and Limitations

Stephens et al. (1993) note it is generally not possible for a model to describe a real environment exhaustively. As the size and complexity of natural systems increase, there is a limit to the level of detailed description and modelling that is practical. In general, simpler models should be preferred over more complex models, but ultimately the choice of models depends upon the nature of the problem being investigated.

1.2.3 Stochastic Modelling Approach

Parameters included in models are subject to uncertainty as a result of a variety of factors. The natural environment changes constantly in response to natural processes and human activities. However, in addition to such variability, there may be measurement error in data due to human error, measurement uncertainty or undetected instrument malfunction, or inherent ambiguity in relating measured data to the value of the parameter of interest. Monte Carlo analysis is intended to assess and provide insight into such uncertainties, and to determine whether model results support decision making processes, or may themselves be suspect.

It is important to differentiate between uncertainty relative to the calibrated value of a parameter (i.e., could the true value of a parameter, such as the water-to-sediment transfer rate for arsenic, actually be higher or lower than the value that was implemented in the deterministic model) and variability in parameter values that have been empirically measured or derived from long-term data sets (e.g., seasonal patterns and monthly variation in surface water runoff from streams flowing into Kenogamisis Lake). In general, uncertainty may be reducible through additional information gathering or analysis, whereas real variability will not change (although it may be more accurately defined) as a result of better or more extensive measurements (Hattis and Burmaster 1994).



January 2017
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Client/Project

Greenstone Gold Mines GP Inc. (GGM)
Hardrock Project

Figure No.
1-1

Title
Kenogamisis Lake and Sub-basins

Where a parameter value is not or cannot be directly measured and is subject to uncertainty, then it may be reasonable to allow such parameters to vary in a Monte Carlo analysis. In this case, random variation may be applied once (at the start of a simulation) and held constant over the course of a single simulation, with a new random value being selected at the start of the next simulation.

Where a parameter value has been measured, and the source and time-scale of variability is well documented, then it may be reasonable to apply random variation on a monthly, seasonal, or annual basis in accordance with documented patterns and magnitude of variation. For some parameter values, it may be unclear as to whether uncertainty or variability is the dominant feature, and the application of random variation may be subject to professional judgement reflecting one or both of these factors.

Mishra (2009) outlines four main steps in application of the Monte Carlo methodology for uncertainty analysis:

- **Selection of imprecisely known model input parameters to be sampled.** The goal of this step is to identify and retain only those input variables that have the greatest impact on the outcomes of interest. It may be carried out using subjective judgment, standard (one parameter at a time) sensitivity analysis, or randomized (one parameter at a time) screening (Mishra 2009). This step identifies two key aspects of parameter selection. First, if the model input parameter value is known precisely, then it may be treated as a constant rather than a variable. Second, even if the value of the model input parameter is not precisely known, it may be excluded from the Monte Carlo analysis if the model output parameter of interest is not sensitive to the variation.

- **Assigning ranges and probability distributions for each selected parameter.** This step involves fitting distributions to measured data using various estimation techniques, or deriving distributions using known constraints with conservative assumptions to avoid under-estimating uncertainty. Expert judgement is also a valid approach to the derivation of probability distributions (Stephens et al. 1993).

- **Generating many sample sets with randomly selected values of model parameters.** This step is a mechanical process of using a random number generator to create input files for the numerical model (corresponding to the selected parameters and their statistical distributions).

- **Running the model for the many sets of model parameters to accumulate model outcomes, with subsequent statistical analysis of the key output variable(s) and uncertainty.** This procedure is relatively inefficient, though robust (often requiring several hundred independent simulations). The results are typically post-processed to determine the central tendency and statistical properties of the parameter(s) of interest (e.g., the mean and 95% confidence interval for the predicted result).

1.3 PURPOSE AND OBJECTIVE

The purpose of this report is to describe the approach that was taken to implement the deterministic model of arsenic cycling in Kenogamisis Lake (Stantec 2018) in a Monte Carlo format.

The objective of this report is to present new data concerning the uncertainty associated with the predicted arsenic concentrations in the waters of Kenogamisis Lake (i.e., the six sub-basins), over the four key phases of the Project (i.e., Baseline, Operations, Closure and Post-closure); and to provide 95% confidence intervals for the estimated mean annual and monthly arsenic concentrations for each of these areas and Project phases.

2.0 SELECTION OF INPUT MODEL PARAMETERS TO BE SAMPLED

Some parameters in a stochastic model are allowed to take on different values within a simulation, or from one simulation to the next, to reflect variability in their expected value or uncertainty about their actual value in the system being simulated. A probability density function (PDF) for each such parameter relates the possible values of the parameter to the probability that it will be observed in the real system (Stephens et al. 1993). The PDF is a mathematical description of the possible values that a parameter can have, and the likelihood that they will be encountered in the real world (Stephens et al. 1993). There are many different distributions that could be applied to PDFs, however, only a small number are commonly invoked. These include:

- Constant – only a single discrete value is allowed.
- Uniform – all allowed values between defined upper and lower limits are equally likely.
- Normal – values have a central tendency with symmetrical uncertainty tails, giving a classic “bell curve” shape. In the normal distribution, the mean and standard deviation are specified, and upper and lower limit values may be imposed. If unbounded, a normal distribution could have lower values that are less than zero, and upper values extending to infinity.
- Log-normal – similar to the normal distribution, except that it is the logarithm of the parameter value that is normally distributed (a very common distribution type for environmental data). This results in a distribution that is skewed so that the lower tail is shorter and the upper tail is longer. In the log-normal distribution, the geometric mean (GM) and geometric standard deviation (GSD) are specified. Upper and lower limit values may be imposed, however, the log-normal distribution cannot have values less than zero.
- Triangular – this distribution is bounded by upper and lower limit values and has a single mode or most likely value. The mode may be shifted to the left or right within the range of allowed values. The triangular PDF is typically employed when detailed knowledge of the characteristics of the distribution may be limited.

The MOECC (2018a) suggested potential model input parameters to be sampled. Appendix A (Table 1) discusses the requested input parameters, and the Expert Review Team that was convened to consider the proposed approach to the Monte Carlo Analysis. Appendix A also explains the input parameters for which probability density functions (PDF) were initially developed. In subsequent consultation with MOECC staff, modifications were made to some of the parameters and associated PDFs. The final selection of stochastic parameters includes:

- Arsenic loading from atmospheric deposition to lake surface, as a function of uncertainty in modelled deposition rates.
- Arsenic loading from surface water runoff to the lake, as a function of variability in seasonal or monthly surface water runoff volume, and variability in arsenic concentration in the inflowing stream water.
- Arsenic loading from groundwater to the lake, as a function of variability in groundwater flow volume, and variability in arsenic concentration in the inflowing groundwater.

- Arsenic loading from an unknown source to Barton Bay West, as a function of uncertainty in the annual mass of arsenic associated with this unknown source[1].

- Water to sediment transfer rate for arsenic (α_{As}), as a function of uncertainty about the true values of this previously calibrated parameter in the various sub-basins of Kenogamisis Lake.

- Sediment-water partition coefficient for arsenic (Kd_{As}), as a function of uncertainty about the true values of this previously calibrated parameter in the various sub-basins of Kenogamisis Lake.

- Sediment arsenic concentration, whether based on measured values (Baseline phase) or modelled values (Operation, Active Closure and Post-Closure phases of the Project).

- Diffusive flux multiplier for arsenic exchange between sediment and water, as a function of the uncertainty in the true value of this previously calibrated parameter in Kenogamisis Lake.

The following parameters suggested by MOECC (2018a) were not subject to stochastic variability, for the following reasons (see also Appendix A for further information).

- Hydrology (as precipitation or runoff) was already captured through the use of runoff based on a regional hydrology model to estimate arsenic loadings from surface water sources, and flushing of the lake sub-basins due to the annual water cycle.

- Air and water temperatures are not included in the arsenic model as explicit variables, however, the effects of seasonal variation in air and water temperature are captured through the use of runoff data as described above; in estimates of arsenic loading from atmospheric deposition; and in the diffusive flux multiplier for arsenic exchange between sediment and water.

- Sedimentation rate was not varied because it was previously shown through sensitivity analysis (Stantec 2018) that the arsenic concentration in lake water has very low sensitivity to variation in the assumed sedimentation rate for the lake.

- Total suspended solids concentration was not varied because it is not an explicit parameter in the arsenic model, although it is implicitly represented through the calibrated values of the water to sediment transfer rate for arsenic.

- Iron concentration in each sub-basin was not varied because it is not an explicit parameter in the arsenic model. Relationships between iron availability and arsenic cycling in Kenogamisis Lake are implicitly

[1] A memorandum from Kathy McDonald to Annamaria Cross (MOECC 2018c) asked whether the unknown source of arsenic loading to BBW could arise from internal cycling of arsenic from sediment to water, rather than from a groundwater source as proposed by Stantec. The internal cycling of arsenic is included in the STELLA models for all lake sub-basins. The internal load of arsenic is proportional to the arsenic concentration in sediment, or more precisely, the arsenic concentration in the sediment pore water. If the additional 400 kg/year was due to internal cycling of arsenic in BBW (where the mean arsenic concentration in sediment is 283 mg/kg (Parks Environmental Inc. 2012)), then we would expect to see an even larger deficiency in the arsenic budget for BBE where the mean sediment arsenic concentration is 680 mg/kg. Put another way, the arsenic concentration in the sediments of BBW would have to be much higher than they presently are, in order to account for an additional 400 kg/year of internal loading. Therefore, this explanation is not supported.

represented through the calibrated values of α_{As} and Kd_{As} in the arsenic model. Additional information regarding relationships between iron availability and arsenic cycling can be found in Section 6.0 of Appendix A.

Additional information regarding the development of the PDFs can be found in Section 3.0 of this report.

3.0 PARAMETER VALUES AND PROBABILITY DENSITY FUNCTIONS

3.1 NON-VARIABLE PARAMETERS

The following physical model parameters describing the lake and its sub-basins are treated as being non-variable or constant for the various sub-basins of Kenogamisis Lake, as they are known to a high degree of precision, and will not vary on the time-scale of the Monte Carlo model simulations.

3.1.1 Lake sub-basin characteristics

Lake sub-basin characteristics are non-variable, and include:

- Surface area, m^2 (see Table 2 of Stantec (2018));
- Mean depth, m (see Table 2 of Stantec (2018));
- Volume, m^3 (see Table 2 of Stantec (2018)); and
- Catchment area, m^2 (see Table 3 of Stantec (2018)).

3.1.2 Treated Mine Effluent Arsenic Load

The treated mine effluent arsenic load (kg/year) applies only during mine operations and closure. This arsenic load is based on mean annual water flow through the mine effluent treatment plant, and an assumed maximum allowable arsenic concentration in the mine effluent (100 µg/L). This results in an estimate of the total arsenic load to the Southwest Arm from treated mine effluent of 296 kg/year. This is a conservative estimate for the following reasons:

- It is not likely that the arsenic concentration would always be at or near 100 µg/L, but rather this would be a maximum value, and most of the time the actual arsenic concentration in treated effluent would be substantially lower.
- The maximum allowable arsenic concentration in mine effluent will be addressed during permitting. The mine would not be allowed to operate if it was unable to comply with both provincial and federal permit conditions in respect of flow volume and effluent quality (including arsenic concentrations).

Rather than trying to anticipate the outcome of permitting discussions between Greenstone Gold Mines GP Inc. and MOECC, this arsenic load is estimated in a conservative manner, and treated as a constant. This source of arsenic represents about 38% of the total estimated arsenic load to Southwest Arm from natural and anthropogenic sources during the operational period of the Project, and less than 10% of the total arsenic loading to Kenogamisis Lake during Operation.

3.1.3 Lake Sedimentation Rate

The lake sedimentation rate (assumed to be 0.16 kg dry mass/m^2/year) was shown in the sensitivity analysis to have virtually no effect on the arsenic concentration in water (see Figure 12 of Stantec (2018)). Therefore, the sedimentation rate is not a parameter of concern for the stochastic analysis of future arsenic concentrations in water and is treated as a constant.

3.1.4 Physical Diffusion Coefficient for Dissolved Arsenic Species in Sediment Pore Water

The physical diffusion coefficient for dissolved arsenic species in sediment pore water (m^2/year) is a physical constant, but is adjusted for water temperature effects between 0°C and 20°C. This parameter is treated as a constant, subject to the existing seasonal temperature adjustment, and is not included in the Monte Carlo analysis. However, a separate parameter value (the diffusive flux multiplier), which increases the rate of arsenic exchange between sediment and water during the ice-free months to reflect physical water movements due to wind forcing, as well as increased biological activity during this period, is subject to uncertainty in the stochastic analysis. The diffusive flux multiplier is further discussed in Section 3.2.5.

3.1.5 Climate Change

The Monte Carlo analysis will not consider the effects of climate change, which were previously investigated up to the year 2100 (Stantec 2018, see Section 7.0). The climate change scenario resulted in a slight reduction of arsenic concentrations in water during the autumn, winter and spring, and very little change in peak arsenic concentrations in water during the summer. Overall, it is conservative to ignore the effects of climate change, as the net effect has been shown to be a slight reduction in the annual average arsenic concentration in water. As noted in Section 1.2.3, even if the value of the model input parameter is not precisely known, the model input parameter may be excluded from the Monte Carlo analysis if the parameter of interest is not sensitive to the variation.

3.2 VARIABLE PARAMETERS

Random values for the Monte Carlo analysis were generated using Monte Carlo routines available in the statistical analysis software program SYSTAT (Version 13.00.05). Each time a set of random numbers was generated using this software, a new random number “seed” was drawn from a published table of random numbers (Ostle and Mensing 1975, Appendix 7).

3.2.1 Arsenic Loads to Lake Sub-Basins (kg/year)

Most arsenic loads (kg/year) are the product of a surface water (or groundwater) flow volume (with units convertible to m^3/year) and the arsenic concentration in the surface water or groundwater (kg/m^3). Depending on the individual loading source, flow volume and arsenic concentrations may change with each progressive Project phase. However, all arsenic loads associated with surface water or groundwater have associated uncertainty deriving from variations in or assumptions about the two principal components of flow volume and concentration. Therefore, uncertainty will be applied to each of the individual components of total arsenic load to Kenogamisis Lake that derive from surface water or groundwater.

3.2.1.1 Arsenic Load from Atmospheric Deposition to Lake Surface (kg/year)

Atmospheric deposition of arsenic to the lake surface as a result of mine operations applies only during mine operations and active closure, and was calculated or extrapolated from estimates of dustfall associated with mine activities, as presented in the Final EIS / EA report (Stantec 2017).

The atmospheric deposition estimates are generally low, with the highest estimated arsenic deposition rate being 13 kg/year to the Southwest Arm. This is a very small load in comparison with estimated arsenic loads from surface water and groundwater. However, it is necessary to apply uncertainty estimates on the deposition values to support the Monte Carlo model simulations for arsenic in the lake water.

The air quality modelling team responsible for the estimate of loading due to atmospheric deposition of arsenic to Kenogamisis Lake advise (G. Crooks, Personal Communication, May 1, 2018) that the atmospheric deposition model estimates are generally considered to lie within a factor of 2 of the true values, and that a log-normal distribution may be appropriate for deposition estimates (i.e., the variance would indicate a skew towards higher values).

On this basis, a log-normal random variate for atmospheric deposition (RV_{AD}) was created, having a GM value of 0 and a GSD of 0.15. In real terms, this resulted in a set of random values having a mean of 1.0, which was truncated at a minimum value of 0.5, and a maximum value of 2.0. The values for mean annual atmospheric deposition of arsenic to the lake surface were then multiplied by the random variate, RV_{AD}, to provide randomly varying values for the atmospheric deposition of arsenic. Each sub-basin received a new and independent value of RV_{AD} at the start of each simulation.

3.2.1.2 Arsenic Load from Surface Water Flows (kg/year)

Arsenic loads to Kenogamisis Lake from surface water inputs are estimated as the product of the volume of water entering the lake as runoff from various watershed areas (i.e., stream flow), and the arsenic concentration in that watercourse.

Runoff (m^3/year)

Surface water flows vary seasonally, and in the deterministic arsenic model are implemented as monthly mean flow rates based on a regional hydrology model that incorporates a minimum 30-year period of monitoring data for each of six regional flow monitoring stations operated by Environment and Climate Change Canada. Each monthly mean runoff value can be assigned a measure of uncertainty based on long-term statistics. A flow monitoring station identified as 02AB008 (Neebing River near Thunder Bay, one of the six stations used to develop the regional flow model) was selected for this purpose. This monitoring station provides a 64-year record of natural runoff data from a watershed having an area of 187 km^2.

Although each river and stream inflow to Kenogamisis Lake has its own flow rate based on watershed area and precipitation, all can be assumed to be highly correlated (i.e., variations in the amount of runoff will be driven by regional patterns of weather and climate affecting all watercourses flowing into Kenogamisis Lake in a similar manner).

The individual monthly mean flow measurements from station 02AB008 were compiled and standardized by dividing each of the individual monthly flow values by the mean of the flow values for that month over the entire flow record.

Next the standardized values were screened to determine their statistical form. The log-normal distribution was selected as appropriate to represent the data. Therefore, the monthly mean flow data were log-transformed before calculating the GM and GSD for each month. These values, truncated at ±3 GSD, were used to generate random values of runoff for each month of the year. The likelihood of an individual monthly runoff value exceeding this limit is approximately 0.14% (about 1 in 740 events).

The formula for the implementation of stochasticity in surface water runoff estimates is therefore:

$$Runoff_{w,m} = MAR_w \times NMR \times RVR_m$$

Where $Runoff_{w,m}$ is the stochastic estimate of surface water runoff in watercourse w and month m; MAR_w is the mean annual runoff of watercourse w (m^3/year) estimated from its watershed area using the regional hydrological model; NMR is the normalized monthly runoff (unitless), used to adjust the mean annual runoff estimate to a mean monthly runoff estimate, and is also based on the regional hydrology model; and RVR_m is a random variate (unitless) used to introduce realistic variability into the mean monthly runoff estimate for month m. Due to the expected high level of correlation in runoff estimates between watercourses in any given month, the same value of RVR_m applies to all watercourses in any given simulation month, but a new and randomly generated value of RVR_m applies to each subsequent month. Table 3-1 provides the monthly mean and standard deviation values for RVR_m.

Table 3-1 Monthly Mean and Standard Deviation (SD) Values for RVR_m

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	1	1	1	1	1	1	1	1	1	1	1	1
SD	0.81	0.85	1.37	0.86	0.84	0.92	1.38	1.28	1.50	1.08	1.12	1.00

Note:
Mean and standard deviation values for standardized runoff based on analysis of a 64-year period of Environment and Climate Change Canada flow records for the Neebing River, Station 02AB008.

Surface Water Arsenic Concentration (g/m^3)

Surface water arsenic concentrations in the various tributaries to Kenogamisis Lake have been the subject of long-term monitoring. However, the actual quantity of data available to represent the various stream inputs varies, depending upon monitoring location. Where the data were sufficient to support this analysis, the watercourses were first segregated into “low background” and “high background” groups, based on whether their annual mean arsenic concentrations were less than or greater than 15 µg/L. In practice, this criterion divided drainage areas that did not include substantial areas of historical mining activity from those that did. Next, mean annual total arsenic concentrations, as well as monthly mean total arsenic concentrations, were calculated for water sampling stations on watercourses flowing into Kenogamisis Lake. The mean annual total arsenic concentrations in water for watercourses flowing into Kenogamisis Lake (MAC_w, g/m^3) are summarized for Baseline (generally based on measured values), and as expected during future Project phases (based on predictions in the EIS, Stantec 2017), in Table 3-2.

Table 3-2 Mean Annual Total Arsenic Concentrations (µg/L) of Low and High Background Watercourses Flowing Into Sub-Basins of Kenogamisis Lake

Sub-Basin of Kenogamisis Lake	Low Background Watercourses	High Background Watercourses
Baseline		
Barton Bay West	Longacre Lake (5.6) Marron Lake(7.87)	Magnet Creek (25.1)
Barton Bay East	Hardrock Creek (6.625)	Mosher Lake (21.7)
Central Basin West	None	None
Central Basin East	Eldee Lake (7.29) Miscellaneous watershed areas and small watercourses (12.09)	None
Southwest Arm	Kenogamisis River (1.02) Goldfield Creek (3.4) Goldfield Creek Trib. (3.43) Puppy Lake (3.7) Pussy Lake (3.7)	Southwest Arm Tributary “a” (19.42)
Outflow Basin	Miscellaneous watershed areas and small watercourses (7.29)	None
Operations		
Barton Bay West	Longacre Lake (5.6) Marron Lake (7.87)	Magnet Creek (25.1)
Barton Bay East	Hardrock Creek (6.625)	Mosher Lake (21.7)
Central Basin West	None	None
Central Basin East	Eldee Lake (7.29) Miscellaneous watershed areas and small watercourses (12.09)	None
Southwest Arm	Kenogamisis River (1.02) Goldfield Creek (3.4) Goldfield Creek Tributary (3.43) Southwest Arm Tributary “b” (3.4) Puppy Lake (3.7) Pussy Lake (3.7) Goldfield Lake (3.24)	Southwest Arm Tributary “a” (19.42)
Outflow Basin	Miscellaneous watershed areas and small watercourses (7.29)	None
Active Closure		
Barton Bay West	Longacre Lake (5.6) Marron Lake (7.87)	Magnet Creek (25.1)
Barton Bay East	Hardrock Creek (6.625)	Mosher Lake (21.7)
Central Basin West	None	None
Central Basin East	Eldee Lake (7.29) Miscellaneous watershed areas and small watercourses (12.09)	None
Southwest Arm	Kenogamisis River (1.02) Goldfield Creek (3.4) Goldfield Creek Tributary (3.43) Southwest Arm Tributary “b” (3.4) Puppy Lake (3.7) Pussy Lake (3.7) Goldfield Lake (3.24)	Southwest Arm Tributary “a” (19.42)
Outflow Basin	Miscellaneous watershed areas and small watercourses (7.29)	None
Post-Closure		
Barton Bay West	Longacre Lake (5.6) Marron Lake (7.87)	Magnet Creek (25.1)
Barton Bay East	Hardrock Creek (6.625)	Mosher Lake (21.7)
Central Basin West	None	None
Central Basin East	Eldee Lake (7.29) Miscellaneous watershed areas and small watercourses (12.09)	None

Table 3-2 Mean Annual Total Arsenic Concentrations (µg/L) of Low and High Background Watercourses Flowing Into Sub-Basins of Kenogamisis Lake

Sub-Basin of Kenogamisis Lake	Low Background Watercourses	High Background Watercourses
Southwest Arm	Kenogamisis River (1.02) Goldfield Creek (3.4) Goldfield Creek Tributary (3.43) Southwest Arm Tributary "b" (3.4) Puppy Lake (3.7) Pussy Lake (3.7) Goldfield Lake (3.24)	Southwest Arm Tributary "a" (19.42) Open Pit Lake Discharge (47.435) Tailings Management Facility Pond to South West Arm Tributary (26.9)
Outflow Basin	Miscellaneous watershed areas and small watercourses (7.29)	None

Next, a standardized monthly arsenic concentration was estimated for high background and low background watercourses, by dividing the monitoring data for any monitoring station by the overall average arsenic concentration value for that station. This gave standardized monthly arsenic concentrations that ranged from a low of about 0.45 times the mean annual value in January, to a high of almost twice the mean annual value in July for high background watercourses; and a low of about 0.68 times the mean annual value in April, to a high of about 1.8 times the mean annual value in August for the low background watercourses. These values are summarized in Table 3-3.

Table 3-3 Values of the Normalized Monthly Arsenic Concentration (NMC, unitless) for High Background and Low Background Watercourses

Month	NMC - High Background	NMC - Low Background
January	0.45	0.75
February	0.79	0.78
March	0.58	0.79
April	0.66	0.68
May	0.92	0.72
June	1.20	0.93
July	1.90	1.50
August	1.80	1.80
September	1.10	1.50
October	0.98	1.00
November	0.94	0.70
December	0.63	0.75

Last, the variability in the monthly mean surface water arsenic concentration values was estimated. The raw arsenic concentration data were standardized by dividing by the mean of the monthly values, and the standardized values were log-transformed. The standardized and log-transformed data for high background and low background monitoring stations were then pooled by month to maximize the number of data points available to support the calculation of monthly statistics. It was found that there was no systematic variation in the monthly standard deviation values (i.e., all values were similar), and so pooled standard deviation values were calculated as the average of the monthly standard deviation values for both low and high background streams. However, the pooled standard deviation value for high background watercourses was greater than the pooled standard deviation value for low background watercourses. The two pooled standard deviation values were then used to generate random variate values for the arsenic concentrations in surface water (RVC_m, unitless) for high background and low background watercourses. The log-RVC_m have GM values of 0, and GSD values of 0.31 (high background watercourses) or 0.15 (low background watercourses), and were truncated at ±2 GSD to avoid unreasonable values. On an arithmetic scale, this results in a mean RVC_m value of 1 with a range of 0.45 to 1.90 for the high background watercourses; and a mean RVC_m value of 1 with a range of 0.68 to 1.80 for the low background watercourses.

The stochastic monthly total arsenic concentrations for watercourses flowing into Kenogamisis Lake were then calculated as follows:

$$\text{Concentration}_{w,m} = \text{MAC}_w \times \text{NMC} \times \text{RVC}_m$$

Where $\text{Concentration}_{w,m}$ is the stochastic estimate of the total arsenic concentration (g/m^3) in watercourse w, and month m; MAC_w is the mean annual arsenic concentration in watercourse w, derived from long-term monitoring data either from that watercourse, or where monitoring data are lacking (typically for watercourses outside of the area of historical contamination), from a surrogate watercourse; NMC is the normalized monthly arsenic concentration for either a high background or low background watercourse, as appropriate, used to adjust the mean annual concentration estimate to a mean monthly concentration estimate; and RVC_m is the random variate used to introduce variability into the mean monthly concentration estimate. To estimate the random variability in arsenic concentrations, a different and unique value of RVC_m is applied to each watercourse and each month throughout the stochastic simulation.

Surface Water Arsenic Load (g/year)

The stochastic estimates of total monthly arsenic load from each individual watercourse w (i.e., $\text{Load}_{w,m}$) to the individual sub-basins of Kenogamisis Lake, in each Project phase, are calculated as:

$$\text{Load}_{w,m} = \text{Runoff}_{w,m} \times \text{Concentration}_{w,m}\,.$$

3.2.1.3 Arsenic Load from Groundwater Seepage (g/year)

As with arsenic load from surface water inflow, arsenic load from groundwater seepage is calculated as the product of the volume of groundwater flow, and the arsenic concentration in the groundwater.

Groundwater Flow (m^3/year)

The three dimensional (3D) groundwater model described in the Final EIS / EA report (Stantec 2017) was completed under steady state conditions and provides an estimate of mean annual groundwater flow. For the Monte Carlo STELLA™ model input, a seasonal distribution of groundwater discharge was required. To address this and to introduce a seasonal component to flow, seasonal variations in groundwater elevations relative to the level of Kenogamisis Lake were investigated. Hydraulic head is the driving force behind groundwater flow and varies seasonally in response to recharge events which typically occur in late spring and late fall. The analysis of monitoring well hydraulic head data indicated a seasonal pattern of rising hydraulic heads over a period of two months in the spring (April and May), followed by a prolonged period of steadily declining heads over the rest of the year. This pattern is illustrated for normalized monthly flow values (i.e., the mean of the monthly values over the course of the year equals 1) in Figure 3-1. Figure 3-1 indicates that there is expected to be a range of monthly flow values, relative to the annual mean groundwater flow value, such that the greatest groundwater flow is likely to occur in late spring and early summer (May - July) following spring thaw and the greatest period of recharge; and the least groundwater flow is likely to occur in winter (January - March), when the ground is frozen, snow is accumulating on the landscape, and recharge is minimal.

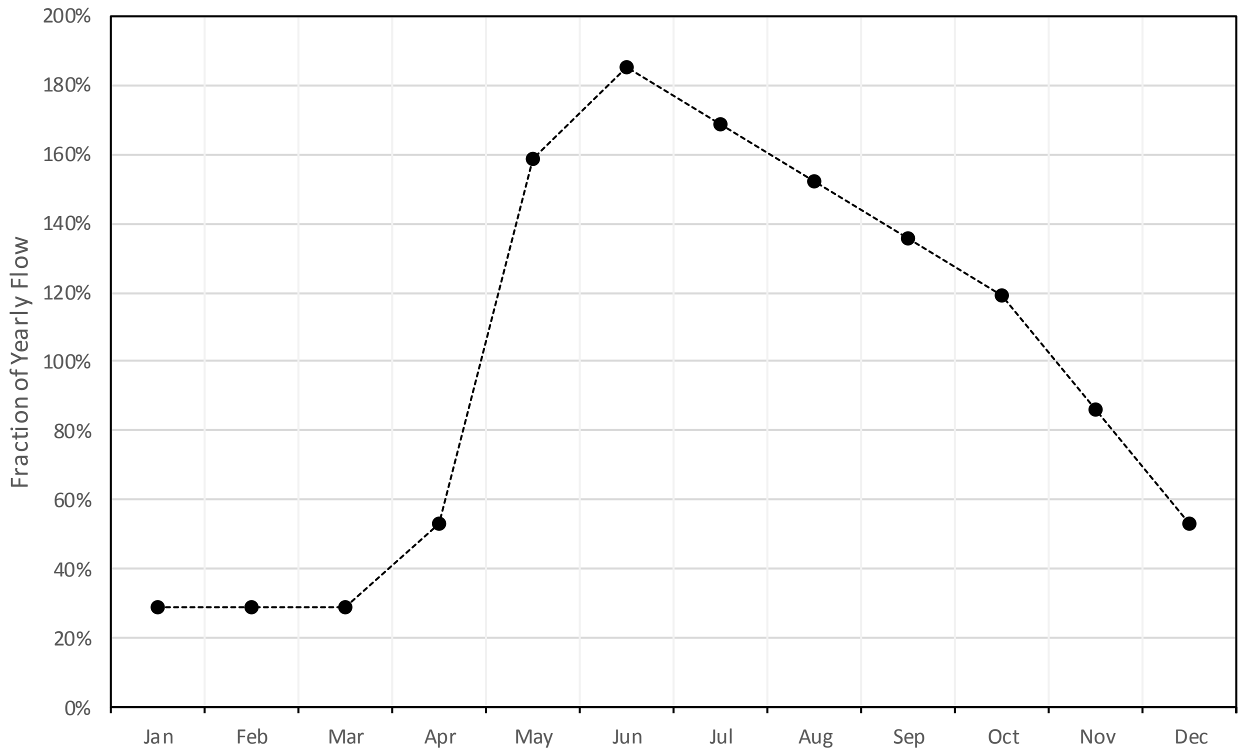

Figure 3-1 Normalized Monthly Groundwater Flow Values

The formula for the implementation of stochasticity in groundwater flow estimates is therefore:

$$Groundwater_{g,m} = MAF_g \times NMF \times RVF_m$$

Where $Groundwater_{g,m}$ is the stochastic estimate of groundwater flow from aquifer unit g in month m; MAF_g is the mean annual flow of aquifer unit g, estimated from the steady state groundwater flow model; NMF is the normalized monthly groundwater flow, used to adjust the mean annual flow estimate to a mean monthly flow estimate; and RVF_m is a random variate used to introduce realistic variability into the mean monthly groundwater flow estimate. Based on consultation with MOECC staff, it was determined that the random variate for groundwater flow should be assigned a normal distribution. Values of RVF_m were assigned a mean value of 1 and were normally distributed with a standard deviation of 0.1. No truncation was applied to this parameter. This resulted in values of RVF_m that varied from approximately 0.6 to 1.45. Due to the expected high level of correlation in flow estimates between aquifer units in any given month, the same value of RVF_m is applicable to all aquifer units in that month of the simulation, but a new and randomly generated value of RVF_m applies to each subsequent month.

Many of the groundwater flows will be modified in future Project phases, when tailings are removed and when the historic mine shafts are pumped down, and the Open Pit is excavated.

Groundwater flow systems presently include:

- BBW: natural groundwater, historical Little Long Lac tailings;
- BBE: natural groundwater, historical MacLeod tailings, historical Little Long Lac tailings;

- CBW: natural groundwater, historical Hardrock tailings, historical MacLeod tailings;
- CBE: natural groundwater;
- SWA: natural groundwater, historical Hardrock tailings, historical MacLeod tailings; and
- OB: natural groundwater.

As the Project progresses, some of the groundwater flow systems will be modified, particularly in the vicinity of SWA, BBE and CBW, as portions of some of the historical tailings deposits are remediated, and as new facilities (e.g., the Tailings Management Facility and Waste Rock Storage Areas) are developed. These effects are captured through the 3D groundwater flow modelling, the results of which were previously presented in the EIS / EA (Stantec 2017).

Project phases to consider for groundwater include:

- 2016-2018 – Baseline;
- 2019-2034 – Operations;
- 2035-2039 – Active Closure; and
- 2040-2100 – Post-Closure.

Groundwater Arsenic Concentration (g/m^3)

The stochastic implementation of the groundwater arsenic concentration ($Concentration_{g,m}$, g/m^3) has two components. These are:

- the mean arsenic concentration, which is conceptualized as a best estimate of the average arsenic concentration entering Kenogamisis Lake from a defined source area (which could be a historical tailings area, a proposed new facility, or simply natural groundwater from an area not affected by either historical mining activity or the Project); and
- variability or uncertainty about the true value of the mean arsenic concentration.

The mean arsenic concentrations expected from historical tailings areas (including MacLeod and Hardrock tailings), and in background areas of the property where groundwater monitoring wells have been installed into overburden or bedrock (OBBR) that have not been affected by historical mining activity, were estimated from arsenic concentrations measured in groundwater monitoring wells. The average values from monitoring wells located within each of these areas was used as the best estimator of the average arsenic concentration entering Kenogamisis Lake from these sources. A reviewer from the MOECC suggested using the median arsenic concentration as this measure of central tendency (MOECC 2018), however, the median value was lower than the average value, and so the average was selected in order to be conservative. Similarly, for the proposed facilities, the average arsenic concentrations previously presented in the EIS / EA (Stantec 2017) were retained as conservative estimators of the central tendency, rather than the median or mode values as suggested by the MOECC reviewer.

Next, the variability in the monthly mean groundwater arsenic concentration values was estimated. Here, the MOECC reviewer (MOECC 2018b) had suggested using log-triangular distributions, with the minimum and maximum measured arsenic concentrations as limits to the distribution. However, the minimum and maximum values are not reasonable estimators of the central tendency of the data or its confidence interval, and therefore this suggestion was not adopted. Instead, the actual groundwater monitoring data were analyzed statistically and found to be log-normally distributed. Where there were 3 or more samples available, the raw arsenic concentration data from monitoring well sampling were standardized by dividing the raw values by the means of the individual well values. After standardization, the values representing the historical MacLeod and Hardrock tailings, as well as areas of historical mine operations, were grouped together by area. The data were found to be best represented by a log-normal distribution, so a logarithmic transformation was applied. From the transformed data, the GM and GSD were determined for the two tailings areas and the Overburden Storage area. The GSD values ranged from 0.15 to 0.23, and a value of 0.20 was selected as representative of variation in groundwater arsenic concentrations. On an arithmetic scale, this results in a random variate for groundwater arsenic concentration (RVG) with a mean value of 1, and a range of approximately 0.38 to 2.58. This PDF was applied to all existing (i.e., the historical MacLeod and Hardrock tailings, and Overburden Storage area), and proposed (e.g., Waste Rock Storage Areas, and the Tailings Management Facility) facilities, as well as areas of natural groundwater.

Groundwater Arsenic Load (g/year)

The stochastic estimates of total monthly arsenic load from groundwater sources (i.e., $Load_{g,m}$) to the individual sub-basins of Kenogamisis Lake, in each Project phase, are calculated as:

$$Load_{g,m} = Groundwater_{g,m} \times Concentration_{g,m}\ .$$

3.2.2 Sediment-Water Partition Coefficient for Arsenic (Kd_{As})

The sensitivity analysis previously (Stantec 2018) investigated the effect of varying the sediment-water partition coefficient for arsenic (Kd_{As}, m^3/kg). This parameter value was deemed to have a log-normal distribution, and for the sensitivity analysis the calibrated values in each lake sub-basin were either halved or doubled to investigate the deterministic model output sensitivity to this parameter. High values of the sediment-water partition coefficient result in strong binding of arsenic to sediment solids, and less recycling from sediment to water (i.e., a smaller internal load of arsenic diffusing from sediment to water).

The calibrated values for Kd_{As} are as follows (from Table 7 of Stantec (2018)):

- BBW: 3 m^3/kg
- BBE: 3.5 m^3/kg
- CBW: 3 m^3/kg
- CBE: 2 m^3/kg
- SWA: 1.5 m^3/kg
- OB: 1.5 m^3/kg

There is no reason to link or correlate values of Kd_{As} with hydrological or loading parameters. However, there is an expected correlation between Kd_{As} and the availability of iron in the various sub-basins. Iron hydrous oxides represent a key binding phase for arsenic in freshwater environments (see Section 6.0 of Appendix A for further discussion). This correlation is addressed through the deterministic model calibration process.

Estimates of uncertainty for the sediment-water partition coefficient for arsenic are scarce. The Kd_{As} values vary according to where the measurement is made (e.g., according to the redox potential and availability of iron). Values for suspended sediment in the water column generally appear to be highest, followed by values for near-surface bed sediment. Values for anoxic buried sediments where iron would be reduced are generally the lowest.

Sheppard et al. (2012) reported values of Kd_{As} for 33 sediment samples from shallow lakes (<5 m) in northwestern Ontario. The mean sediment arsenic concentration was 13 mg/kg, which is similar to pre-mining values measured in sediment cores from SWA, CBW, CBE, and OB in Kenogamisis Lake. The mean sediment iron concentration reported by Sheppard et al. (2012) was 21,000 mg/kg, a value that is slightly higher than mean values measured in SWA and OB, but lower than values measured in BBW, BBE, CBW, and CBE (see Table 6-2 of Appendix A). A de-transformed GM Kd_{As} value of 1.4 m^3/kg was presented by Sheppard et al. (2012). This value is very close to the calibrated values of 1.5 m^3/kg for SWA and OB (Stantec 2018). Sheppard et al. (2012) reported a de-transformed GSD value of 4.3 for values of Kd_{As} in the 33 northwestern Ontario lakes. This would suggest that Kd_{As} values could range from about 0.08 to 25.9 m^3/kg. This is similar to the range of values reported in the literature for measurements of Kd_{As} values reflecting the range of conditions from highly oxic suspended sediments, to anoxic buried sediments. Cornett et al. (1992) reported Kd_{As} values in Moira Lake, Ontario, to range from <1 m^3/kg in buried sediments, to 20 m^3/kg on suspended particles in the water column. Similarly, Kuhn and Sigg (1993) reported Kd_{As} values on suspended particles ranging from 2 to 19 m^3/kg in Lake Greifen, Switzerland. However, it is reasonable to assume that when focusing on near-surface sediment from a single lake or sub-basin, the uncertainty estimate for the Kd_{As} value would be lower. It is also important to respect the deterministic model sensitivity analysis and model calibration and validation processes for the model of arsenic cycling in Kenogamisis Lake (Stantec 2018), which places constraints on the values of Kd_{As}.

Therefore, the calibrated values of Kd_{As} are treated as modal values for this parameter in the various lake sub-basins. These values apply specifically to arsenic sorption to sediment solids within the mixed sediment layer of each sub-basin of Kenogamisis Lake. In the stochastic analysis, the calibrated values of Kd_{As} are multiplied by a random variate that has a GM value of 0 and a GSD of 0.15. On an arithmetic scale, this results in a set of random variate values for the sediment-water partition coefficient (RV_{Kd}, unitless) having a mean of 1.0, which was truncated at a minimum and maximum values of approximately 0.5 and 2.0, respectively. Each sub-basin received a new and independent value of RV_{Kd} at the start of each simulation. The value of the sediment-water partition coefficient for that simulation was then calculated as the product of the calibrated Kd value for that lake sub-basin, and the value of the random variate (RV_{Kd}).

3.2.3 Water to Sediment Transfer Rate (α_{As})

The sensitivity analysis previously investigated the effect of varying the water to sediment transfer rate (α_{As}, 1/year). This parameter value was deemed to have a log-normal distribution, and for the sensitivity analysis, the calibrated values in each lake sub-basin were either doubled or halved to investigate sensitivity. The impact of a change in α_{As} was greatest in sub-basins with low hydraulic flushing rates, and least in sub-basins with high hydraulic flushing rate, as these two processes (dilution vs. removal to sediment) compete.

The calibrated values for α_{As} are as follows (see Table 7 of Stantec (2018)):

- BBW: 4 $year^{-1}$
- BBE: 4 $year^{-1}$
- CBW: 3 $year^{-1}$
- CBE: 2.5 $year^{-1}$
- SWA: 2 $year^{-1}$
- OB: 2 $year^{-1}$

There is no reason to link values of α_{As} to hydrological or loading parameters. However, there is an expected correlation between α_{As} and sediment Kd_{As} due to the relationship that both have to the availability of iron in the various sub-basins.

Bird et al. (1993) reported α_i values for 42 elements (not including arsenic), with individual geometric mean values ranging from 0.001/year(tritium) to 16.9/year (tin), and GSD values ranging from 1.2 to 31.7. However, these GSD values in some cases incorporate uncertainty about geochemical speciation, as well as a wide range of lake types and water chemistry conditions. As for the Kd_{As} value, it is expected that within an individual lake, the uncertainty will be considerably lower, and the values are constrained by the previously presented deterministic model sensitivity analysis, calibration, and validation processes (Stantec 2018). It was also previously shown (Equation 5 in Stantec (2018)) that α_{As} can be conceptualized as being a function of the Kd_{As} value, and this approach was used to estimate an α_{As} value of 2.1/year for a shallow lake similar to Kenogamisis Lake. This value is consistent with the range of calibrated values of α_{As} for CBE, SWA, and OB, where iron concentrations are not highly enriched. This in turn indicates that the random variate adopted for the sediment Kd_{As} value (i.e., RV_{Kd}) can also be used to estimate uncertainty in α_{As} values. By applying the same random variate to both α_{As} and Kd_{As} values in the Monte Carlo analysis, the two values become correlated. Therefore, in the stochastic analysis, the calibrated values of α_{As} are multiplied by the random variate, RV_{Kd}, with a new and independent value of RV_{Kd} being drawn at the start of each new simulation.

3.2.4 Sediment Arsenic Concentration

In addition to being affected by the sediment-water partition coefficient, the arsenic flux from sediment to water is also affected by the sediment arsenic concentration. Higher sediment arsenic concentrations will generally result in higher dissolved arsenic concentrations in sediment pore water and support a higher flux of arsenic from the sediment to the overlying water as a result of chemical diffusion, or resuspension of particulate matter.

The sediment arsenic concentration was measured using grab and core samples by Parks Environmental Inc. (2012). Where sectioned core samples were available, the average sediment arsenic concentration was calculated for the upper 10 cm of sediment. These values were then combined with arsenic concentrations measured in grab samples, to estimate the mean sediment arsenic concentration, and the 95% confidence interval of the mean, for each sub-basin of Kenogamisis Lake (Table 3-4). Owing to the generally small number of grab and core samples that were available, it was not possible to ascertain whether the data conformed to a normal or to a log-normal distribution. In consequence, triangular distributions were used to represent the sediment arsenic concentration data, with the modes being represented by the mean arsenic concentrations, and the limits of the distributions being represented by the limits of the 95% confidence interval of the mean. In this context, there is only a 2.5% likelihood that the true value of the mean would be lower than the range of values represented by the triangular distribution.

Table 3-4 Measured Sediment Arsenic Concentrations (mg/kg) in Sub-Basins of Kenogamisis Lake

	Barton Bay West	Barton Bay East	Central Basin West	Central Basin East	Southwest Arm	Outflow Basin
Cores	328	649	--	--	81	122
Grabs	293	407	201	180	9.4	18
	274	562	563	112	12.4	18
	261	639	229	84	16.3	35
	298	1020	327	141	7.1	18
	189	262	--	26	39.2	7
	235	812	--	106	82	37
	300	1020	--	--	49.3	50
	325	826	--	--	16.9	51
	--	772	--	--	66	7
	--	349	--	--	--	--
Arithmetic Mean	278	665	330	108	38	36
95% Confidence Interval of Mean	243 - 312	493 - 837	68 - 592	53 - 163	17 - 59	12 - 61

Notes:
All data from Parks Environmental Inc. (2012). Data from Central Basin West (MacLeod Basin Core C-1) were rejected due to concerns about the integrity of that core. No core sample was collected from Central Basin East.
-- Data not available

Measured sediment arsenic concentrations are available only for the Baseline (present-day) phase of the Project, and were also assumed to persist into the early part of the Operation phase. For future phases of the Project (i.e., Active Closure and Post-Closure) the sediment arsenic concentration was obtained from the previous deterministic modelling of water and sediment quality (Stantec 2018). The average sediment arsenic concentrations for those Project phases are presented in Table 3-5.

Table 3-5 Modelled Mean Sediment Arsenic Concentrations (mg/kg) for Future Project Phases

	Barton Bay West	Barton Bay East	Central Basin West	Central Basin East	Southwest Arm	Outflow Basin
Active Closure	323	618	217	127	27	33
Post-Closure	340	582	201	112	21	29

Note:
Values presented are the modelled mean sediment arsenic concentrations over the top 10 cm of the simulated core profiles from the years 2034 (Active Closure) and 2051 (Post-Closure) from Stantec (2018).

Stochasticity was implemented in the sediment arsenic concentrations by multiplying the mean sediment arsenic concentration values by random variates (RVS_{As}) that were based on the measured uncertainty for the mean sediment arsenic concentration in each sub-basin. The values of RVS_{As} were calculated for the measured values by dividing the arithmetic mean and 95% confidence interval values by the respective arithmetic mean values. Thus, for Barton Bay West, the PDF for RVS_{As} was assigned a triangular distribution with a mode of 1.0 and upper and lower limits of 0.877 and 1.123, respectively. Similarly, for Central Basin West the PDF for RVS_{As} had a mode of 1.0 and upper and lower limits of 0.207 and 1.793. The PDF values reflecting uncertainty in the present-day mean sediment arsenic concentrations in Kenogamisis Lake (Table 3-6) were applied in the same manner to the future (modelled) sediment arsenic concentrations. In practice, six sets of PDF values (one per sub-basin of Kenogamisis Lake) were randomly generated and applied to the mean measured sediment arsenic concentrations at the start of each stochastic model simulation. The same values were subsequently applied to the modelled mean sediment arsenic concentrations (i.e., values in Table 3-5) for subsequent Project phases in that simulation. A new set of randomly determined PDF values was applied to the mean sediment arsenic concentrations in each subsequent simulation within the stochastic set.

Table 3-6 Probability Density Function Values (RVS_{As}) for Sub-Basins of Kenogamisis Lake

	Barton Bay West	Barton Bay East	Central Basin West	Central Basin East	Southwest Arm	Outflow Basin
Mode	1.0	1.0	1.0	1.0	1.0	1.0
Range	0.877 - 1.123	0.754 - 1.246	0.207 - 1.793	0.494 - 1.506	0.437 - 1.563	0.328 - 1.672

3.2.5 Diffusive Flux Multiplier (DFM)

The diffusive flux multiplier (DFM, unitless) is used to amplify the diffusive flux of arsenic from sediment to water during the ice-free season. When the lake is ice-covered, it is not subject to wind stress, and benthic invertebrates present in the sediment can be assumed to be functioning at a low level of activity. Under these conditions the arsenic flux from sediment to water (i.e., the internal loading of arsenic) is assumed to be based on chemical diffusion alone. During the summer months when the lake water and sediment are warmer, benthic invertebrates that burrow in the sediment will function at a higher level of metabolic activity and will enhance the rate of arsenic exchange between sediment and the overlying water. There will also be episodes of wind stress leading to some resuspension of surface sediment. Under these conditions, the release of arsenic from sediment to water will be enhanced.

In the model, the physical diffusion coefficient for dissolved arsenic species in water (i.e., arsenite and arsenate) is considered to be a constant, but is adjusted for water temperature effects between 0°C and 20°C. This is reasonable, as diffusion coefficients in still water are physical constants at any given temperature.

The DFM is not a constant, and is subject to uncertainty that can be included in the stochastic analysis. The DFM has a value of 1 (i.e., no enhancement of molecular diffusion) during the period of December through April, when the lake is assumed to be ice-covered. However, during the ice-free season (May through November), the calibrated DFM value of 3 for Kenogamisis Lake is subject to uncertainty. This value (3) is therefore selected as the mode of a triangular distribution. The lower limit value of DFM cannot be less than 1, as this would result in an exchange rate lower than that of chemical diffusion alone. Therefore, a value of 1 was selected as the lower limit value for the triangular distribution, and an upper limit value of 5 was selected to complete the triangular distribution.

4.0 MONTE CARLO SIMULATION PROCESS

The existing deterministic STELLA^{TM} model of arsenic cycling in Kenogamisis Lake was modified to include the random variate parameters, as well as any other minor modifications required to transform the previous deterministic model into a Monte Carlo model. An Executive Program was developed, with the capacity to run the STELLA^{TM} model repeatedly, and save results automatically after each simulation.

In addition, because the model output parameter of concern (arsenic concentrations in water for the six sub-basins of Kenogamisis Lake) was previously shown to respond quickly to changes in arsenic loadings and other input parameters, and to remain stable over the various Project phases (see Figures 31 to 36 in Stantec 2018), the simulations were reduced to an 8-year period, thus reducing the required computing time and providing greater overall efficiency. The 8-year simulation period included two years in the simulation representing each Project phase (i.e., Baseline, Operation, Active Closure, and Post-Closure). Data from the first year of simulation for each Project phase were discarded (as they could be subject to transient effects reflecting the shift from one Project phase to the next). Data from the second year of each phase of any given Monte Carlo simulation were saved as representative of the model output for that phase.

The Monte Carlo model was initialized using water quality data from the year 2015 in the earlier deterministic model output, as the model had been calibrated to closely approximate present-day conditions for both water and sediment. Specifically, the values for masses of arsenic present in any of the water compartments were extracted from the deterministic model as of the last day of 2015 in that simulation and were installed as initial values in the Monte Carlo model. For sediment, the mean arsenic concentrations measured in sediment core and grab samples by Parks Environmental Inc. (2012) were used to estimate the Baseline masses of arsenic in the surface sediment compartments of the various lake sub-basins. For subsequent Project phases, values representing arsenic masses in sediment at the end of the years 2034 (representing the start of Active Closure), and 2051 (representing the start of Post-Closure) were also inserted as representative values in the Monte Carlo model. In this way, any small changes in the average arsenic concentration of the mixed sediment layer over the period leading up to the Active Closure and Post-Closure phases were accounted for. Each of these values (i.e., sediment arsenic concentrations at Baseline and in subsequent Project phases) was subject to randomization as outlined in Section 3.2.4.

The Monte Carlo model was allowed to run through 200 cycles of simulation, with each cycle being initialized with a new and randomly-generated selection of variable input parameters. As in the deterministic model, arsenic concentration data were calculated using a 3-hour time step, with values saved at the end of each day in the simulation. The daily values were subsequently aggregated into monthly and annual average values for statistical processing.

As a quality assurance measure, the Monte Carlo version of the model was tested in a format where the values of the random variates were all set to 1.0. In this mode, the Monte Carlo version of the STELLA^{TM} model produced output that replicated the deterministic output (as previously presented in Stantec 2018).

5.0 RESULTS AND DISCUSSION

The Monte Carlo version of the STELLA™ model was allowed to run for 200 cycles, to generate 200 sets of results representing each of the four phases of the Project (i.e., Baseline, Operation, Active Closure and Post-Closure). The key output parameter of concern was the arsenic concentration in surface water.

The arsenic concentration in surface water data generated using the Monte Carlo model were found to be log-normally distributed. Therefore, the data were log-transformed before calculating the mean and 95% upper and lower confidence limits (UCL and LCL) of the mean values. Log-transformed statistics were then de-transformed (hereafter referred to as the geometric mean and associated 95%UCL and 95%LCL values, respectively) before plotting in an arithmetic scale alongside the underlying model output and other data. Figure 5-1 shows the progressively calculated yearly geometric mean values for arsenic concentration in surface water (µg/L), with associated 95%UCL and 95%LCL values, for Barton Bay West and the Southwest Arm of Kenogamisis Lake. These results are typical of results for the other sub-basins and Project phases, in that the geometric mean and 95% confidence interval (95%CI) values stabilize within the first 100 simulations, and do not change in any meaningful way over the second set of 100 simulations. Based on this observation, 200 simulations were deemed sufficient for the Monte Carlo model to achieve a stable result for the current investigation. Additional simulations would not result in a meaningful change to the model output or conclusions.

5.1 MEAN ANNUAL ARSENIC CONCENTRATIONS IN SURFACE WATER

Figures 5-2 through 5-7 show the Monte Carlo model predictions for the mean annual arsenic concentration in surface water, for each sub-basin of Kenogamisis Lake (i.e., BBW, BBE, CBW, CBE, SWA and OB) over each phase of the Project (i.e., Baseline, Operation, Active Closure, and Post-Closure).

Figure 5-2 shows the range of predicted arsenic concentrations in BBW during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 27.1 µg/L (95%CI 26.2 to 28.1 µg/L) are similar to the deterministic model prediction (27.3 µg/L). Barton Bay West lies outside of and upstream from the area of Project environmental effects, and is not expected to be materially affected by the Project. The slight increase in predicted arsenic concentrations in the water of BBW between Baseline and Post-Closure phases of the Project (when the predicted geometric mean arsenic concentration is 28.6 µg/L), is largely the result of slow ongoing accumulation of arsenic in the sediments of BBW as a result of arsenic loading from upstream sources associated with the Magnet Creek sub-watershed, not related to the Project. This slow accumulation results in a slight increase in the internal arsenic cycling within BBW. This phenomenon was previously observed in the results of the deterministic model and was discussed in the deterministic model report (see Table 20 in Stantec 2018).

Figure 5-3 shows the range of predicted arsenic concentrations in BBE during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 75.2 µg/L (95%CI 71.5 to 79.0 µg/L) are higher than the deterministic model prediction (65.9 µg/L). This result indicates that the Baseline groundwater arsenic loadings to BBE are conservatively estimated, and that the level of conservatism has been increased through the Monte Carlo modelling process. The deterministic and Monte Carlo model results both show a substantial decrease in expected arsenic concentrations in BBE during Operation (geometric mean 31.1 µg/L, 95%CI 29.5 to 32.7 µg/L) and Active Closure (geometric mean 30.1 µg/L, 95%CI 28.5 to 31.8 µg/L) phases of the Project when compared to the Baseline phase. The deterministic model predictions for the Operation and Active Closure phases (29.4 and 29.0 µg/L, respectively) lie very close to the 95%LCL values of the Monte Carlo model predictions. In Post-Closure, the Monte Carlo model predicts a geometric mean arsenic concentration of 49.7 µg/L (95%CI 47.4 to 52.2 µg/L). This is higher than the value (41.2 µg/L) predicted by the deterministic model, but remains significantly below the range of concentrations predicted during the Baseline phase. However, even if the Baseline groundwater arsenic loadings to BBE are conservatively estimated, the relative reductions in arsenic concentrations in future Project phases are still applicable to the measured arsenic concentrations. The Monte Carlo model predictions are therefore consistent with the intent of Water Management, Policy 2. The observation that the Monte Carlo model results lie very close to the deterministic model results during the Operation and Active Closure phases of the Project (when groundwater flow is expected to be towards the Open Pit rather than towards Kenogamisis Lake) is further evidence to suggest that the Monte Carlo process has increased the conservatism associated with groundwater arsenic loading to BBE. This phenomenon is most evident in the results for BBE because this sub-basin of Kenogamisis Lake receives by far the largest overall arsenic load from groundwater.

Figure 5-4 shows the range of predicted arsenic concentrations in CBW during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 23.2 µg/L (95%CI 22.2 to 24.2 µg/L) are very similar to the deterministic model prediction (22.0 µg/L). During Operation and Active Closure, the arsenic concentrations in the water of CBW are predicted to decrease (with geometric mean of 11.7 µg/L and 95%CI of 11.1 to 12.4 µg/L during Operation, and geometric mean of 10.4 µg/L and 95%CI of 9.8 to 10.9 µg/L during Active Closure). The deterministic model predictions during these Project phases were 10.8 and 10.0 µg/L, respectively. The Monte Carlo model predicts an increase in the surface water arsenic concentration of CBW from Active Closure to Post-Closure (with a geometric mean of 14.5 µg/L and 95%CI of 13.8 to 15.2 µg/L). The previous deterministic model prediction for the Post-Closure phase was 13.4 µg/L. The predicted arsenic concentrations in Post-Closure remain significantly below the predicted concentrations for Baseline, consistent with the objectives of Water Management, Policy 2.

Figure 5-5 shows the range of predicted arsenic concentrations in CBE during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 14.4 µg/L (95%CI 13.8 to 15.1 µg/L) are slightly higher than the deterministic model prediction (12.9 µg/L). During Operation and Active Closure, the arsenic concentrations in the water of CBE are predicted to decrease (with geometric mean of 8.5 µg/L and 95%CI of 8.1 to 8.9 µg/L during Operation, and geometric mean of 7.4 µg/L and 95%CI of 7.0 to 7.8 µg/L during Active Closure). The deterministic model predictions during these Project phases were 7.5 and 6.7 µg/L, respectively. The Monte Carlo model predicts an increase in the surface water arsenic concentration of CBW from Active Closure to Post-Closure (with a geometric mean of 9.8 µg/L and 95%CI of 9.3 to 10.3 µg/L). The previous deterministic model prediction for the Post-Closure phase was 8.5 µg/L. The predicted arsenic concentrations in Post-Closure remain significantly below the predicted concentrations for the Baseline phase, consistent with the objectives of Water Management, Policy 2.

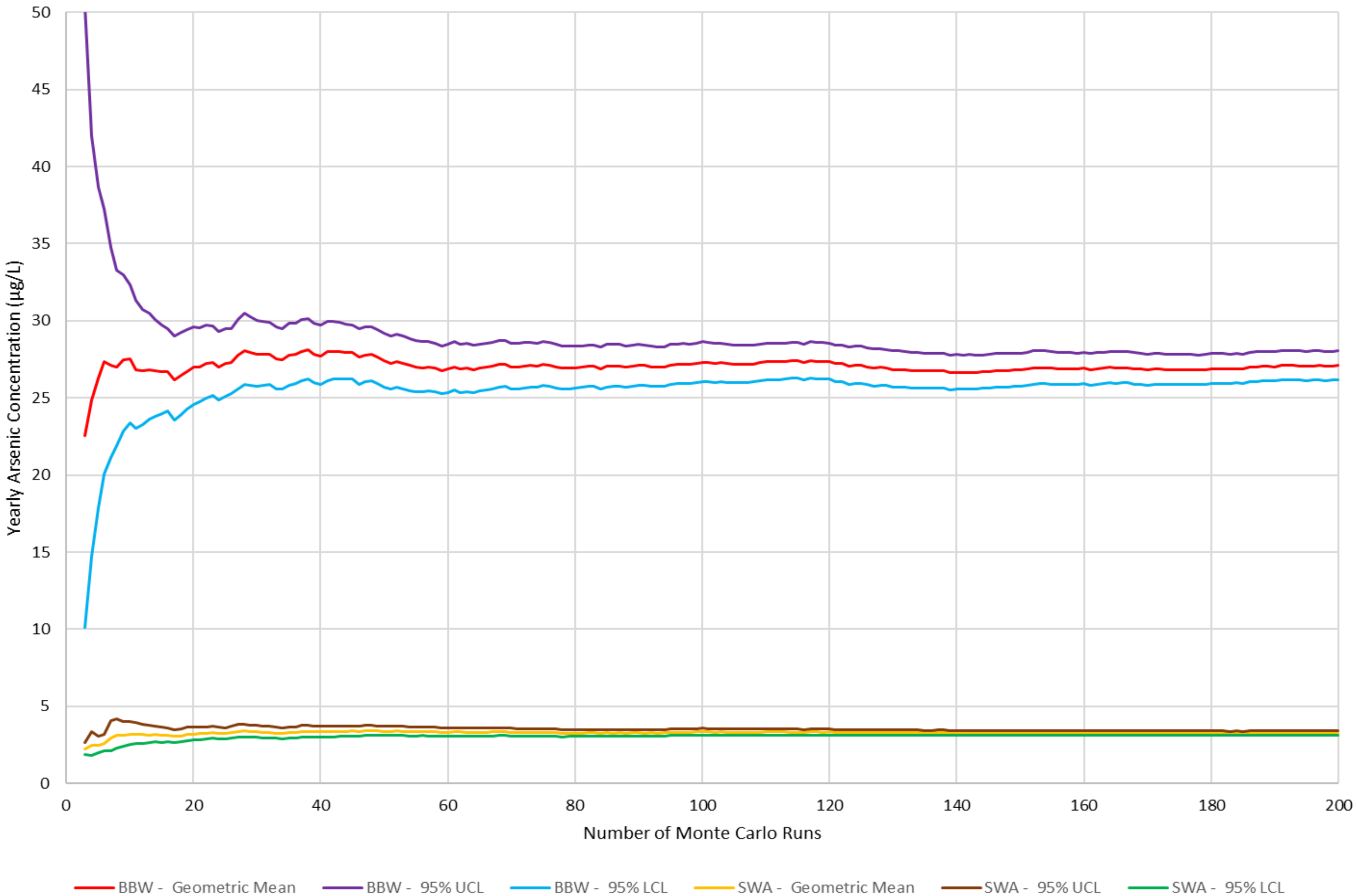

Figure 5-1 Calculated Values of the Geometric Mean Arsenic Concentration and Associated 95% Confidence Interval of the Geometric Mean, as a Function of the Number of Simulations Completed for Barton Bay West and Southwest Arm

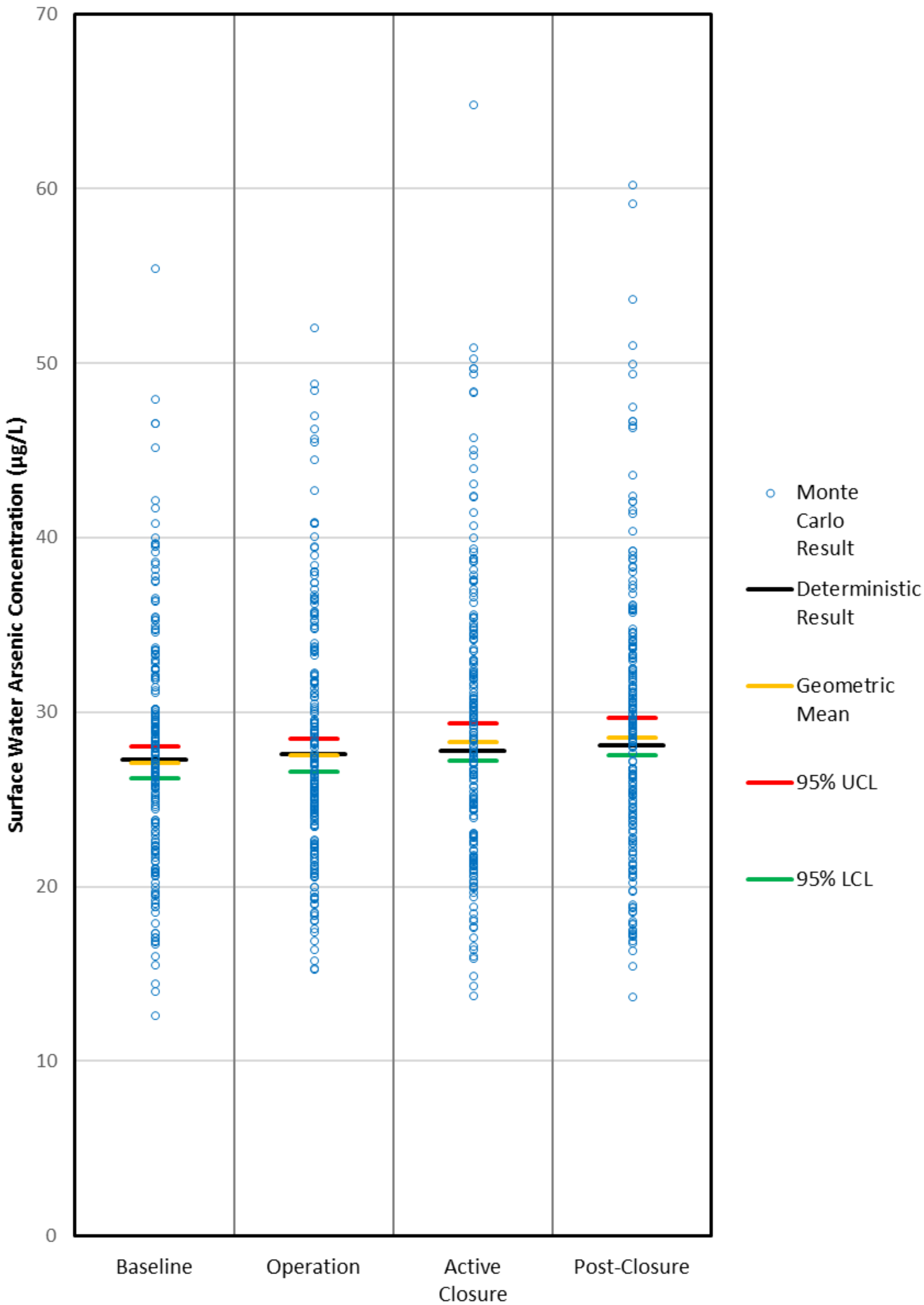

Figure 5-2 Annual Geometric Mean Arsenic Concentration (µg/L) for Barton Bay West

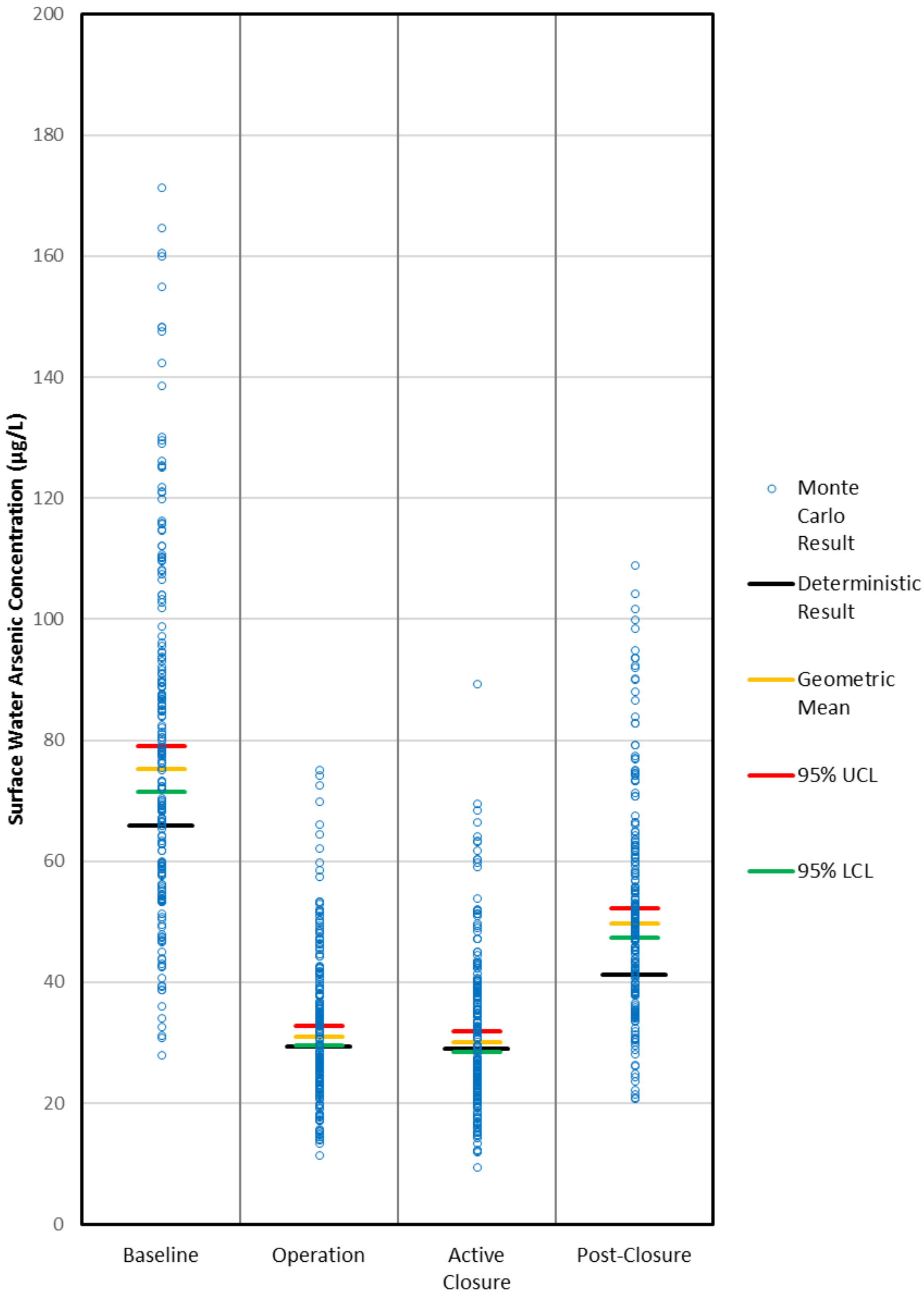

Figure 5-3 Annual Geometric Mean Arsenic Concentration (µg/L) for Barton Bay East

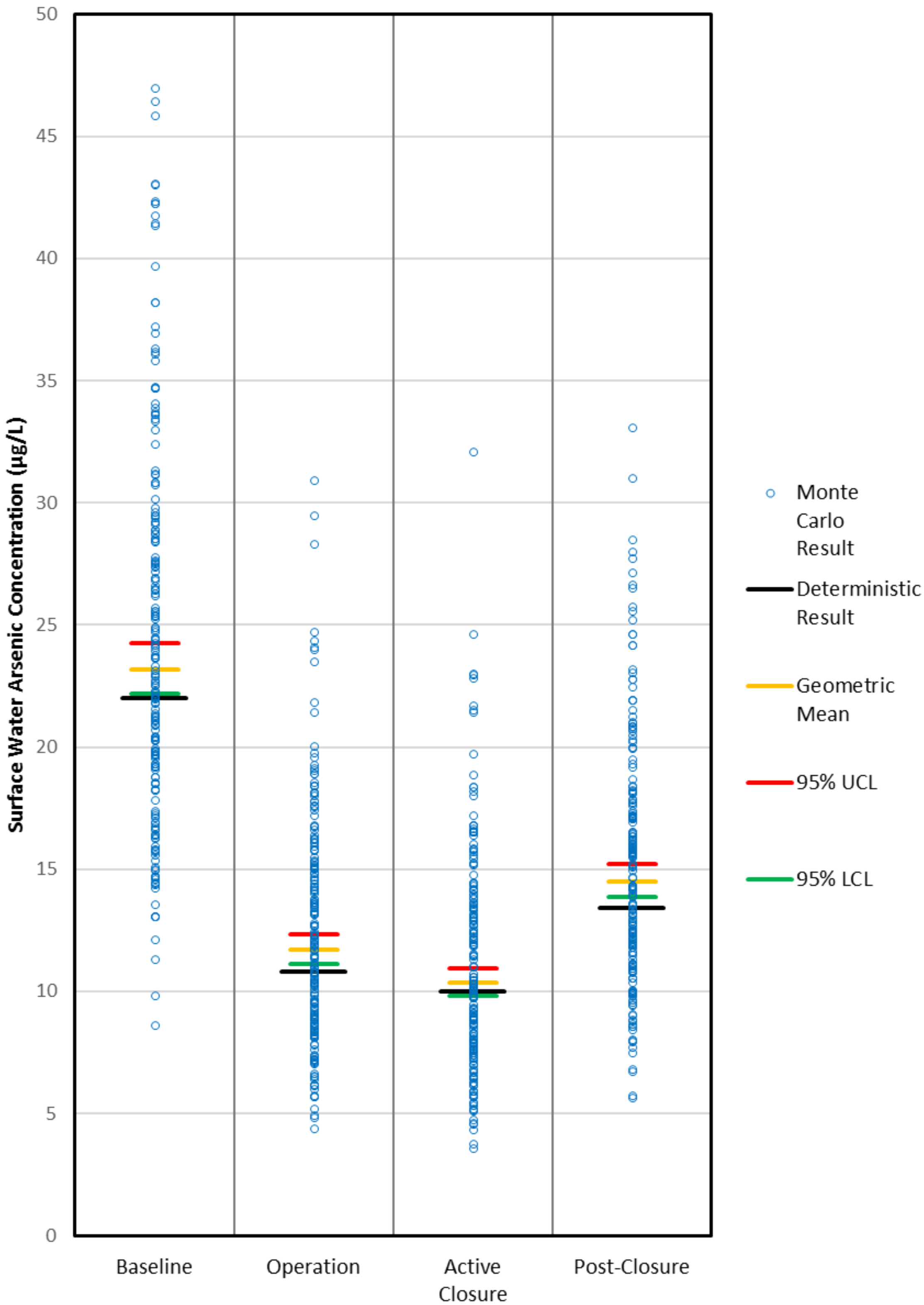

Figure 5-4 Annual Geometric Mean Arsenic Concentration (µg/L) Central Basin West

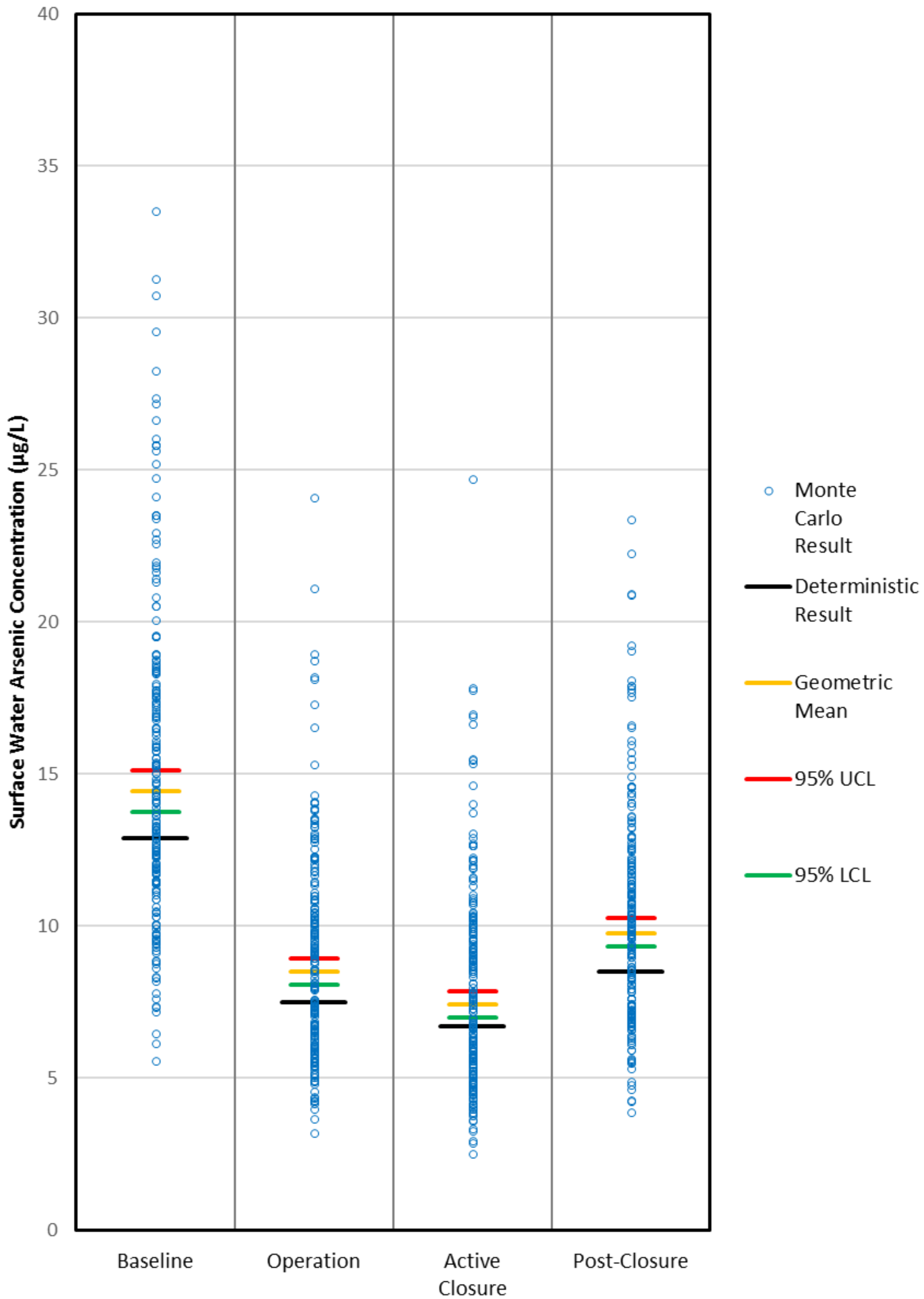

Figure 5-5 Annual Geometric Mean Arsenic Concentration (µg/L) for Central Basin East

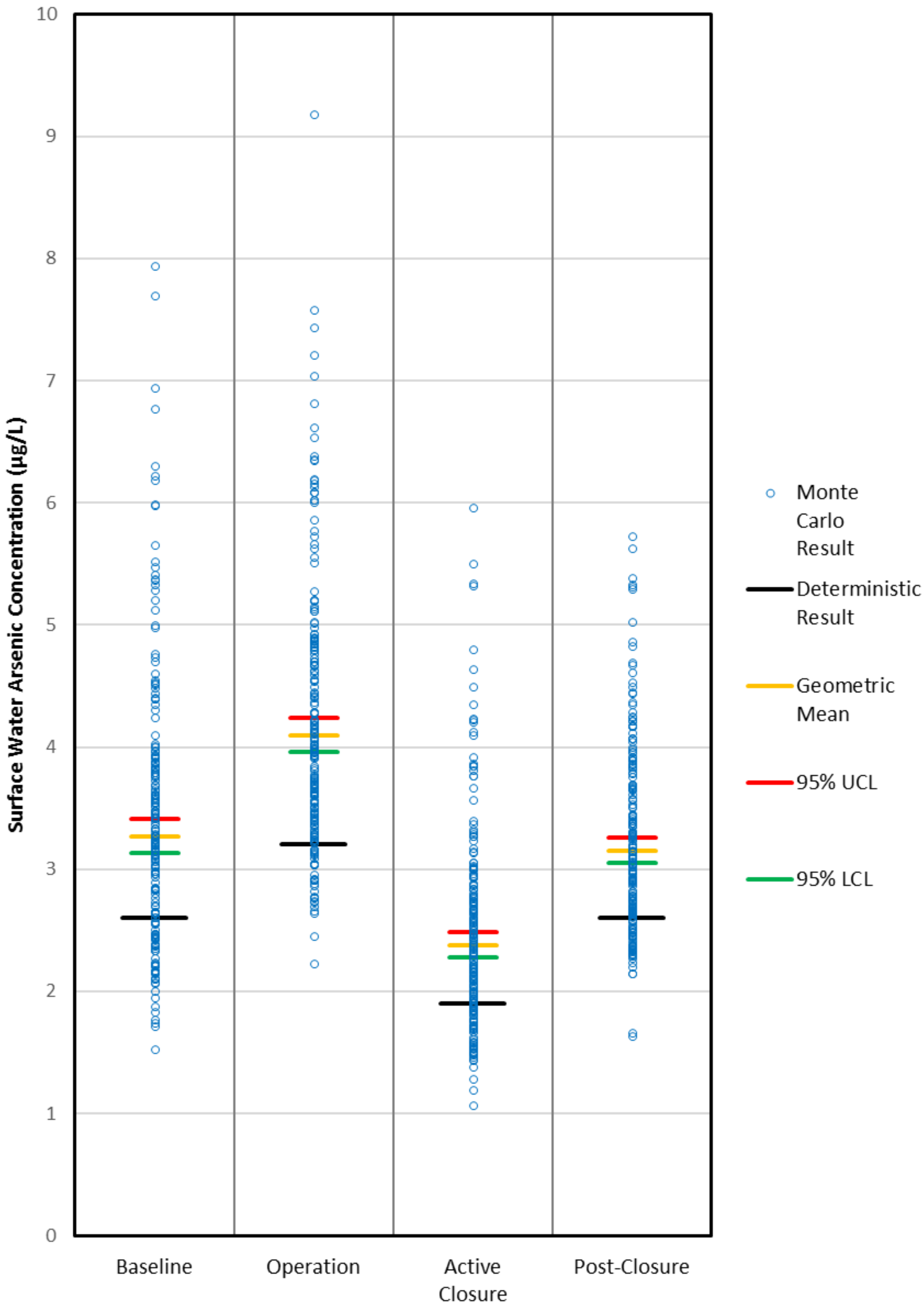

Figure 5-6 Annual Geometric Mean Arsenic Concentration (µg/L) for Soutwest Arm

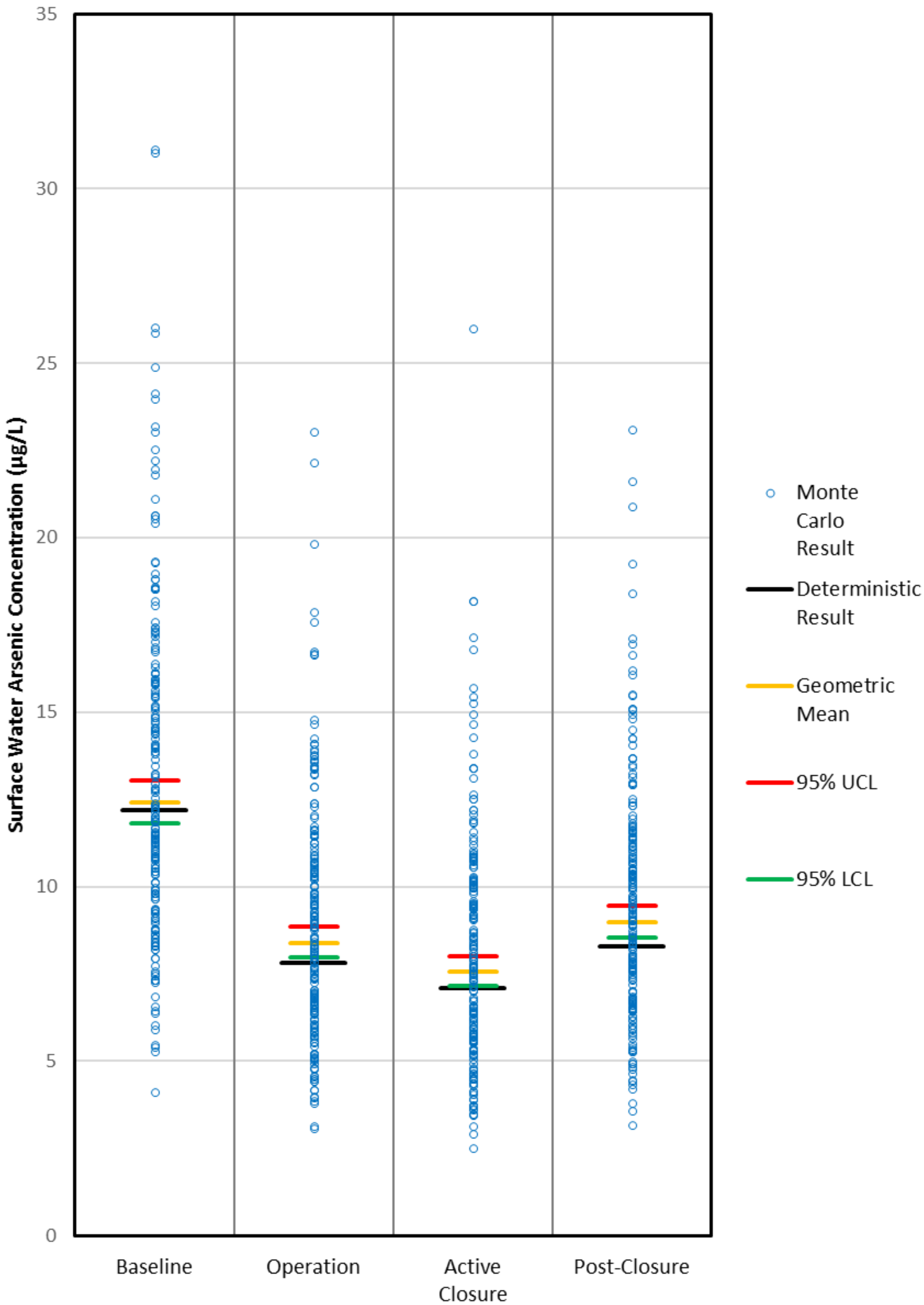

Figure 5-7 Annual Geometric Mean Arsenic Concentration (µg/L) for Outflow Basin

Figure 5-6 shows the range of predicted arsenic concentrations in SWA during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 3.3 µg/L (95%CI 3.1 to 3.4 µg/L) are slightly higher than the deterministic model prediction (2.6 µg/L). During Operation, the arsenic concentration in the water of SWA is predicted to increase slightly as a result of Project activities. The Monte Carlo model predicts a geometric mean of 4.1 µg/L (95%CI of 4.0 to 4.2 µg/L) during Operation. However, the arsenic concentrations in SWA are predicted to decrease slightly during Active Closure, with a Monte Carlo predicted geometric mean of 2.4 µg/L (95%CI 2.3 to 2.5 µg/L). The deterministic model predictions during these Project phases were 3.2 and 1.9 µg/L, respectively. In Post-Closure, the Monte Carlo model predicts a return of the surface water arsenic concentration of SWA to conditions similar to that observed during the Baseline phase (with a geometric mean of 3.2 µg/L and 95%CI of 3.1 to 3.3 µg/L). The deterministic model prediction for this phase was 2.6 µg/L. Although there is a very small predicted increase in the surface water arsenic concentration of SWA during Operation, this is offset by much larger predicted decreases in the arsenic concentrations of other lake sub-basins, notably BBE, CBW, CBE and OB. The predicted changes in arsenic concentration for Kenogamisis Lake as a whole are therefore consistent with the objectives of Water Management, Policy 2.

Figure 5-7 shows the range of predicted arsenic concentrations in OB during the four phases of the Project. The Monte Carlo model results for the Baseline phase, with a geometric mean arsenic concentration of 12.4 µg/L (95%CI 11.8 to 13.0 µg/L) are similar to the deterministic model prediction (12.2 µg/L). During Operation and Active Closure, the arsenic concentrations in the water of OB are predicted to decrease (with geometric mean of 8.4 µg/L and 95%CI of 8.0 to 8.8 µg/L during Operation, and geometric mean of 7.6 µg/L and 95%CI of 7.1 to 8.0 µg/L during Active Closure). The deterministic model predictions during these Project phases were 7.8 and 7.1 µg/L, respectively. The Monte Carlo model predicts a slight increase in the surface water arsenic concentration of OB between Active Closure and Post-Closure (with a geometric mean in Post-Closure of 9.0 µg/L and 95%CI of 8.5 to 9.4 µg/L). The previous deterministic model prediction for this phase was 8.3 µg/L. The predicted arsenic concentrations in Post-Closure remain significantly below the predicted concentrations for the Baseline phase, consistent with the objectives of Water Management, Policy 2.

5.2 SEASONAL PATTERNS OF ARSENIC CONCENTRATIONS IN SURFACE WATER

Figures 5-8 through 5-13 show seasonal trends in surface water arsenic concentrations. In these Figures, the Monte Carlo predictions are summarized as the geometric mean monthly arsenic concentrations in surface water, with bars representing the 95%UCL and 95%LCL values. The deterministic model results (from Stantec 2018) are also plotted on these Figures, as are data points representing the empirical total arsenic concentration data for the period 2013 to 2016.

For BBW (Figure 5-8), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally consistent with the range of values provided previously using the deterministic model (Stantec 2018). In these comparisons, it must be noted that the Monte Carlo results are shown as the mean and confidence interval of the mean, whereas the deterministic model results are shown as predicted daily values, and that the range of individual values over the course of a single month will always be greater than the confidence interval for the monthly mean value. The measured arsenic concentrations in BBW (data from water quality monitoring Station 2, see Figure 1-1 for Station locations) over the period 2013 to 2016 are also shown in Figure 5-8. The Monte Carlo model predictions of monthly mean arsenic concentration are also generally consistent with the measured values. For BBW, the results for subsequent Project phases (i.e., Operation, Active Closure and Post-Closure) are essentially unchanged from Baseline.

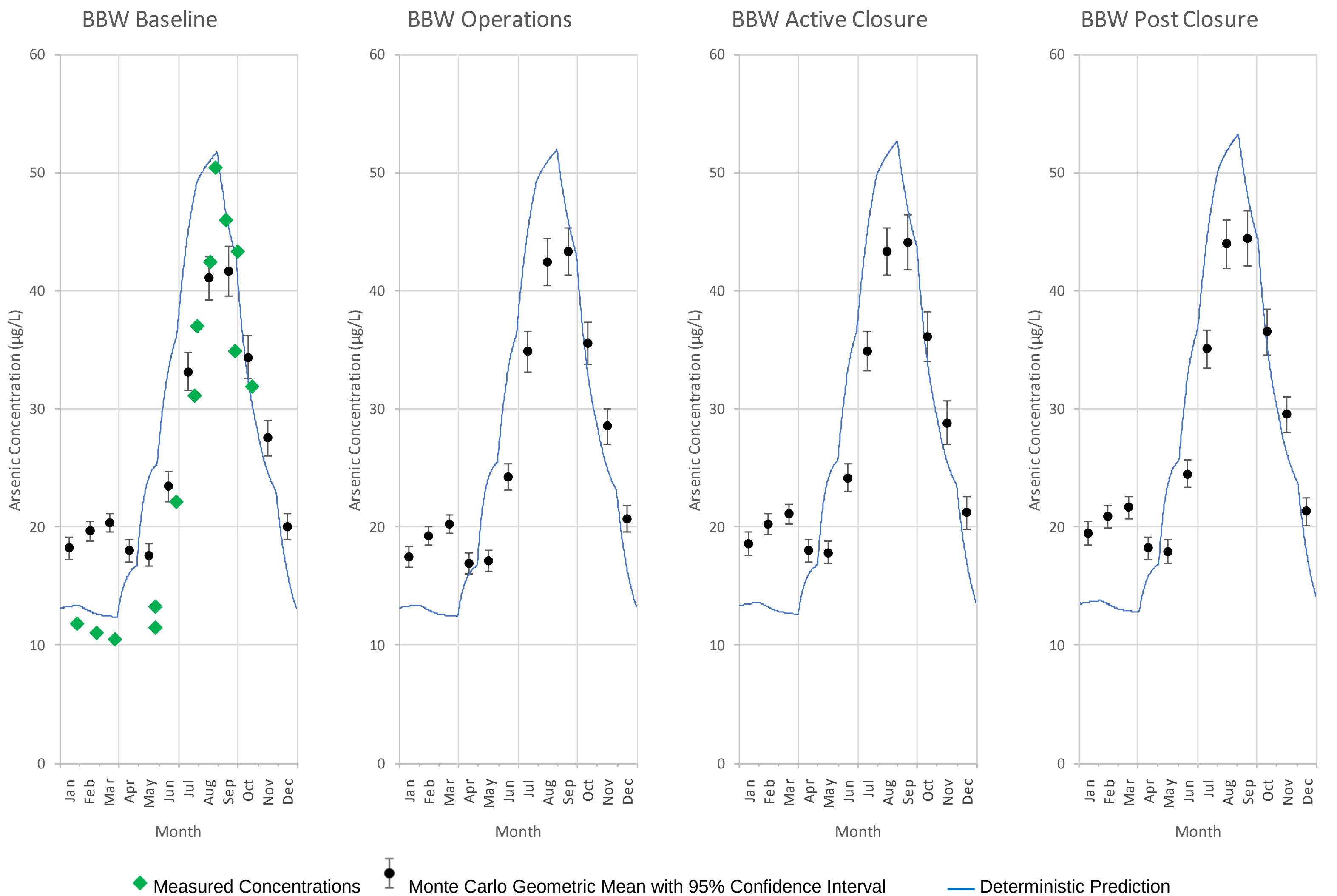

Figure 5-8 Monthly Geometric Mean Arsenic Concentration (µg/L) for Barton Bay West including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 2 Between 2013 and 2016

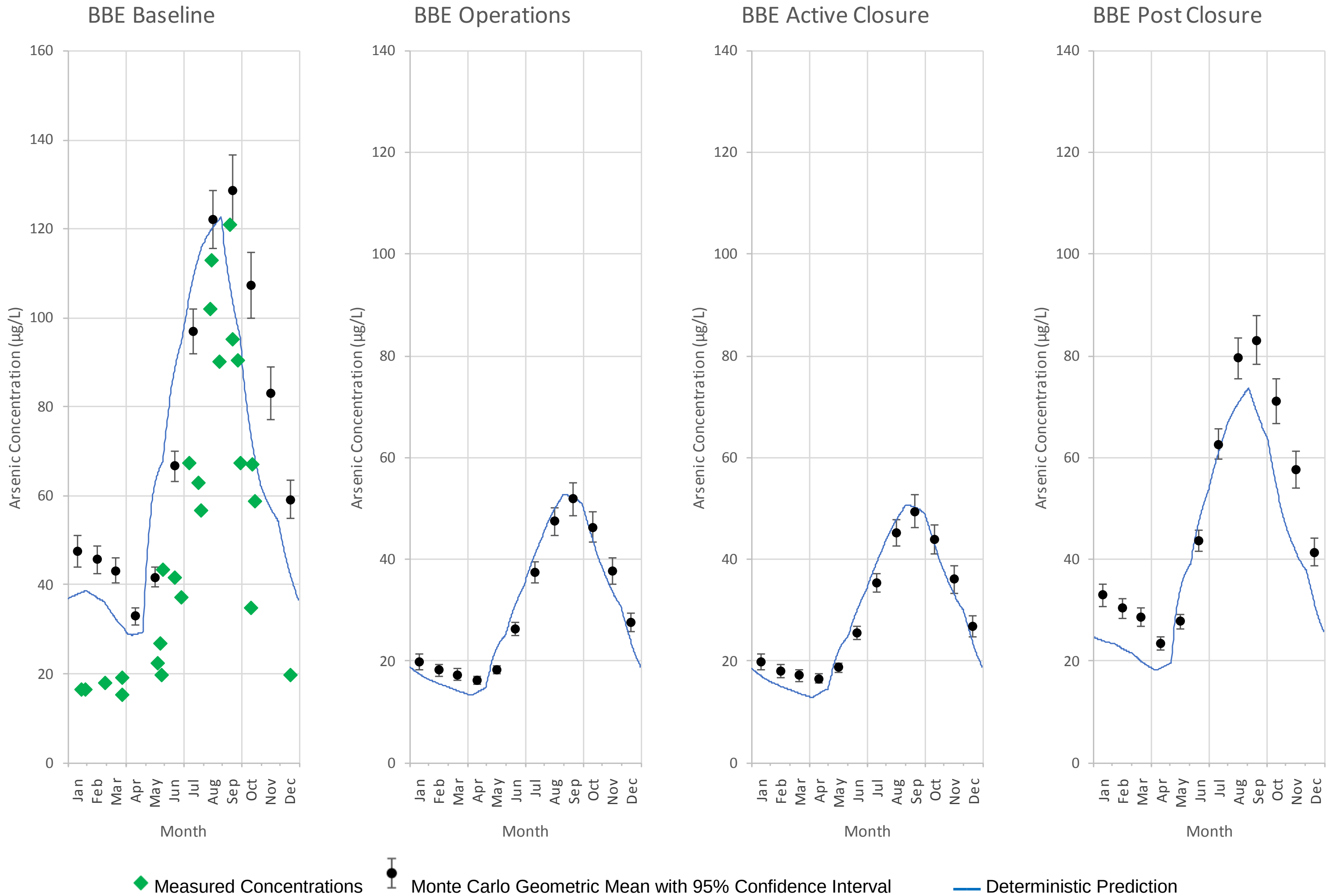

Figure 5-9 Monthly Geometric Mean Arsenic Concentration (µg/L) for Barton Bay East including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 4 Between 2013 and 2016

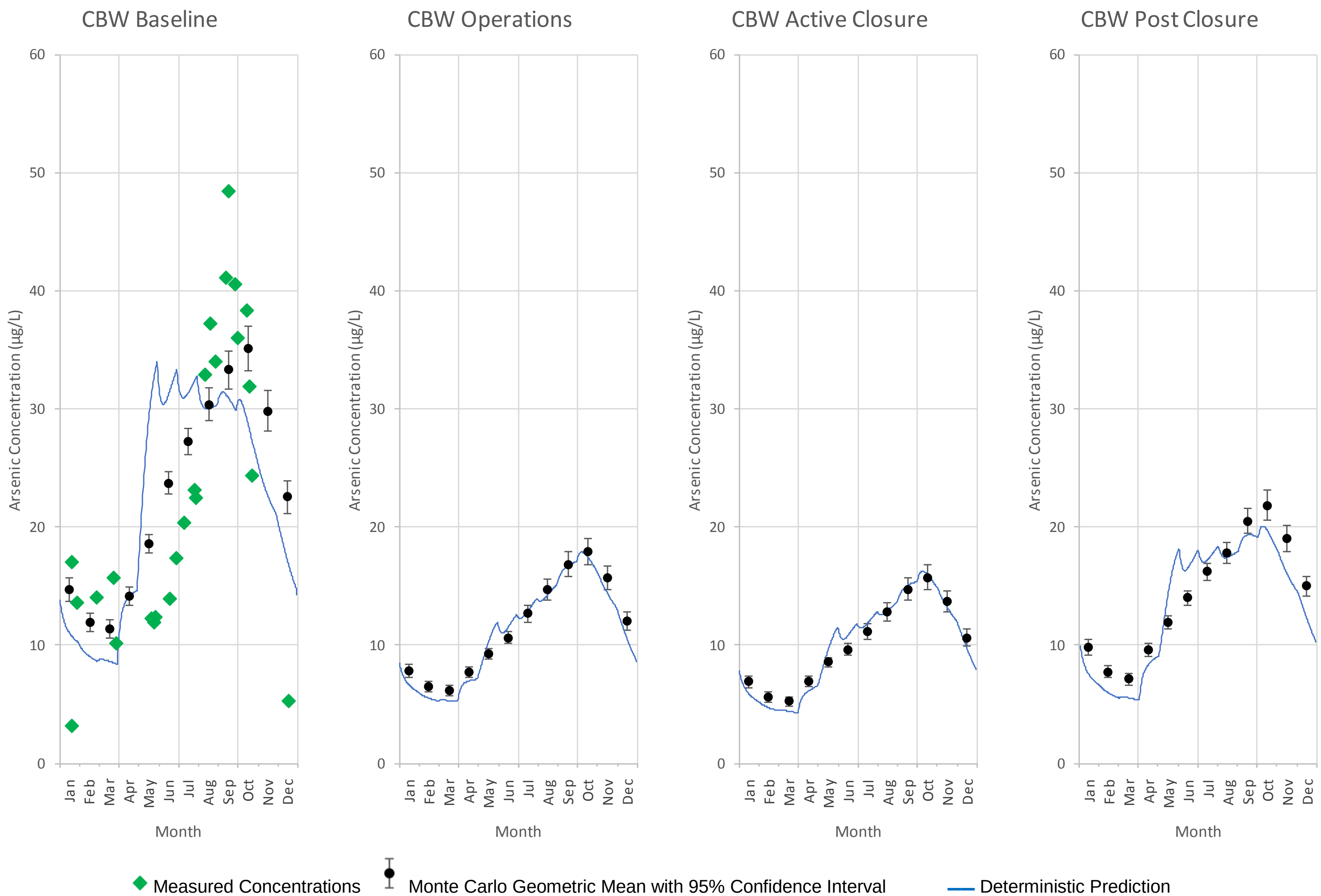

Figure 5-10 Monthly Geometric Mean Arsenic Concentration (µg/L) for Central Basin West including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 7 Between 2013 and 2016

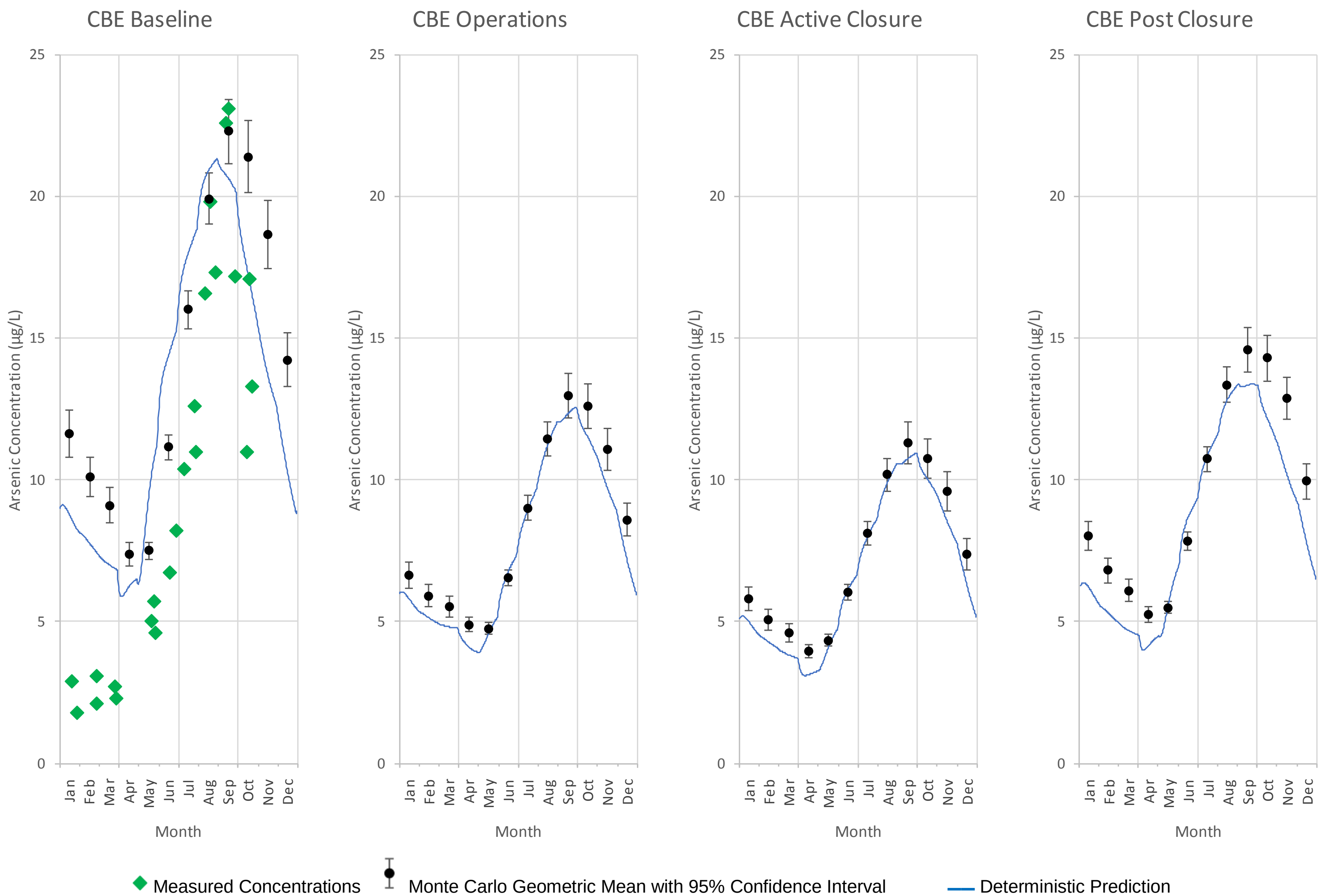

Figure 5-11 Monthly Geometric Mean Arsenic Concentration (µg/L) for Central Basin East including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 8 Between 2013 and 2016

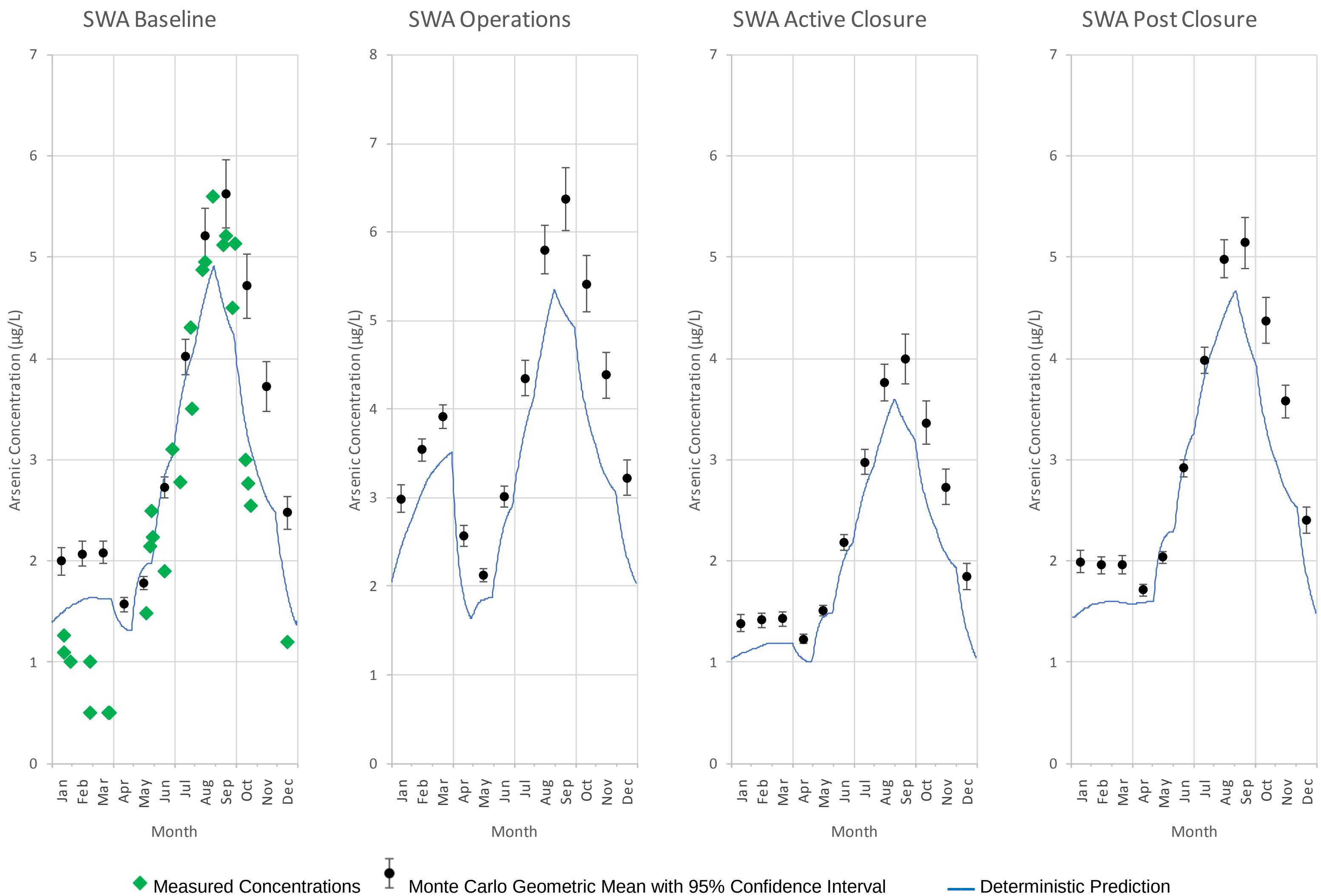

Figure 5-12 Monthly Geometric Mean Arsenic Concentration (µg/L) for Southwest Arm including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 1 Between 2013 and 2016

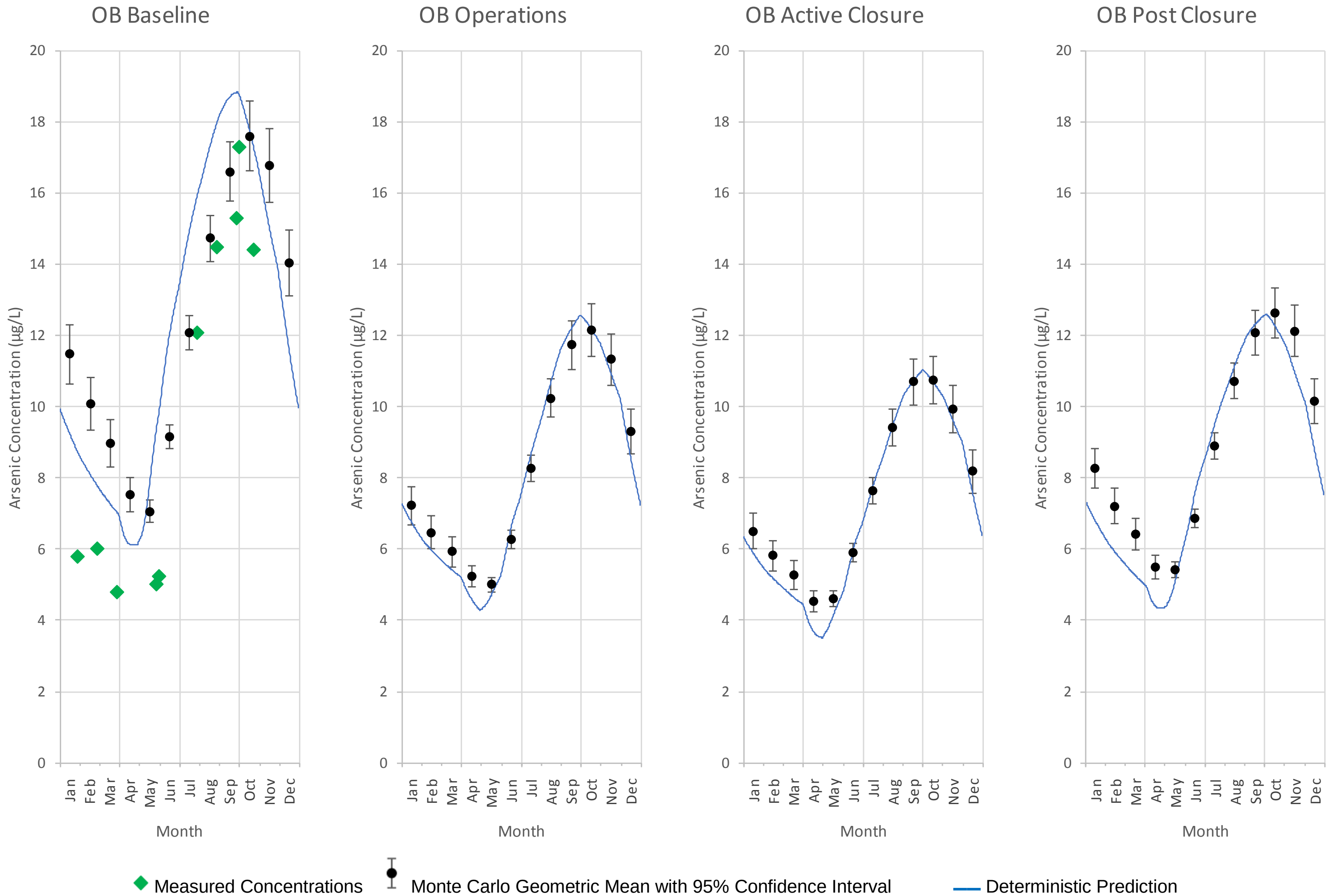

Figure 5-13 Monthly Geometric Mean Arsenic Concentration (µg/L) for Outflow Basin including Monte Carlo Model Output, Deterministic Model Output, and Values Measured at Surface Water Monitoring Station 11 Between 2013 and 2016

For BBE (Figure 5-9), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally higher than the range of values provided previously using the deterministic model (Stantec 2018), as well as the empirically-measured arsenic concentrations from water quality monitoring Station 4 during the period 2013 to 2016. This is most pronounced during the winter period (January to March) when both the deterministic and Monte Carlo models overpredict the measured arsenic concentrations. This overprediction during winter period is attributed to the difficulty in partitioning steady-state groundwater flow rates determined from the three-dimensional groundwater flow model into monthly discharge rates. The Monte Carlo model predictions of monthly mean arsenic concentration for BBE tend to be higher than the measured values, suggesting that the arsenic loadings used to model arsenic concentrations in BBE are conservatively estimated (i.e., the loadings used in the model are higher than the true loadings). For BBE, the results for subsequent Project phases (i.e., Operation, Active Closure and Post-Closure) are essentially the same when the deterministic and Monte Carlo model results are compared, showing arsenic concentrations that are significantly lower than the concentrations at Baseline.

For CBW (Figure 5-10), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally consistent with the range of values provided previously using the deterministic model (Stantec 2018. The Monte Carlo and deterministic model results are generally similar and are in general agreement with the empirically-measured arsenic concentrations from water quality monitoring Station 7 during the period 2013 to 2016. For CBW, the results for subsequent Project phases (i.e., Operation, Active Closure and Post-Closure) are essentially the same when the deterministic and Monte Carlo model results are compared. The results for Operation and Active Closure show arsenic concentrations that are significantly lower than the concentrations at Baseline. The arsenic concentrations are predicted to increase slightly between Active Closure and Post-Closure but remain significantly lower than at Baseline.

For CBE (Figure 5-11), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally consistent with the range of values provided previously using the deterministic model (Stantec 2018). The empirically-measured arsenic concentrations from water quality monitoring Station 8 during the period 2013 to 2016 are also plotted in Figure 5-11. Divergence between the modelled and measured arsenic concentrations occurs in the early months of the year (January, February and March) when the model predictions are higher than the measured values. This result is due to the relatively high modelled concentrations of arsenic present in BBE during these months, mixing with the water coming from SWA in CBE. For CBE, the results for subsequent Project phases (i.e., Operation, Active Closure and Post-Closure) are similar when the deterministic and Monte Carlo model results are compared, showing arsenic concentrations that are significantly lower than the concentrations at Baseline. The results for Operation and Active Closure show arsenic concentrations that are significantly lower than the concentrations at Baseline. Arsenic concentrations are predicted to increase slightly between Active Closure and Post-Closure but remain significantly lower than at Baseline.

For SWA (Figure 5-12), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally consistent with the range of values provided previously using the deterministic model (Stantec 2018), as well as the empirically-measured arsenic concentrations from water quality monitoring Station 1 during the period 2013 to 2016. The model results show a general increase in arsenic concentrations in the lake water from Baseline to Operation, although the increase is generally less than 1 µg/L. A sharp rise in the modelled arsenic concentrations in water during January, February and March of the Operation phase is attributed to the discharge of treated mine effluent. The mine effluent discharge is treated as a constant source of arsenic loading during Operation, and the increase in predicted arsenic concentration in water for SWA is the result of seasonally low surface water runoff during these months. The results for subsequent Project phases (i.e., Active Closure and Post-Closure) are essentially the same when the deterministic and Monte Carlo model results are compared, showing arsenic concentrations that are lower than the concentrations at Baseline during Active Closure, returning to concentrations similar to Baseline in Post-Closure.

For OB (Figure 5-13), the geometric mean monthly arsenic concentrations in surface water from the Monte Carlo model are generally consistent with the range of values provided previously using the deterministic model (Stantec 2018), as well as the empirically-measured arsenic concentrations from water quality monitoring Station 11 during the period 2013 to 2016. To the extent that the modelled arsenic concentrations tend to be higher than the measured values, this result is due to the conservatively estimated concentrations of arsenic present in BBE, and exported downstream through the Central Basin to OB. For OB, the results for subsequent Project phases (i.e., Operation, Active Closure and Post-Closure) are essentially the same when the deterministic and Monte Carlo model results are compared, showing arsenic concentrations that are significantly lower than the concentrations at Baseline.

5.3 CONSERVATISM IN THE MONTE CARLO SIMULATIONS

Inspection of the monthly mean and mean annual arsenic concentration data has identified a tendency for some of the model results to be higher than the measured data, and for the Monte Carlo model results to be higher than the deterministic model results. These tendencies can be termed conservative tendencies in the sense that the model results tend to be higher than the empirically-measured values.

Conservatism arises in the Monte Carlo model results through several pathways.

- Arsenic loadings to BBE (and to a lesser extent other sub-basins) from groundwater flow appear to be over-estimated. This involves particularly the arsenic loadings associated with the historic MacLeod tailings, which account for almost 95% of the direct arsenic loading to BBE (i.e., 2,613 of 2,764 kg/year at Baseline). The arsenic loading to BBE from these tailings could be over-estimated as a result of over-estimating the average groundwater arsenic concentration to characterize the discharge, over-estimating the groundwater flow and discharge predicted in the three-dimensional groundwater flow model, or both of these terms; or not accounting for attenuation of arsenic concentrations in the groundwater flow system prior to discharge to BBE. Reducing the loading from BBE would subsequently extend to sub-basins downstream of BBE, including CBW, CBE and OB, and result in slight improvements in the model results in comparison to measured Baseline conditions.

- Independently of the arsenic loading to BBE, several parameter values were assigned log-normal distributions. The log-normal distribution is not symmetrical, but instead is skewed towards higher values, causing a tendency towards higher arsenic concentrations in water. In some cases, these parameter values can interact leading to still higher modelled arsenic concentrations in water. Examples of parameters that are subject to such effects include several of the arsenic loading terms (through the estimated values of the arsenic concentration in groundwater), as well as the water to sediment transfer rate, and the sediment-water partition coefficient for arsenic. Each of these when examined in isolation was found to be capable of introducing a conservative tendency on the order of 3 to 5% in the Monte Carlo results.

Due to these factors, a positive bias results in the deterministic model and is accentuated in the Monte Carlo model results. However, the Monte Carlo model results and seasonal trends remain closely aligned with empirical measurements of the behavior of arsenic in the water of Kenogamisis Lake. Conclusions arising from the Monte Carlo model results are consistent with the results of earlier deterministic modelling.

Most importantly, the Monte Carlo model results demonstrate that as the Project goes ahead, future arsenic concentrations in BBE, CBW, CBE and OB will be significantly lower than present-day concentrations, and that the magnitude of these reduced arsenic concentrations will be much greater than the slight increase in arsenic concentrations predicted in SWA during Operation. The expected reductions in arsenic loading to BBE, CBW and SWA arise because a large part of the historical tailings that are responsible for the groundwater loading of arsenic to Kenogamisis Lake will be physically removed and placed in the new Tailings Management Facility, and the remaining tailings will be rehabilitated with an enhanced cover applied that will reduce infiltration of groundwater. These measures will unquestionably reduce the arsenic loading to the lake. The Monte Carlo model shows expected mean annual arsenic concentrations in Barton Bay East during Operation and Active Closure that are less than 50% of the existing (Baseline) concentration; and during Post-Closure that are about 65% of the Baseline concentration. In this context, the Monte Carlo results provide further assurance to the previous deterministic model results (Stantec 2018) and the Final EIS / EA (Stantec 2017) finding, that the Policy 2 objective for water quality will be achieved for arsenic.

6.0 CONCLUSIONS

The Hardrock Project includes development of an open pit mine in an area presently occupied in part by portions of the historical MacLeod and Hardrock tailings. Enhanced reclamation of the historical MacLeod and Hardrock tailings as part of the Project plan, in combination with the changes in groundwater flow due to dewatering of the open pit, will substantially reduce arsenic loadings to Kenogamisis Lake, and in particular to Barton Bay, even when accounting for the discharge to the SWA of treated mine effluent during Project operations, and pit lake discharge during post-closure.

A deterministic mass balance model of lake water and sediment (Stantec 2018) was previously developed to support prediction of arsenic concentrations in water and sediment of Kenogamisis Lake, and was implemented in the STELLA™ modelling framework. The objectives of that modelling were to:

- Develop and perform an initial calibration of the model by evaluating historical arsenic loading based on arsenic concentrations in water and sediment in the various sub-basins of Kenogamisis Lake.
- Conduct a sensitivity analysis on the initial model calibration to demonstrate the sensitivity of the overall model to certain key parameter values.
- Perform a detailed calibration of the model by simulating arsenic concentrations measured in lake water (2001 – 2011 data) and sediment (2011 data) as reported by Parks Environmental Inc. (2011, 2012).
- Validate the calibrated model by simulating arsenic concentrations in lake water (2013 – 2017 data) and sediment (2013 – 2016 data) as reported by Stantec (2017).
- Provide estimates of future arsenic concentrations in the lake water, based on the mine development plan, to support a human health risk assessment for the Project.
- Evaluate present day and expected future fluxes of arsenic between sub-basins, and between water and sediment, to provide further insight into the behavior of arsenic within the lake.
- Evaluate the potential effects of changing precipitation patterns between 2020 and 2100, resulting from a climate change scenario, on predicted future arsenic concentrations in lake water and sediment.

The deterministic model reproduced the main features of the seasonal cycle of arsenic concentrations in water, as well as historical accumulation of arsenic in sediment. The expected future reductions in arsenic loading to Kenogamisis Lake were deemed to be of sufficient magnitude that the model predictions were reliable indicators of the relative magnitude of future arsenic concentrations in water and sediment. Without changes due to the Project, arsenic concentrations in water and sediment would be expected to remain similar to concentrations that have been observed over the past decade.

Following review by MOECC staff (MOECC 2018a) it was confirmed that Stantec had satisfied the MOECC technical comments on the deterministic modelling of arsenic in Kenogamisis Lake. However, it was noted that a comment remained outstanding, that “appropriate confidence intervals for the STELLA™ modelling tool are needed” in the context of the Water Management, Policy 2 with respect to arsenic concentrations in the lake water. The memorandum outlined a suggested Monte Carlo approach to evaluating the uncertainty in STELLA^{TM} model predictions of arsenic concentrations in the water of Kenogamisis Lake.

The Monte Carlo model results are consistent with and support the results of the deterministic modelling. Importantly, it is shown through the Monte Carlo uncertainty analysis tool that the projected future reductions in arsenic concentrations in Kenogamisis Lake will be significant, and will achieve the Water Management, Policy 2 objective for arsenic in the lake water.

With the Project plan, there will be a significant overall reduction in arsenic loading and concentrations in Barton Bay East, the Central Basin, and the Outflow Basin of Kenogamisis Lake. When compared with present day Baseline conditions, arsenic concentrations in the water of SWA will increase slightly during Operation (2018 to 2033), due to point and non-point source discharges associated with the Project. The arsenic concentration will decrease during Active Closure while the open pit is filling, and then increase slightly again (to concentrations similar to present-day concentrations) in Post-Closure, when the open pit is filled and begins to discharge to the SWA. The slight increase in total arsenic concentrations in the water of SWA during Operation will be more than offset by substantial decreases in total arsenic concentrations in the waters of BBE, CBW, CBE and OB.

The significant net positive effects that are predicted can be attributed to Project design measures addressing historical tailings within the Project Development Area, thereby meeting the intent of the MOECC Policy 2 designation for arsenic in Kenogamisis Lake.

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7.1 PERSONAL COMMUNCIATIONS

G. Crooks, M.Eng., P.Eng., Principal, Atmospheric Engineer. Stantec Consulting Ltd. Email: Airborne deposition of arsenic to Kenogamisis Lake. May 1, 2018.

APPENDIX A

Workshop Report from May 31, 2018 in Guelph, Ontario

Parameters for Monte Carlo Analysis of Arsenic Concentrations in Water, Kenogamisis Lake

FINAL REPORT

June 6, 2018

File: 160961223

Prepared for:

Greenstone Goldmine GP Inc.

Prepared by:

Stantec Consulting Ltd

Sign-off Sheet

We have participated in the review of the proposed parameters for the Arsenic Monte Carlo analysis. In our professional opinion, the specific parameters, and ranges and distribution for each parameter reflect accepted statistical practices above those routinely applied by industry and will achieve the stated objective of confirming the 95% confidence intervals for estimated minimum, mean and maximum annual concentrations of Arsenic over the four key phases of the Project (i.e., Baseline, operations, Closure and Post-Closure). The content of this report accurately reflects the conclusions of the expert review team convened by Greenstone Gold Mines GP Inc.

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1.0 INTRODUCTION / BACKGROUND

Stantec Consulting Ltd. (Stantec) (2018) has previously developed a model of arsenic concentrations in the water and sediments of Kenogamisis Lake, near Geraldton, Ontario. The model was implemented using a commercially available software system known as “STELLA”, and the model of arsenic in the water and sediments of Kenogamisis Lake is often referred to as “the STELLA model”. The purpose of that deterministic modelling effort was to provide further detail and support for arsenic inputs to inform the Human Health Risk Assessment for the Final Environmental Impact Statement (EIS) / Environmental Assessment (EA) completed for the Greenstone Gold Mines GGM Ltd. (GGM) Hardrock Project published in 2017.

A recent memorandum from the Ontario Ministry of the Environment and Climate Change (MOECC) confirms that Stantec has largely satisfied the MOECC technical comments on the deterministic modelling of arsenic in Kenogamisis Lake (J. Martherus, May 1, 2018). However, the memorandum also notes that there remains an outstanding comment that “appropriate confidence intervals for the STELLA modelling tool are needed” (Martherus 2018). The MOECC memorandum suggests a “Monte Carlo” approach to evaluating the uncertainty in STELLA model predictions of arsenic concentrations in the water of Kenogamisis Lake.

The objective of this technical memorandum is to document the adopted approach used to characterize key input parameter ranges for this Monte Carlo exercise. The presented approach is to be used to generate the a statistical distribution of potential arsenic concentrations in the waters of Kenogamisis Lake (i.e., the six sub-basins; Barton Bay West (BBW), Barton Bay East (BBE), Southwest Arm (SWA), Central Basin East (CBE), Central Basin West (CBW), Outlet Basin (OB)), over the four key phases of the Project (i.e., Baseline, Operations, Closure and Post-closure); and to provide 95% confidence intervals for the estimated minimum, mean, and maximum annual concentrations for each lake sub-basin and Project phase.

2.0 OVERVIEW OF APPROACH AND METHODOLOGY

Mishra (2009) outlines four main steps in application of the Monte Carlo methodology for uncertainty analysis:

- **Selection of imprecisely known model input parameters to be sampled.** The goal of this step is to identify and retain only those input variables that have the greatest impact on the outcomes of interest. It may be carried out using subjective judgment, standard (one parameter at a time) sensitivity analysis, or randomized (one parameter at a time) screening (Mishra 2009). This step identifies two key aspects of parameter selection. First, if the model input parameter value is known precisely, then it may be treated as a constant rather than a variable. Second, even if the value of the model input parameter is not precisely known, it may be excluded from the Monte Carlo analysis if the parameter of interest is not sensitive to the variation.

- **Assigning ranges and probability distributions for each selected parameter.** This step involves fitting distributions to measured data using various estimation techniques, or deriving distributions using known constraints with conservative assumptions to avoid under-estimating uncertainty. Expert judgement is also a valid approach to the derivation of probability distributions (Stephens et al. 1993).

- **Generating many sample sets with randomly selected values of model parameters.** This step is a mechanical process of using a random number generator to create input files for the numerical model (corresponding to the selected parameters and their statistical distributions).

- **Running the model for the many sets of model parameters to accumulate model outcomes, with subsequent statistical analysis of the key output variable(s) and uncertainty.** This procedure is relatively inefficient, though robust (often requiring several hundred independent simulations). The results are typically post-processed to determine the central tendency and statistical properties of the parameter(s) of interest (e.g., the mean and 95% confidence interval for the predicted result).

Two key criteria were therefore considered in the selection of input parameters to be included in the Monte Carlo Simulation (MCS):

- The model output of interest (i.e., the predicted arsenic concentration in lake water) must be sensitive to variation in the input parameter; and

- The value or values of the model input parameter must be imprecisely known.

3.0 UNCERTAINTY AND VARIABILITY

It is important to differentiate between uncertainty and variability relative to the calibrated value of a parameter (Haimes et al. 1994).

Where a parameter value cannot be directly measured and is subject to uncertainty, then it is reasonable to allow such parameters to vary, and to apply random uncertainty once (at the start of the simulation), holding the randomly determined value as a fixed quantity over the course of a single simulation.

Where a parameter value has been measured, and the magnitude and temporal pattern of variation is well understood, then it is reasonable to apply random variation on a monthly, seasonal, or annual basis in accordance with documented patterns and magnitude of variation.

For some parameter values, it may be unclear as to whether uncertainty or variability is the dominant feature, and the application of random variation in the PDF may be subject to professional judgement reflecting one or both of these factors.

4.0 MOECC LIST OF RECOMMENDED MONTE CARLO PARAMETERS

The MOECC memorandum (J. Martherus, May 1, 2018) included a list of suggested parameters to consider in the MCS, as follow:

- Arsenic loadings (air, surface water, groundwater and unrecognized sources)
- Concentration of arsenic in sediments
- Hydrology (precipitation and runoff)
- Hydraulic flushing
- Air and water temperatures
- Sedimentation rate
- Transfer rate for suspended solids from water to sediment
- Solid-water partition coefficient for arsenic
- Total suspended solids concentration in the lake
- Iron concentration in each sub-basin (as it may affect transfer of arsenic from water to sediment).

Table 1 addresses the list of parameters suggested in the MOECC memorandum and outlines the approach that Stantec will take to address the suggested parameters and implement the MCS.

5.0 EXPERT REVIEW OF MONTE CARLO PARAMETERS

Monte Carlo analysis often uses expert judgment as one method to select the model input parameters and assign ranges and probability distributions for each selected parameter.

To validate the approach, input parameters and ranges and distributions that were being proposed by Stantec, GGM convened an expert review team to review, discuss and conclude on the proposed implementation of the stochastic modelling to be completed in the STELLA Model of Arsenic Cycling in Kenogamisis Lake.

The review team was composed of the following experts:

- **Craig Johnston, M.Sc. P.Geo., SLR Consulting (Canada) Ltd.** – Craig is a professional geoscientist in Ontario and has over 27 years experience in the field of groundwater and geochemical processes. Craig provided technical oversight of water related areas of the Final EIS/EA, contributed as an author and reviewed several of the Final EIS/EA chapters and supporting appendices.
- **Dr. Christopher Wren, Ph.D., LRG Environmental** – Dr. Wren is a Water Quality Specialist with over 30 years' experience in environmental consulting providing services to industry and government with a focus on the mining and aggregate sector in Canada and internationally. His particular areas of expertise are in water quality, fisheries science, human health and ecological risk assessment, environmental toxicology and environmental monitoring. He obtained his Ph.D. in Aquatic Sciences from the University of Guelph in 1983 and undertook Postdoctoral research in Environmental Toxicology at University of Toronto and Trondheim, Norway.
- **Mr. Mike Jones, M.Sc., P.Geo., Azimuth Environmental Consulting, Inc** – Mr. Jones is a founding member and President of Azimuth Environmental Consulting. Mr. Jones is a Senior Hydrogeologist with 30 years of experience and his areas of specialty include water supply and wastewater treatment, ground water geochemistry and contaminant hydrogeology. He has provided expert testimony before the Joint Board, the Ontario Municipal Board, the Environmental Review Tribunal and civil court.
- **Mr. Greg Rose, B.Sc. (Hons), M.Sc., Golder Associates Ltd**. – Mr. Rose is a water resources specialist with over 15 years of experience in the investigation and analysis of surface water systems. He has completed numerous multi-year, large-scale programs including watershed monitoring and modelling studies, hydrodynamic, water quality and contaminant transport, modelling investigations, environmental assessments and development impact evaluations.
- **Mr. Peter Thompson, M.A.Sc., P.Eng., GeoProcess Research Associates** – Mr. Thompson is a Senior Hydrologist and Hydrologic Modeller and his specific areas of focus include the analysis of groundwater/surface water interactions with numerical models, the effects of urbanization on the hydrologic regime, future impacts of climate change on a watershed scale, and in-stream ecological flow needs assessment. He has constructed, calibrated, and applied environmental numerical models in multiple domains including hydraulic (HEC-RAS, WaterCAD), hydrologic (PRMS, HEC-HMS, HBV), hydrogeologic (MODFLOW-NWT, FEFLOW) as well as integrated groundwater/surface water (GSFLOW) models.

The objectives of the expert review team were to:

- validate whether the parameters included in the Monte Carlo analysis (either directly or indirectly through another parameter) are consistent with standard practice and are reasonable in the context of the Monte Carlo objectives;
- confirm whether the scientific basis for the assumptions on iron/arsenic cycling are sound, and are appropriately considered in the Monte Carlo analysis; and
- confirm whether the basis of the range and distribution for each parameter is appropriate.

The expert review team was provided with documentation on the "Proposed Implementation of Stochasticity in the STELLA Model of Arsenic Cycling in Kenogamisis Lake" ahead of the review session. Other documentation that was requested and provided during and after the session included:

- MOECC comment letter titled, "Review Comments on GGM/Stantec's Proposal for establishing next steps on addressing the STELLA Model Uncertainty" (E-mail date April 23, 2018 10:17 AM)
- Update to: Mass Balance Modelling of Arsenic Concentrations in Water and Sediment of Kenogamisis Lake, Geraldton, Ontario. Report prepared by Stantec Consulting Ltd. for Greenstone Gold Mines GP Inc., February 1, 2018.

The expert review team met in person in Guelph at the Stantec offices on May 30, 2018. Dr. Malcolm Stephenson (Stantec) started the session by providing background and context on the initial mass balance model, the subsequent STELLA Model for arsenic and an overview of the status of the current work on the Monte Carlo model.

The group then reviewed and discussed in detail each parameter suggested by the MOECC as well as one additional parameter (the diffusive flux multiplier) that was proposed by Stantec. The discussion covered how the parameter was considered in the model, any correlation between various parameters, the approach to establishing the range for each parameter and the basis for selecting the distribution type and distribution limits (triangular, normal, log-normal, other). The review team agreed to the representation of each parameter as represented in Table 5-1, subject to the following two considerations.

The expert review team recommended further follow up and analysis on the following:

- Groundwater – consider whether the baseline data would support the development of a statistical approach for the distributions based on measured concentration variability in the individual wells, rather than a triangular approach; and
- Iron – provide additional explanation of the relationships between iron and arsenic geochemistry and cycling in lakes, and justification for the conclusion that changes in the iron loadings to BBE are not likely to materially affect arsenic cycling in Kenogamisis Lake over the course of the Project.

This final report reflects the results of the expert review team discussions and input, subsequent analysis as recommended, and final report review comments by the expert review team.

Table 5-1: Proposed Monte Carlo Approach to Parameters Included in the STELLA Model, or Suggested by MOECC

Parameter	Relevance and Uncertainty Characterization	Additional Information and Adopted Probability Density Functions (PDF)
Arsenic Loadings: From Atmospheric Deposition on Lake Surface	Future loadings to Kenogamisis Lake from atmospheric deposition over the lake surface during mine Operations and Closure have been modeled but are subject to uncertainty. This parameter is randomized as part of MCS. Note: the As loading from air is very small relative to other sources and will have little effect on As cycling in the lake.	Estimated Project-induced atmospheric arsenic deposition values to the surface of sub-basins of Kenogamisis Lake are small (range 2-13 kg/year) and apply only during Operations and Closure. The air quality modeling team indicated (G. Crooks, pers. comm.) that the estimated deposition values may vary by up to a factor of 2. The existing values of arsenic deposition to each sub-basin of the lake are modified by random variates. The random variates have log-normal distributions, with geometric mean (GM) of 0 and geometric standard deviation (GSD) of 0.15. The probability density functions (PDF) are truncated at ±2 GSD. This results in random variate PDFs that have minimum values of 0.5, maximum values of 2.0 and means of 1.0. These PDFs are applied independently to each sub-basin of Kenogamisis Lake, with values that remain fixed for the duration of each simulation and are then replaced with new values for each subsequent simulation.
Arsenic Loadings: From Surface Water Runoff	Surface water flows and arsenic concentrations in stream inflows are based on long periods of measurement, so they are subject to documented variability, which is used to characterize uncertainty. This parameter is randomized as part of MCS.	Arsenic loadings from surface water inflows are represented as the product of estimated mean annual runoff (m^3/year), and mean arsenic concentration in the inflowing water (mg/m^3). For surface water flows, estimated mean annual flows are developed from a regional hydrology model based on measured flows at a set of 6 Environment Canada gauging stations located in the region. The variation in monthly mean flow was estimated from measured variation in monthly flow for the Neebing River (one of the rivers included in the regional hydrology model). A set of 12 PDFs was developed, one for each month of the year. These were applied as random variates to all 19 surface water inflows to Kenogamisis Lake in a like manner (as all stream inflows are subject to similar variations in precipitation and runoff). The PDF are log-normally distributed, with mean values of 1, and standard deviations reflecting actual variance in flow for the Neebing River. The PDFs and are truncated at ±3 GSD to restrict unreasonably large or small values. For arsenic concentrations in surface water, the surface water inflows are segregated into those “affected” (5 watercourses) and “unaffected” (14 watercourses) by historical and/or future mining activity. The affected watercourses have higher arsenic concentrations and greater variability than the unaffected watercourses. Variations in concentration (both seasonal trends and inherent variability) are informed by measured variability in the total arsenic concentrations from the historical monitoring data. These PDF are log-normally distributed, with GM of 0 and GSD of 0.31 (affected watercourses) and 0.15 (unaffected watercourses). This results in random variate PDFs that have means of 1. For the affected streams, minimum and maximum values were approximately 0.24 and 4.17, respectively. For unaffected streams, minimum and maximum values were approximately 0.5 and 2.0. These PDF are applied independently to streams flowing into each sub-basin of Kenogamisis Lake, with values vary randomly in each month of each simulation.

Parameter	Relevance and Uncertainty Characterization	Additional Information and Adopted Probability Density Functions (PDF)
Arsenic Loadings: From Groundwater Seepage	Groundwater flows are based on a steady-state model, and subject to uncertainty. Groundwater arsenic concentrations have been measured for some sources (e.g., the historic Hardrock and MacLeod Tailings), but not for others (e.g., facilities pertaining to the Project, that have not yet been constructed), and are subject to uncertainty. Groundwater from the historical tailings is considered one of the largest sources of arsenic to Kenogamisis Lake. This parameter is randomized as part of MCS.	Arsenic loadings from groundwater inflows are represented as the product of a predicted steady-state (annual average) groundwater flow (m^3/year) derived from the three-dimensional groundwater flow model, and an estimated arsenic concentration (mg/m^3) in the inflowing groundwater. For groundwater flows, a three-dimensional steady-state groundwater flow model was used to estimate mean annual flow to Kenogamisis Lake from each of the existing and proposed facilities. However, for the STELLA model, it was necessary to apportion the mean annual flow into monthly increments to account for the seasonality in groundwater discharge. The variation in monthly mean flow is estimated from measured variations in hydraulic head in the historical tailings deposits. This is reasonable since groundwater flow is directly proportional to the hydraulic heads. The data showed an increase in hydraulic head during May and June as a result of groundwater recharge, followed by a general decline in hydraulic head over the summer, fall and winter, reaching a low in April. On this basis, mean monthly groundwater flows were estimated to range from a high of 118% of mean annual flow in June, to a low of 82% of mean annual flow in April. The monthly flow adjustments are further subject to a random variate that is applied to all groundwater sources in a like manner (as all are subject to similar variations in recharge). These are characterized by log-normal distributions, with geometric mean (GM) of 0 and geometric standard deviation (GSD) of 0.15. The probability density functions (PDFs) are truncated at ±2 GSD. This results in random variate PDFs that have minimum values of 0.5, maximum values of 2.0 and means of 1.0. New, randomly generated values of the random variate for groundwater flow are applied in each year of every simulation. For arsenic concentrations in groundwater, two types of groundwater sources are considered: • Historical deposits (e.g., Hardrock, MacLeod, and Little Long Lac tailings; and Overburden and Bedrock storage area) and areas of natural groundwater, where monitoring data are available to estimate uncertainty in groundwater arsenic concentrations; and • Facilities that are proposed (but do not yet exist) and where geochemical testing data has been used to estimate a source concentration (e.g., Waste Rock Storage Areas, Overburden Stockpile, Ore Stockpile, Tailings Management Facility, Little Long Lac Tailings). Based on a suggestion from the expert review team, the arsenic concentration in groundwater monitoring data for wells located within the Hardrock and MacLeod tailings areas, and in areas of overburden and bedrock storage, were re-examined to determine whether the variation in arsenic concentrations could be estimated from these sources. The Little Long Lac tailings were not included in this analysis due to insufficient data. For each monitoring well having 3 or more measurements, the measured values were divided by the mean of the values for that well to provide a standardized measure of variability. The standardized values for each well located with the Hardrock, MacLeod, or overburden and bedrock storage were then combined to provide an aggregate measure of the standardized variation within each area. It was unclear whether a normal or log-normal distribution provided a better fit to the data sets. Therefore, a log-normal distribution was assumed, as this conservatively propagates a positive “skew” in the uncertainty. Based on the results for the Hardrock and MacLeod tailings, and the areas of overburden and bedrock storage, the PDF based on the log-normal distributions had a resulting GM value of 0 and GSD of 0.20. This resulted in a random variate PDF that had a mean value of 1, and was truncated at lower and upper limit values of approximately 0.40 and 2.51 respectively. This PDF was used as a random variate to adjust the mean value of the groundwater arsenic concentration for each of the groundwater sources (both existing and future). Specifically, the groundwater concentration for each groundwater source is multiplied by an independent random variate during each month of the model simulation to account for variability in arsenic concentrations. Broader concentration distribution boundaries (i.e., the maximum and minimum measured values from the underlying data), as recently suggested in a MOECC communication (REF), are not considered representative of the average arsenic concentration in groundwater flowing into Kenogamisis Lake (an aggregate parameter), and this suggestion was rejected to avoid substantial over- and/or under-estimation of loadings.
Arsenic Loadings: From Unknown Source	This source of arsenic loading is treated as a groundwater source in the model and is subject to uncertainty. This parameter is randomized as part of MCS.	An additional arsenic loading of 400 kg/year was identified as required in the deterministic version of the STELLA Model to calibrate to observed sediment and water concentrations in BBW. The estimated additional value of 400 kg/year resulted in conservative predictions of water quality in BBW, and therefore this is considered to be an upper limit for the additional arsenic loading (i.e., it is not greater than 400 kg/year). This input is treated as an additional (unknown) groundwater source, as the surface water inflows to BBW are well characterized with respect to both watershed area and arsenic concentrations. This PDF has a triangular distribution, with a mode of 350 kg/year, and limits of 300 to 400 kg/year. A new, randomly generated value for the unrecognized arsenic loading to BBW is applied at the start of every simulation.

Parameter	Relevance and Uncertainty Characterization	Additional Information and Adopted Probability Density Functions (PDF)
Concentration of arsenic in sediments	While this parameter is included in the STELLA model it will not be randomized in the MCS because: • this parameter is accurately known from sediment cores, which integrate sediment over long periods of time, and • the arsenic concentrations in the lake water are not sensitive to the initial arsenic concentrations in sediment.	The arsenic concentration of sediments is both an input and an output of the model. The initial sediment arsenic concentrations are treated as constants (values assumed for the year 1920), based on concentrations measured from the lower portions (pre-mining deposits) of sediment cores from different sub-basins of the lake. The values implemented in the deterministic STELLA model are 10 mg/kg for SWA, CBW, CBE and OB, and 50 mg/kg for BBW and BBE.
Hydrology (precipitation and runoff)	The STELLA model accepts monthly average runoff values as inputs for hydrology, and these are included in the MCS. Precipitation is effectively captured through the runoff parameter in the STELLA model, and not explicitly represented as a model input. Runoff is randomized as part of the MCS process.	PDF for monthly average runoff values for the individual stream inputs to Kenogamisis Lake are used. See: Arsenic Loadings: Surface Water. This parameter explicitly captures the hydrologic variability within the streamflow inputs to the STELLA model.
Hydraulic flushing (water residence time)	The STELLA model accounts for hydraulic flushing as being directly related to the monthly runoff from inflowing streams and groundwater, and the volumes of the individual sub-basins. Runoff is randomized as part of the MCS process.	Individual sub-basin volumes are treated as constants, as they are known to a high level of precision from extensive bathymetric measurements carried out as part of the EA/EIS program. See: Arsenic Loadings: Surface Water
Air and water temperatures	The effects of seasonal temperature variations (e.g., winter freezing, and evapotranspiration) are effectively captured in the use of runoff data as described above; in estimates of arsenic loading from atmospheric deposition; and in the diffusive flux multiplier for arsenic exchange between sediment and water. Hence, they are not included as explicit variables in the STELLA model.	See: Arsenic Loadings: Surface Water, Arsenic Loadings: Air, and Diffusive Flux Multiplier for Arsenic Exchange Between Sediment and Water for additional information.
Sedimentation rate	It has previously been demonstrated through sensitivity analysis of the STELLA model (Stantec, Feb. 1, 2018) that the arsenic concentration in lake water has very low sensitivity to variation in the assumed sedimentation rate for the lake.	Sedimentation rate is included in the STELLA model but will not be included in the MCS since the model output of interest (i.e., the predicted arsenic concentration in lake water) is not sensitive to variation in this input parameter.
Water to sediment transfer rate for arsenic	The water to sediment transfer rate for arsenic has been calibrated and validated within each sub-basin as part of the deterministic model development process but has not been directly measured. It remains subject to uncertainty. This parameter is randomized as part of MCS.	The water to sediment transfer rate for arsenic (α_{As}) is randomized as part of MCS. This parameter was subject to calibration during the model development process, and values for the various sub-basins implicitly reflect variations in other factors, such as the availability of iron and total suspended solids in the lake water, and iron in the sediment deposits. See also discussion of iron cycling below. A random variate (PDF) having a log-normal distribution, with geometric mean (GM) of 0 and geometric standard deviation (GSD) of 0.15 is applied to the calibrated values of α_{As}. The probability density function is truncated at ±2 GSD. This results in a random variate PDF that has a minimum value of 0.5, maximum value of 2.0 and mean of 1.0. This PDF is applied to all values of α_{As} for a given simulation, and a new random value is applied in all subsequent simulations. This PDF will also be applied to variations in the sediment solid-water partition coefficient, as the two parameters are closely related.

Parameter	Relevance and Uncertainty Characterization	Additional Information and Adopted Probability Density Functions (PDF)
Solid-water partition coefficient for arsenic	The solid-water partition coefficient for arsenic has been calibrated and validated within each sub-basin but has not been directly measured. It remains subject to uncertainty. This parameter is randomized as part of MCS.	The sediment-water partition coefficient for arsenic (Kd_{As}) is randomized as part of MCS. Due to the expected high degree of correlation between the rate of arsenic deposition to sediment and the retention of arsenic in sediment, the same random variate that is used to modify values of α_{As} is also applied to values of Kd_{As}.
Total suspended solids (TSS) concentration in the lake	TSS is involved in the process of arsenic deposition from the water column to sediment in the lake. This parameter is effectively captured in the water to sediment transfer rate for arsenic and is not included as a separate model variable.	See: Solid-Water Partition Coefficient for Arsenic
Iron concentration in each basin	The effect of iron availability relates to sedimentation and binding of arsenic in lake sediments and was considered in the model calibration and validation processes. It is effectively captured in the specification of a random variate PDF to modify the water to sediment transfer rate, and solid-water partition coefficient for arsenic.	Both arsenate and arsenite have low overall reactivity or binding strength with particles, when compared to more commonly studied trace metals. This is supported by measurements in Kenogamisis Lake where about 90% of total arsenic in the water column is in dissolved rather than particulate form. One consequence of this low overall binding strength is that net rates of arsenic deposition from water to sediment are low. Kenogamisis Lake has a large catchment area, and the sub-basins of the lake are all subject to rapid flushing rates, so that the average water residence time in any sub-basin is on the order of 6 weeks or less. As a direct consequence of these rapid flushing rates and the low particle reactivity of arsenic, the principal fate of arsenic in Kenogamisis Lake is to be flushed to a downstream sub-basin. Sedimentation is the secondary fate, and only a portion of the arsenic that is deposited to sediment will subsequently diffuse back to the water as an internal load. Iron loading to BBW will not change as a result of the Project. Similar to arsenic loadings, iron loading to BBE will decline relative to baseline loadings during Project Operations and Active Closure, and will increase slightly (although still remaining below the baseline loading) in Post-Closure. These reductions in iron loadings are not of sufficient magnitude to materially affect the geochemistry of arsenic in this sub-basin. Iron will remain relatively abundant in the surface water relative to arsenic, and the substantial reservoir of iron present in sediments will ensure that no significant change to arsenic cycling will occur. Conversely, the predicted reductions in arsenic loading will not have any effect on the geochemical behavior of iron in Kenogamisis Lake. Relationships between iron availability and arsenic cycling in Kenogamisis Lake are implicitly captured and reflected in the calibrated values of α_{As} and Kd_{As} in the STELLA model, and as such will not be considered separately in the MCS. Additional information on iron and arsenic cycling in Kenogamisis Lake can be found in Section 6.0 of this report.
Diffusive flux multiplier for arsenic exchange between sediment and water	The diffusive flux multiplier for arsenic has been calibrated and validated for Kenogamisis Lake but has not been directly measured. It remains subject to uncertainty. This parameter is randomized as part of MCS.	Soluble arsenic is assumed to diffuse from sediment to overlying water. During the winter months when there is ice cover, this exchange is limited to molecular diffusion. During the ice-free season when there is wind mixing of the water column as well as greater biological activity, an enhanced rate of exchange is allowed as defined by the diffusive flux multiplier. The calibrated value of the diffusive flux multiplier was 3 (unitless). The PDF for this parameter has a triangular distribution, with a mode of 3 and limits of 1 and 5. This PDF is applied randomly to all values of the diffusive flux multiplier during the ice-free season in a given simulation, and a new random variate is applied in all subsequent simulations.

6.0 IRON / ARSENIC INTERACTION

6.1 INTRODUCTION

This section has been prepared to address questions about iron and arsenic geochemistry and cycling in Kenogamisis Lake. The following key points are presented as a summary of the work completed:

- Both arsenate and arsenite (the common forms of arsenic in fresh water) have low overall reactivity or binding strength to particulate matter, including iron hydroxides within the water column, when compared to more commonly studied trace metals. This observation is supported in Kenogamisis Lake by numerous measurements conducted as part of the EA/EIS, showing that about 90% of total arsenic in the water column exists in dissolved form.
- One consequence of this low overall binding strength is that net rates of arsenic deposition from water to sediment are low.
- Kenogamisis Lake has a large catchment area, and the sub-basins of the lake are all subject to rapid flushing rates, so that the average water residence time in any sub-basin is on the order of 6 weeks or less. As a direct consequence of these rapid flushing rates and the low particle reactivity of arsenic, the principal fate (approximately 65-75%) of arsenic in Kenogamisis Lake is to be flushed to a downstream sub-basin. Sedimentation is the secondary fate (25-35%), and only a portion of the arsenic that is deposited to sediment will subsequently diffuse back to the water as an internal load.
- Iron loading to BBW will not change as a result of the Project.
- Similar to arsenic loadings, iron loading to BBE will decline relative to baseline loadings during Project Operations and Active Closure, and will increase slightly (although still remaining below the baseline loading) in Post-Closure. These reductions in iron loadings are not of sufficient magnitude to materially affect the geochemistry of arsenic in this sub-basin. Iron will remain abundant relative to arsenic in the surface water. The substantial reservoir of iron present in sediments will prevent change to arsenic cycling. Conversely, the predicted reduction in arsenic loading will not have any effect on the geochemical behavior of iron in Kenogamisis Lake because arsenic is a trace element relative to iron, and does not exhibit any geochemical characteristics that would cause it to regulate the behavior of iron.
- The mass balance equation describing how arsenic behaves in the lake water (in response to flushing and sedimentation) is provided below.

6.2 BACKGROUND

The role iron plays in controlling arsenic concentrations in water and sediment is related to oxidation and reduction reactions. In the water column, as reduced iron (Fe^{2+}) enters Kenogamisis Lake it will be oxidized to Fe^{3+} and form precipitates of iron hydroxides, typically in combination with humic substances (organic matter). During this process, small amounts of arsenic can be bound within the iron hydroxide structure, resulting in the deposition of iron and arsenic to sediment. The arsenic typically represents a minor component of the iron floc. Laboratory studies (Crecelius 1975, Fuller and Davis 1989) suggest arsenic to iron ratios of up to 3%. Field measurements of arsenic to iron ratios in the sediments of

Kenogamisis Lake (data from Parks Environmental Inc. 2012) show ratios ranging from 1.4% in BBE, to 0.2% in the SWA and OB.

Once in the sediments, the decomposition of organic matter reduces oxygen concentrations and lowers the redox potential within the sediment profile. Under these conditions, the iron hydroxide solids can become reduced and result in the re-release of dissolved (reduced) iron and arsenic to sediment pore-water, from which it can diffuse back into the overlying water column at rates determined by the overlying concentration gradient.

The process of sedimentation and removal of arsenic from the water column plays a limited role in the cycling of arsenic within Kenogamisis Lake. For example, under baseline conditions in BBE, which has the highest iron concentrations in both water and sediment, the model-estimated arsenic mass transfer to sediment is approximately 1,300 kg/year (Stantec 2018), while the total arsenic loading to the water of BBE is approximately 4,800 kg/year. Most of the arsenic entering BBE (approximately 3,500 kg/year) is flushed with water flow to the downstream basin, CBW (Stantec 2018). This is consistent with the work of Kuhn and Sigg (1993) who concluded that particle formation and sedimentation play only a limited role in the cycling of arsenic because the binding coefficients for arsenic on suspended sediment particles tend to be low (i.e., only a small fraction of the inorganic arsenic in the water column is found to be bound to settling particles). This observation is also supported by measurements of total and dissolved arsenic in Kenogamisis Lake where approximately 90% of the total arsenic was found to be present in dissolved form, regardless of which sub-basin the measurements were taken in, or the corresponding iron concentrations (Environmental Baseline Data Report (combined 2014 and 2015) – Hardrock Project: Surface Water Quality; Appendix E4 of the Final EIS/EA, Parks Environmental Inc. 2011).

As discussed in a Memorandum prepared by Stantec and SLR Consulting dated May 14, 2018, total iron concentrations for each basin are predicted to decrease by up to 47% during operations and active closure, and 36% in post-closure due primarily to the removal of historical MacLeod and Hardrock tailings and capping of the remaining historical MacLeod high tailings (see Table 6-1). While these reductions in iron concentrations represent improvements in water quality in Kenogamisis Lake and will achieve the Policy 2 Provincial Water Quality Objective for iron, both BBW and BBE are projected to remain relatively iron-rich, and as a result, deposition of iron hydrous oxide flocs will continue to provide for the removal of arsenic from water to sediment through the processes discussed above.

Table 6-1: Table 1 (From Stantec and SLR Consulting Memorandum dated May 14, 2018) Summary of Measured and Predicted Mean Total Iron Concentrations (µg/L) for Sub-Basins of Kenogamisis Lake, During Different Project Phases

Basin	Baseline	Operations	Active Closure	Post-Closure
Barton Bay West	275	275 (0%)	275 (0%)	275 (0%)
Barton Bay East	319	233 (-27%)	233 (-27%)	266 (-17%)
Southwest Arm	115	98 (-14%)	90 (-21%)	95 (-17%)
Central Basin	145	84 (-42%)	79 (-45%)	93 (-36%)
Outlet Basin	109	66 (-39%)	58 (-47%)	72 (-34%)

6.3 RESPONSE TO INFORMATION REQUEST

The following provides our response to the two specific MOECC Questions:

1. How iron was considered in the arsenic modeling exercise?
2. How GGM considered the relationship between arsenic and iron in their modelling and a clear understanding of the interrelationship between iron and arsenic?

The STELLA model of arsenic cycling in Kenogamisis Lake (Stantec 2018) accounts for the availability of iron in the water and sediments of the lake through two model variables: the water to sediment transfer rate for arsenic (α_{As}) and the solid-water partition coefficient for arsenic in sediment (Kd_{As}), as described below.

For water, the STELLA model was developed based on the approach by Bird et al. (1993) and uses the following mass balance equation to describe the behavior of arsenic in the lake water:

$$dM_{As}(t)/dt = L_{As} - ((A_d \times R(t)/V) + \alpha_{As}) \times M_{As}(t)$$

Where:

- $M_{As}(t)$ is the mass of arsenic in the lake at time t,
- L_{As} is the arsenic loading to the lake (kg/time), including arsenic loading from atmospheric deposition, surface water runoff, groundwater, and sediment-to-water exchange processes.
- A_d is the drainage area (m^2) supplying runoff to the lake or lake sub-basin,
- R is the amount of runoff (m/time) supplying water to the lake or lake sub-basin,
- V is the volume of the lake or lake sub-basin (m^3), and
- α_{As} is the rate constant describing the net rate of arsenic transfer between the water column and the sediment of the lake or lake sub-basin.

The arsenic concentration at any given time (t) in the water of a lake sub-basin is calculated as the mass of arsenic present at a specific time ($M_{As}(t)$) in water, divided by the volume of water in the lake sub-basin. Based on the studies to date we have reliable measurements of arsenic concentrations in each sub-basin over time as well as very good volume calculations of each sub-basin.

The sedimentation process through which arsenic is moved from water to sediment is governed by the term α_{As}. To account for the variations in water quality amongst the basins, the α_{As} rate constant was varied during calibration and sensitivity analysis. The initial variations considered the differences in water quality between the basins, and in particular the iron concentrations. Through the model calibration and validation process it was determined that higher α_{As} rate constants were required in BBW and BBE, than in other basins, to match observed arsenic concentrations in water, and to simultaneously account for the arsenic concentrations in sediment. These values are correlated with mean iron concentrations in the respective sub-basins of Kenogamisis Lake (Table 2).

Table 6-2: Model Parameters and Calibration Related to Arsenic Cycling between Sediment and Water, and Comparison to Mean Iron Concentrations in Water and Sediment

Sub-Basin	Calibrated Value of α_{As} (1/year)	Mean Iron Concentration in Water (µg/L)	Calibrated Value of Kd_{As} (m^3/kg)	Mean Iron Concentration in Sediment (mg/kg)
BBW	4	275	3	27,062
BBE	4	319	3.5	48,330
CBW	3	168	3	37,750
CBE	2.5	112	2	24,783
SWA	2	115	1.5	15,329
OB	2	109	1.5	12,548

Note: Sediment data from Parks Environmental Inc. (2012). Other data from Stantec.

Arsenic that is deposited to sediments in a sub-basin typically remains in the sediments, although there is also provision in the model for diffusion of soluble arsenic from the sediments back into the overlying water column. To model this process, the dissolved arsenic concentration in the sediment pore water was estimated using a solid-liquid partition coefficient (Kd_{As}, m^3/kg), so that the diffusion of arsenic from sediment back to the overlying water column could be represented in the model. The values of Kd_{As} (see Table 2) also reflect the availability of iron in the sediments of the various sub-basins.

The model calibration process established the final values of α_{As} and Kd_{As} for each sub-basin, which are generally proportional to the availability of iron in the various sub-basins.

The water quality assessment work (Chapter 10 of the Final EIS/EA) indicates that there is a predicted decrease of both arsenic and iron loadings and concentrations for Kenogamisis Lake, particularly for basins adjacent to historical tailings deposition such as BBE.

Barton Bay West, located upstream of BBE, will not be materially affected by the Project, and so this estimated loading remains essentially unchanged through all Project phases. Table 10-40 of Chapter 10 of the Final EIS/EA (Stantec 2017) presents estimated iron loadings to BBE over the various Project phases. At baseline, the total iron loading to BBE is estimated to be 58.9 kg/day, with the majority (36.9 kg/day or 63%) entering from the upstream basin, BBW. An estimated 3.8 kg/day (6%) enters BBE from other direct stream inflows, and 18.2 kg/day (31%) enters BBE with groundwater flow. Over 90% of the groundwater loading (16.6 kg/day) is associated with the historical MacLeod tailings.

When the Project commences, several factors (i.e., removal of some of the historical tailings, capping of remaining historical tailings, and groundwater drawdown caused by dewatering of the former underground workings and open pit mine) will reduce groundwater loadings of iron, arsenic, and other elements to Kenogamisis Lake, in particular BBE. As a result, during Operations and Active Closure, the total iron loading to BBE is expected to decrease from 58.9 kg/day to 41.7 kg/day (about a 30%

reduction). This decrease is due to the reductions of groundwater loadings. The iron loading to BBE from BBW will continue unchanged.

There will be no material effect of the Project on iron concentrations in BBW (where the baseline concentration is approximately 275 µg/L). Importantly, the reduced iron loading to BBE from groundwater is expected to result in improvement in water quality for this parameter, with concentrations during Operations and Active Closure expected to be around 233 µg/L, increasing slightly in Post-Closure to 266 µg/L. These changes will achieve the Policy 2 Provincial Water Quality Objective for a reduction in iron loading and improvement in water quality. However, the water of BBE will remain iron-rich in comparison to the other basins of Kenogamisis Lake (i.e., 266 µg/L in BBE compared to 161 µg/L in the SWA).

As with the iron loadings, a substantial reduction in arsenic loadings to BBE is also expected during Project Operations and Active Closure. Therefore, although there will be somewhat less iron available in the water of BBE, there will also be less arsenic seeking binding sites.

The sediments of BBE are iron-rich and will remain so for the foreseeable future. The mean concentration of iron in BBE is 48,330 mg/kg (Table 2) compared with a mean arsenic concentration of 684 mg/kg (from Parks Environmental Inc. 2012). Modelling of sediment arsenic concentrations (Stantec 2018) has shown that the sediments respond slowly (i.e., on a time-scale of decades to hundreds of years) to changes in metal deposition due to the thickness of the mixed layer. Therefore, the modest changes in iron loading that are expected in BBE will not materially affect the availability of iron in those sediments, nor will they affect the geochemical behavior of arsenic, as it relates to iron in the sediments.

Lastly, changes in the arsenic loadings to Kenogamisis Lake will not have any effect on the cycling or geochemistry of iron in the water or sediment. Arsenic is a trace element (<0.1% by weight in sediment) as compared to iron, which is a major element present at levels of up to 6% by weight in the sediment. Ratios of arsenic to iron in sediment presently range from about 1.4% by weight (in BBE) to 0.2% by weight (in SWA and OB).

6.4 CONCLUSIONS RELEVANT TO IRON / ARSENIC INTERACTION

The following presents the conclusions of this memo and documents the adopted approach used to characterize key input parameter ranges for this Monte Carlo exercise as requested by the MOECC and developed by an expert review team:

- Due to the Project, there is a predicted reduction in iron loading, and iron concentration in BBE and downstream sub-basins as a result of the proposed operation and removal of historical tailings.
- The above-noted prediction is considered to have high certainty.
- The reduced iron concentrations will achieve compliance with the Policy 2 Provincial Water Quality Objective.

- Despite iron reduction to Kenogamisis Lake both BBW and BBE are projected to remain iron-rich relative to arsenic, and as a result, the geochemistry and deposition of arsenic into sediments will not be materially affected by the Project.

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ANNEX A: REVIEW TEAM MEMBER CVs

CRAIG JOHNSTON, M.SC., P.GEO.

Chief Operating Officer / Senior Hydrogeologist

EDUCATION

- M.Sc., University of Waterloo / Hydrogeology, Waterloo, Ontario, 1994.
- B.Sc., McMaster University / Geology, Hamilton, Ontario, 1990.

TECHNICAL REGISTRATIONS

- Professional Geoscientist, Association of Professional Geoscientist of Ontario

Craig is the Chief Operating Officer of SLR Consulting (Canada) Ltd. where he has specific responsibility for operations management and growth of the business in Canada.

Over his 25-year career, Craig has worked for a wide variety of clients, including mining, petrochemical, manufacturing, transportation, resource based industries, and various municipal and federal government agencies. His efforts in the mining sector have been focused on developing technical teams and guiding clients on strategic approaches to address environmental approval and permitting challenges associated with mining projects, from initial project development through to closure and post closure.

Craig’s technical background is in hydrogeology where he focuses on the areas of groundwater supply development and protection, contaminant hydrogeology, and impact assessment related to resource development projects. Whether providing strategic advice, technical direction, or overall project management, Craig's technical experience, common sense approach, strong communication skills, and dedication to quality ensures that projects are delivered in a timely and cost effective manner.

SELECTED PROJECT EXPERIENCE

(project completed at another firm)**

MINING

- **Baseline Study for Greenstone Gold Mines Hardrock Project, Geraldton, Ontario (Senior Hydrogeologist)****
  In support of the baseline program and proposed mining plan, a detailed hydrogeologic assessment is being completed. The study is assessing shallow groundwater flow conditions in the area of the mine footprint, and the potential interaction between the shallow and deep groundwater systems. A key consideration in the assessment was establishing the interaction between the overlying lake, and the underlying resource which was proposed to be mined.
- **Environmental Assessment for Greenstone Gold Mines Hardrock Project, Geraldton, Ontario (Technical Director/Senior Hydrogeologist)****
  Technical direction on the overall Environmental Assessment with specific focus modelling and technical impact assessments related to surface water and groundwater and the overall integration of mine closure to address long term water quality. A key component of the role included presenting technical work to regulatory agencies and stakeholders and integration of the technical assessments into the overall Federal and Provincial Environmental Assessments.

- **Baseline Study and Dewatering Impact Analysis for Elmtree Resources Open Pit Gold Mine, New Brunswick (Senior Hydrogeologist)****
  A detailed hydrogeologic assessment was completed in support of a baseline study to document groundwater conditions in the area of the proposed mine, and to identify potential water users in the area, including the natural environment and private domestic wells. A conceptual hydrostratigraphic frameworks was developed and a groundwater flow model created to evaluate potential impacts of dewatering and to allow identification of key data gaps and uncertainty with respect to the proposed mine and dewatering plan.

- **Environmental Baseline Program for Alamos Gold's Proposed Open Pit Gold Mines at MacLellan and Farley Lake, Lynn Lake, Manitoba (Technical Director/Senior Hydrogeologist)****
  Stantec is completing the full environmental baseline program to support environmental assessment and approvals for the proposed MacLellan and Farley Lake open pit gold mines to be developed at the former brownfield sites. Technical and strategic direction was provided for the program development with direct oversight of the hydrology and hydrogeology baseline programs.

- **Preliminary Economic Assessment (PEA) of the Proposed Brookbank and Hardrock Mines, Geraldton, Ontario (Technical Reviewer)****
  Provided input and technical review of Section 20 of the PEA for the proposed Brookbank and Hardrock PEAs.

- **Environmental Permitting and Approvals for Northern Graphite's Proposed Bissett Creek Graphite Mine, Bissett, Ontario (Project Manager / Senior Hydrogeologist)****
  Strategic direction was provided to advance the proposed Bissett Creek Graphite Mine through the environmental approvals and permitting process. The approvals required completion of a MNRF and MNDM Class EA and environmental permitting related to Endangered Species Act, Permit to Take Water, Environmental Compliance Approvals for Air and Industrial Sewage, and several other MNRF, DFO, and local municipal approvals Technical review was provided on all technical components of the project, including the hydrogeology and hydrology baseline studies, water quality assessments, and the prediction of open pit dewatering requirements and impacts.

- **Evaluation of Mine Inflows at a Potash Corporation Mine in New Brunswick, New Brunswick (Senior Hydrogeologist)****
  In support of legal action, a review of available hydrogeologic, geologic, and mine operations data was completed to evaluate potential impacts of mine dewatering and inflows on shallow groundwater resources. Witness statements and technical supporting documents were prepared and an ultimate settlement was reached.

- **Baseline Monitoring for Yamana Gold's Monument Bay Gold/Tungsten Open Pit Mine, Manitoba (Project Director / Senior Hydrogeologist)****
  To support future permitting of the proposed open pit mine, a hydrogeologic baseline program was initiated to document regional hydrogeologic conditions and define seasonal variations in groundwater levels and quality. The first phase of the baseline program will be advanced in 2015 and involve more detailed assessment of groundwater/surface water interactions, characterization of hydrogeologic conditions in the overburden and shallow bedrock around key mine infrastructure, and assessment of deep bedrock hydrogeology in the area of the proposed open pit. A key consideration in the assessment will be the influence of lake diversions on groundwater flow conditions and mine inflows.

BEDROCK HYDROGEOGEOLOGY

- **Construction and Testing of Replacement Production Well FDC03R, Carlisle, Ontario (Senior Project Reviewer)****
  As a result of poor water quality a detailed video log was completed under pumping conditions and confirmed that the existing production wells was not properly sealed into bedrock, resulting in a direct hydraulic connection with the overlying overburden aquifer. A new 200 mm diameter bedrock production well was designed and constructed as a replacement to the existing production well. The new production well was

tested at rates up to 30 L/s and permitted together with a new production well to increase the supply capacity for the community. Since construction of the new well water quality has been excellent with no detections of E.coli.

- **Municipal Well Construction, Rural Municipality of East St. Paul, Manitoba, Manitoba (Senior Project Reviewer)****
  To meeting immediate water supply requirements an exploration permit was obtained from Manitoba Conservation to complete test for the development of a new production well. A 254 mm diameter production well was completed within the Upper Carbonate Aquifer and long term pumping tests confirmed a sustainable yield of 20 L/s. To confirm the well yield and potential impacts on adjacent private wells Manitoba Conservation issued the permit for the well with the condition that a detailed monitoring program was completed. The monitoring program was designed and approved by Manitoba Conservation and the well has beencommissioned.

- **Monitoring Well Installation and Upgrades, Middleton Street Well Field, Cambridge, Ontario (Project Manager)****
  To allow better determination of in-situ filtration processes and the potential hydraulic influence of the Grand River on groundwater levels, a multi-level monitoring well was completed adjacent to the river near the Middleton Street Well Field. The bedrock was cored to up-date the conceptual hydrogeologic model and to evaluate the properties of the aquitard unit identified during previous studies. In conjunction with researchers from the Ontario Geological Survey, the core was logged and major stratigraphic units identified. The results of the geological logging, together with detailed geophysical testing, velocity flow profiling, and hydraulic conductivity testing were used to characterization the aquifer/aquitard units and hydrogeologicconnections.

GROUNDWATER AND GEOCHEMICAL MODELING

- **Evaluation of the Migration of Road Salt Impacts, Waterloo, Ontario (Project Manager)****
  Assessment of chloride impacts from winter road salt was completed to determine the distribution and controls on road salt migration to the water table. A series of monitoring sites were instrumented with water table monitoring wells and tracer tests were completed at two locations to document the distribution and migration of chloride to through the unsaturated zone. A1-D unsaturated zone model was completed and calibrated with the bromide trace data to estimate recharge rates and the vertical migration and mass of chloride within the unsaturated zone. From the modelling estimates of chloride mass loading were determined and related to the chloride loading from road salting.

- **Road Salt Management and Chloride Reduction Study, Waterloo, Ontario (Project Manager)****
  A GIS based mass balance model was developed for the key well fields to determine the impact from winter road salting, and provide an indication of future chloride concentrations under a variety of management scenarios. The model utilized particle tracking data from ground surface to the production wells developed from existing groundwater flow models to provide travel time estimates. This data was combined with detailed road salt application data, recharge rate estimates, and soil and groundwater chloride profiles to calibrate the loading source function for the mass balance model. Using an integrated mass balance model, chloride within the well field capture zones was allowed to travel to the well field, providing an estimate of chloride concentrations over time. Following calibration to the observed historical chloride concentrations, the model was used to evaluate future chloride concentrations under a variety of management options, including the complete elimination of road salting within a variety of travel times around the well field. The result of the mass balance modeling were compared with detailed 3-D numerical solute transport modeling completed using the University of Waterloo flow model WATFLOW and the transport model WTC.

- **Nitrate Management Study, Wilmot Township, Ontario (Project Hydrogeologist)****
  To better understand the impacts of agricultural practices on groundwater, and the benefits of potential reduction measures, a GIS based mass balance model was developed for a Production Well with elevated nitrate concentrations in an agricultural setting. The model utilized particle tracking data from existing

groundwater flow models to provide travel time estimates. This data was combined with detailed fertilization practices data, recharge rate estimates, and soil and groundwater nitrate profiles to calibrate the loading source function for the mass balance model. Using an integrated mass balance model, nitrate within the well field capture zone was allowed to travel to the well, providing an estimate of nitrate concentrations over time. Following calibration to observed nitrate concentrations, the model will be used to evaluate future nitrate concentrations under a variety of BMPs. The result of the mass balance modeling will be compared with detailed 3-D numerical solute transport modeling completed using the University of Waterloo flow model WATFLOW and transport model WTC.

- **Hydrogeologic Assessment of Road Salt Impacts, Regional Municipality of Waterloo, Ontario (Project Manager)****
  Assessment of chloride impacts from winter road de-icing compounds at a municipal well field. The study involved mass balance modeling techniques to predict future chloride concentrations and detailed tracer tests to confirm the vertical migration rate of chloride through the unsaturated zone. 1-D unsaturated zone modeling was completed to quantify the tracer test results. (2005).

- **Nitrate Migration Control System, Regional Municipality of Waterloo, Township of Wilmot, Ontario (Project Manager)****
  Assessment and design of a nitrate migration control system, through computer transport modeling, to prevent the migration of a large scale nitrate plume to a primary municipal well field. (1999).

GROUNDWATER CONTROL:

- **Supplementary GUDI Investigation, Greenbrook Well Field, Kitchener, Ontario (Hydrogeologist)****
  A supplementary GUDI investigation was completed at the Greenbrook Well Field including a review of updated stratigraphy based on recent continuous core drilling, seasonal LPC monitoring up to 340 hours at individual production wells and seasonal MPA sampling. A thorough review of water level data was completed from 2004 to 2009, including Greenbrook well field shutdown and start-up of individual wells.

- **Woolner Flats Well Field Water Quality Assessment, Regional Municipality of Waterloo, Ontario (Environmental Scientist)****
  An assessment of the nitrate distribution within the Woolner Flats Well Field in Kitchener, Ontario was completed. The spatial distribution of nitrate concentrations within the overburden aquifer were evaluated under pumping and nonpumping conditions. The impacts of this contamination on water quality within the municipal production wells wasconsidered.

- **Middleton Street Well Field GUDI Assessment, Cambridge, Ontario (Project Manager)****
  To evaluate in-situ filtration processes within a fractured bedrock system, and the effect of seasonal variations on water quality, a detailed study was completed to document the effects of precipitation, river stage, and pumping on particles and surface water indicator organisms (bioparticles) within the raw groundwater from production wells at the Middleton Street Well Field. The study involved collection of particle count and MPA data over a 12 month period to document seasonal variations in water quality. The results indicated bio-particle concentrations >4-log lower than the river, suggesting high removal rates in the fractured rock environment, and supporting effective in-situ filtration processes.

- **Microbial Contamination Control Plan – Freelton Water Supply, Freelton, Ontario (Senior Reviewer)****
  Stantec is in the process of completing a MCCP for the Freelton Water Supply, which is owned by the City of Hamilton. The land use setting in the community of Freelton consists of rural agricultural development, as well as some commercial activity. The study will include an in situ filtration assessment; delineation of microbial risk management zones; completing an inventory and risk ranking of all actual and potential land use activities and microbial contamination sources within the microbial risk management zones; recommended control measures to protect the well from microbial contamination and to protect the aquifer's in situ filtration capacity, and a schedule for implementation.

- **Microbial Contamination Control Plan - Region of Waterloo, Region of Waterloo, Ontario (Senior Reviewer)****
  Stantec completed an in situ filtration assessment that involved a review of historical microbial water quality and the collection of additional inline laser particle counting data; delineated microbial risk management zones by integrating groundwater intrinsic susceptibility index mapping with the Region's policy time-of-travel capture zones; completed an inventory and risk ranking of all actual and potential land use activities and microbial contamination sources within the microbial risk management zones; recommended control measures to protect the well from microbial contamination and to protect the aquifer's in situ filtration capacity; developed appropriate monitoring and contingency plans; and, provided a schedule for implementation.

- **Microbial Contamination Control Plan – Dorchester Water Supply, Ontario (Senior Project Reviewer)****
  A MCCP was completed for the Dorchester Water Supply. The MCCP focused on four key components that included providing a background review of the geology and hydrogeology, an in situ filtration assessment, delineation of microbial risk management zones and identification of potential microbial contamination management options. In all, Stantec provided 14 recommendations that were grouped into three general categories including; general microbial control measures, microbial control measures for municipally owned land, and microbial control measures for privately owned land. After reviewing the proposed microbial contamination management options, the municipality noted that many of the recommendations conformed with their long-term water supply protection strategy.

- **Assessment of Groundwater Under the Direct Influence of Surface Water (GUDI) – Middlesex Centre (Project Manager)****
  A hydrogeologic assessment of a municipal production well was completed to confirm potential surface water influences. Given the site location and hydrogeologic setting the assessment focused on water quality and groundwater age to confirm that the supply source was a groundwater based supply. Despite the groundwater being over 50 years old, elevated turbidity levels were occasionally detected and a program was implemented to prove that the elevated turbidity was in fact related to inorganic water quality, and not surface water influences.

- **Assessment of Groundwater Under the Direct Influence of Surface Water (GUDI) - Waterloo Region, Regional Municipality of Waterloo, Ontario (Project Manager)****
  An assessment of potential surface water influences and impacts to water quality at seven well fields was completed to meet the Certificate of Approval requirements for Groundwater Under the Direct Influence of Surface Water studies. The assessment involved detailed characterization aquifer characterization, evaluation of source water quality, aquifer testing, and assessment of the insitu filtration provided by the aquifer system.

- **Assessment of Groundwater Under the Direct Influence of Surface Water (GUDI) - Peel Region, Regional Municipality of Peel, Ontario (Project Manager)****
  Seven individual groundwater supply systems within north Peel were evaluated to determine the potential influence of surface water features. The assessment provided a clear determination of the hydraulic connection between groundwater and surface water systems, and an assessment of the insitu filtration capacity.

GROUNDWATER MONITORING AND REPORTING

- **Caledon East Wellfield Optimization Study, Caledon, Ontario (Project Manager)****
  A Class B EA was completed to determine the optimal pumping configuration of the existing wellfield. Caledon East is situated in an area that forms the headwaters of several creeks and wetland features. A detailed monitoring network of shallow piezometers were installed within key natural heritage features in addition to the establishment of several surface water gauge stations. The entire well field was pumped at its maximum capacity for a period of 7-days to document any potential hydraulic connections to surface water. The pumping test information was supplemented with detailed terrestrial and aquatic habitat surveys. All of the

information was considered when determining the optimal pumping rate of each municipal well. The data was used to support a new Category 3 Permit To Take Water application.

- **Monitoring Well Installation and Upgrades, Middleton Street Well Field, Cambridge, Ontario (Project Manager)****
  To allow better determination of in-situ filtration processes and the potential hydraulic influence of the Grand River on groundwater levels, a multi-level monitoring well was completed adjacent to the river near the Middleton Street Well Field. The bedrock was cored to up-date the conceptual hydrogeologic model and to evaluate the properties of the aquitard unit identified during previous studies. In conjunction with researchers from the Ontario Geological Survey, the core was logged and major stratigraphic units identified. The results of the geological logging, together with detailed geophysical testing, velocity flow profiling, and hydraulic conductivity testing were used to characterization the aquifer/aquitard units and hydrogeologic connections.

- **Caledon East Permit to Take Water Monitoring, Caledon, Ontario (Project Manager)****
  To support the re-issue of a Permit to Take Water for the Caledon East Well Field in the Regional Municipality of Peel, Stantec designed a detailed long-term monitoring program to collect data and determine the potential impact of production well operations on private water wells and surface water features in the surrounding region. The program included the establishment of an "early warning monitoring well network", detailed discharge analysis of local watercourses, and an evaluation of the hydraulic connections between the aquifer and surface water systems under static and pumping conditions.

- **Groundwater Monitoring Program, Regional Municipality of Waterloo, Ontario (Project Manager)****
  Initiation of a groundwater monitoring program including supervision of multi-level monitoring well installations, installation of data loggers, and development and organization of existing well records for integration into a hydrogeologic database.

GROUNDWATER RESOURCE INVENTORY, PLANNING & PROTECTION

- **Greenbrook Well Field Hydrogeological Assessment, Kitchener, Ontario (Senior Hydrogeologist)****
  Stantec completed a detailed hydrogeologic assessment of the well field that focused on determining the source and controls on 1,4-dioxane migration within the aquifer, predicting existing and future 1,4-dioxane concentrations at the five production wells under various pumping scenarios, and evaluating potential water quality concerns that may impact on the treatment of 1,4-dioxane. The evaluation involved the development of a detailed mass balance models to predict the 1,4-dioxane concentrations in the production wells and an assessment of hydrogeologic controls on surface water ponding that resulted during shutdown of the well field. The evaluation identified hydraulic connections with the shallow aquifer system and as a result the well field was identified as groundwater under the direct influence of surface water (GUDI). Project #161110526.

- **Tier 3 Water Budget and Water Quantity Risk Assessment, Regional Municipality of Waterloo, Ontario (Senior Hydrogeologist)****
  A Tier 3 Water Budget and Water Quantity Risk Assessment is being completed for the Regional Municipality of Waterloo as part of on-going projects in support of the Clean Water Act.
  The Tier 3 project represents a pilot study being completed by the Region and is intended to better understand the overall water budget in the Region in order to identify areas where the long term sustainability of the water supply may be of concern. As part of the project, detailed characterization of the groundwater systems is being completed at major well fields in Waterloo, Kitchener, and Cambridge. The detailed characterization is being used to refine the 3-D groundwater flow model for the Region for use in completing the water budget and quantity risk assessments. (Project #160900498).

- **The Study of the Hydrogeology of the Waterloo Moraine, Waterloo and Kitchener, Ontario (Project Manager)****
  A regional study of the Waterloo Moraine, a glacial aquifer system located within the Township of Wilmot and the Cities of Waterloo and Kitchener, was completed as part of the Regional Municipality of Waterloo’s Groundwater Protection Program. A conceptual model for the area was developed through detailed borehole

drilling, aquifer testing, water level monitoring, well field pumping and shut down tests, and hydrogeochemical analysis. A preliminary interpretation of well field capture zones was prepared based on the detailed understanding of the distribution and extent of the various aquifer units, groundwater flow directions, and hydrogeochemical data.

- **Middleton Water Supply System Upgrades - Hydrogeologic Assessment, Waterloo, Ontario (Senior Hydrogeologist)****
  A hydrogeologic evaluation of the Middleton Street Well Field, a high capacity bedrock aquifer system was completed to address a range of water quality concerns, and to evaluate the long- term yield of the aquifer in the area of the well field.
  Detailed hydraulic monitoring of water level response in the various aquifer units, together with groundwater modeling and water quality analyses were used to confirm GUDI classifications and the in-situ filtration capacity of the aquifer system. Water quality concerns related to TCE, 1,4- dioxane, E.coli, and chloride were evaluated in efforts to confirm potential sources and controls on water quality and solute transport within the fractured bedrock aquifer system. A quantitative assessment of aquifer filtration was completed using MPA data with a 8-log reduction of algae/diatom particles in the size range of 2 µm to >15 µm identified, indicating that high levels of filtration are obtained through the thin overburden sediments.

- **Development of methodologies to evaluate road salt impacts from residential developments, Region of Waterloo, Ontario (Senior Technical Specialist)****
  Assisted senior staff at the Region of Waterloo with the development of a methodology to evaluate impacts to groundwater quality from road salting associated with new developments. The methodology considered both impacts at the proponent property boundary, and the potential impacts at municipal well fields. As part of the work a case study was completed at one of the Region's most important well fields. The methodology has provided the Region with clear targets for development applications that are consistent with other government legislation.

- **East St. Paul Water Supply Master Plan, Rural Municipality of East St. Paul, Manitoba (Senior Project Reviewer)****
  Due to increasing growth pressures and limited water supply sources, a water supply master plan was completed for the Rural Municipality of East St. Paul to confirm the long term water supply potential, and to identify strategic test drilling areas. The study is being used to support an aquifer exploration license from Manitoba Conservation to complete the test drilling program and the ultimate construction and permitting of new production wells within the carbonate aquifer system.

- **Conestoga Golf Course Subdivision Class EA, Conestoga, Ontario (Project Manager)****
  As part of a Schedule C Class EA for the Conestoga Golf Course Subdivision, a hydrogeologic assessment was completed to confirm if the aquifer could meet increased supply demands, and to confirm potential water quality concerns related to surface water influences and upward migration of poor quality bedrock water under increased pumping. The study concluded that the supply source was a groundwater system and a new 250 mm diameter production well was installed to meet the increased supply needs.

- **Carlisle Water Supply Master Plan, Carlisle, Ontario (Senior Project Reviewer)****
  A detailed hydrogeologic assessment was completed as part of a Class EA to confirm the long term sustainable yield of the bedrock aquifer system, and to assess potential surface water influences and impacts to water quality. As part of the study detailed aquifer testing was completed to evaluate the interconnection between the bedrock and overburden aquifer systems, confirm the degree of in-situ filtration, and provide recommendations on the ultimate supply capacity and treatment requirements for the community water supply.

- **Wellhead Protection Study, Regional Municipality of Waterloo, Ontario (Hydrogeologist)****
  Completion of a detailed hydrogeologic and modeling assessment for a Wellhead Protection Study of the Baden and Wilmot Centre Well Fields.

- **Contaminant Hydrogeology Assessment, Municipal Well Field, Regional Municipality of Waterloo, Ontario (Hydrogeologist)****
  Assessment of impacts to a municipal well field as a result of historical PAH and TCE contamination. Detailed characterization of hydrogeochemical conditions, delineation of potential source areas and mass balance calculations to predict future concentrations at the well field were completed.
- **The Study of the Parkway Well Field Area (Project Manager)****
  A detailed study of the Parkway Well Field area was completed to develop a conceptual hydrogeological model to be used in a 3-D groundwater flow model for delineation of well field capture zones. Data collection for the study involved borehole drilling and monitoring well installations, geophysical surveys, detailed pumping and well field shut down tests, and hydrogeochemical sampling. The field data and conceptual model was used to develop a 3-D groundwater flow model and the prediction of the 2-, 10-, and 20 year time of travel capture zones.
- **Hydrogeologic Assessment of Water Supply Systems, Baden and New Hamburg, Regional Municipality of Waterloo, Ontario (Hydrogeologist)****
  Hydrogeologic assessment of various water supply systems related to the development of a Water Supply Master Plan under the Class EA for the communities of Baden and New Hamburg. Study involved the construction, testing, and permitting of a new production well (45 L/s) for the communities of Baden and New Hamburg, which required iron and manganese removal.
- **Hydrogeologic Assessment and Long Term Water Supply Evaluation, Township of North Dorchester, Ontario (Project Manager)****
  A hydrogeologic assessment and long term water supply evaluation was completed as part of a Class EA Master Plan. The study resulted in the installation of a replacement well and involved the implementation of the new drinking water regulations.
- **Hydrogeologic Assessment of Rural Water Systems, Regional Municipality of Waterloo, Ontario (Hydrogeologist)****
  A hydrogeologic assessment of the rural water systems in Roseville, West Montrose and Conestoga Golf Course Subdivisions was completed as part of the Class EA study for Upgrading Rural Water Systems. The Class EA resulted in the construction, testing, and permitting of new production wells (7 to 15 L/s) for the Roseville and Conestoga Golf Course Subdivisions and design and construction of a infiltration gallery in West Montrose. Iron and manganese removal systems were installed for both the Roseville and West Montrose systems.
- **Hydrogeologic Assessment of Septic System Suitability, Various Locations, Ontario (Hydrogeologist)****
  Assessment of septic system suitability and potential impact on groundwater quality at various proposed development sites in Ontario.
- **Hydrogeologic Assessment of Subsurface Storm Water Management, Various Locations, Ontario (Hydrogeologist)****
  Assessment of infiltration rates and suitability for subsurface storm water management options at various development sites throughout Southern Ontario.
- **Hydrogeologic Assessment of Proposed Cemetery Sites, Various Locations, Ontario (Hydrogeologist)****
  Assessment of hydrogeological conditions at proposed cemetery sites with respect to burial depth and potential impact to groundwater quality.
- **Reconnaissance Survey, Regional Municipality of Waterloo (Hydrogeologist)****
  Reconnaissance geochemical and isotopic survey of groundwater from the Waterloo Moraine.

GROUNDWATER SUPPLY / WELLS

- **Hydrogeological Assessment Production Wells G7 & G8, Region of Waterloo, Ontario (Project Manager)****
  Occasional low level detections of volatile organic compounds (VOCs) and a rising trend in the concentration of chloride, suggesting that the Shades Mill well field may be vulnerable to land use activities in the area. As a result, the Region retained Stantec Consulting Ltd. (Stantec) to complete a hydrogeological assessment to improve the understanding of the hydrogeology and water quality in areas around G7 and G8. Borehole Drilling and Monitoring Well Installations, Drive-Point Piezometer Installations, Hydraulic Response Testing, Water Quality Sampling, Water Level Monitoring; and a 13 Week Shut Down Testing were all preformed. The data was used to assess the vulnerability of the aquifer and wells to local potential contaminant sources in order to minimize water quality risks.

- **Construction and Testing of Production Well C6, Conestoga Golf Course Well Field, Kitchener, Ontario (Hydrogeologist)****
  A hydrogeologic assessment was completed as part of Schedule C Class EA for the Conestoga Golf Course subdivision. A 72 hour pumping test was completed to evaluate long-term supply of the newly installed production well, source water quality and potential interference with neighbouring wells.

- **Replacement of Production Wells K1 and K2, Kitchener, Ontario (Project Manager)****
  Replacement Production Wells K1A and K2A were constructed at Greenbrook Well Field to replace existing Production Wells K1 and K2, which were installed in 1920's. The testing and construction program included continuous core drilling within the entire overburden, geophysical analysis, monitoring well and production well installation. The production wells were completed as 14" naturally developed wells. Following installation, variable rate and constant rate testing were completed to confirm well capacity and GUDI-EF status and a report was submitted in support of a consolidated PTTW for the well field.

- **Optimization Study, Mannheim ASR System, Kitchener, Ontario (Hydrogeologist)****
  Initial monitoring of the Aquifer Storage and Recovery (ASR) system from 2005 to 2008 indicated a decline in well performance at all ASR wells resulting in a decrease in system performance and in some cases requiring well rehabilitation. Stantec is currently completing an optimization study to evaluate potential options to improve performance of individual wells and the overall system. The investigation includes baseline performance testing, injection/pumping rehabilitation cycling within the production wells, review of operation procedure and a 30 day pumping test to evaluate system performance. Reporting will include recommendations for on-going rehabilitation efforts and operational changes to maximize yield.

- **Well Abandonment Program, Mannheim ASR System, Kitchener, Ontario (Senior Project Reviewer)****
  A well abandonment program was completed at the Mannheim ASR System which included the abandonment of twenty-eight (28) monitoring wells. The majority of these wells were submerged or partially submerged within an on- site pond and represented a potential preferential pathway to the Region's supply aquifer. The abandoned monitoring wells ranged from 32 mm to 914 mm in diameter to depths of 7 m to 70 m below ground surface. Following well abandonment, a geophysical survey was completed to confirm that there were no remaining unabandoned wells in the area.

- **Production Well Construction, Dorchestor, Ontario (Senior Hydrogeologist)****
  Production Well 3PW-2B and 3PW-8 were constructed within Dorchester Well Field No. 3 in 2005 and 2009, respectively. Both wells are constructed within the shallow unconfined sand and gravel aquifer. The testing and construction program included production well design, construction, performance and constant rate pump testing. During the twenty-four (24) hour constant rate pumping tests, water quality sampling was completed for complete ODWS analysis and continuous LPC monitoring and MPA sampling was completed to confirm the effective filtration status of the aquifer.

- **Groundwater Exploration and Municipal Well Construction, Regional Municipality of East St. Paul, Manitoba (Senior Project Reviewer)****
  A groundwater exploration program was completed for East St. Paul to determine the potential location of additional production wells. The program included test drilling and pump testing at multiple locations. An additional bedrock production well was constructed and a 72 hour pump test was completed. The well and aquifer assessment indicated that the production well could sustainably supply 20 L/s. This second bedrock supply well is expected to be on-line by Summer 2007.

- **Arkell Collector System - Hydrogeologic Assessment, Guelph, Ontario (Senior Hydrogeologist)****
  Stantec completed an evaluation of the Arkel Spring Collector and potential options for up- grading or replacing the aging collector system. The evaluation involved characterization of the shallow overburden groundwater flow system and aquifer extents using existing well information, and results of new test well drilling and aquifer testing. The evaluation identified a Ranney Collector well as the preferred option of replacing and increasing the capacity of the Glen Collector system.
  Preliminary groundwater flow modelling and analytical flow solutions were used to evaluate the feasibility and possible yields from a Ranney Collector well, as well as various design configurations.

- **Mannheim ASR Commissioning and Hydrogeologic Monitoring, Waterloo, Ontario (Senior Hydrogeologist)****
  Stantec was retained by the Region to complete the final design and construction of the Mannheim ASR System. In support of the commissioning and to meet the requirements of the PTTW, a detailed hydrogeologic monitoring program was development and undertaken. The monitoring program involved the both hydraulic and water quality monitoring to document the influence of both injection and recovery cycles on aquifer levels, ASR well performance and maintenance requirements, and potential impacts on water quality. During the initial year of operation decreases in well performance and the formation of THM within the aquifer resulted in the need for more detailed assessments. Benchscale testing and geochemical modelling was completed to confirm controls on THM formation and modifications to the injection process were completed, successfully eliminating the formation of THMs within the aquifer. On-going monitoring and well rehabilitation is being completed to confirm long term well performance and rehabilitation requirements.

- **Construction and Permitting of Production Well K19 (Senior Hydrogeologist)****
  A test drilling program was completed to evaluate the potential for developing a new production well within the bedrock and overburden aquifer system adjacent to existing Production Well K18. Two bedrock test wells were completed in the area, yielding high volumes of water, but with very poor water quality, and as a result the study focused on the development of a new overburden production well. Several test holes were completed in the area due to the variability of the aquifer material. Using the test drilling results, a suitable location was identified and a 362 mm diameter gravel pack production well was designed and installed. The production well was tested with a firm capacity of 47 L/s. The hydrogeologic report was submitted to the Ministry of Environment and a Permit To Take Water was received for the requested rates.

- **Municipal Well Construction, Rural Municipality of East St. Paul, Manitoba (Senior Project Reviewer)****
  To meeting immediate water supply requirements an exploration permit was obtained from Manitoba Conservation to complete test for the development of a new production well. A 254 mm diameter production well was completed within the Upper Carbonate Aquifer and long term pumping tests confirmed a sustainable yield of 20 L/s. To confirm the well yield and potential impacts on adjacent private wells Manitoba Conservation issued the permit for the well with the condition that a detailed monitoring program was completed. The monitoring program was designed and approved by Manitoba Conservation and the well has been commissioned.

- **Ayr Water Supply Class EA and Production Well Construction, Ayr, Ontario (Senior Hydrogeologist)****
  As part of a Schedule C Class EA for the Village of Ayr water supply, a detailed hydrogeologic testing program was completed to confirm if the existing production wells were hydraulically connected to Cedar Creek and the Nith River, and to provide an estimate of the sustainable yield of the aquifer. A 96-hour constant rate pumping test of Production Wells A1 and A2 was completed at a combined pumping rate of 59 L/s. Based on the results

of this aquifer test, a revised Permit To Take Water for 63 L/s was obtained for the well field, with the need for a third supply well identified to provide firm supply capacity. A 324 mm diameter natural developed well was constructed and tested at a rate up to 60 L/s. A Permit To Take Water for the new well was obtained.

- **Construction and Testing of Replacement Production Well FDC03R, Carlisle, Ontario (Senior Project Reviewer)****
  As a result of poor water quality a detailed video log was completed under pumping conditions and confirmed that the existing production wells was not properly sealed into bedrock, resulting in a direct hydraulic connection with the overlying overburden aquifer. A new 200 mm diameter bedrock production well was designed and constructed as a replacement to the existing production well. The new production well was tested at rates up to 30 L/s and permitted together with a new production well to increase the supply capacity for the community. Since construction of the new well water quality has been excellent with no detections of E.coli.

- **Communal Water Supply System, Residential Golf Course, Ontario (Hydrogeologist)****
  Assessment and design of large communal water supply system (45 L/s) for residential golf course development within a sensitive groundwater recharge area of the Oak Ridges Moraine.

WATERSHED PLANNING

- **North Waterloo Scoped Subwatershed Study, Waterloo, Ontario****
  A hydrogeologic assessment is currently being completed within a proposed 170 ha development property within the Laurel Creek Watershed in Waterloo. The assessment involves a detailed field investigation including shallow and deep monitoring well installation and on-going groundwater level monitoring as well as test pit installation, Guelph permeameter testing, hydraulic testing of the monitoring wells and drivepoint installation and monitoring. Based on these results, local geology and hydrostatigraphy conditions were reviewed in relation to the regional interpretations of the Waterloo North area as presented in the recent Tier 3 investigations. The hydrogeologic report will present a pre- and post- construction water balance, detail potential effects on Beaver Creek and nearby Regional production wells and provide recommendations for mitigation measures for the proposed development as required.

- **Alder Creek Watershed Study, Grand River Conservation Authority, Wilmot Township, Ontario (Hydrogeologist)****
  A review of hydrogeologic data was completed to develop a conceptual hydrogeologic model for Alder Creek Watershed Study.

- **Torrance Creek Monitoring Program, City of Guelph, Ontario (Project Manager)****
  Development and implementation of the Torrance Creek Monitoring Program in conjunction with the project steering committee.

WATER

- **Salt Assessment, Township of North Dumfries, Ontario (Project Manager)****
  Sodium and chloride were identified under the Clean Water Act (2006) as a drinking water issue for two municipal supply wells. A salt assessment was completed to assess the current extent of chloride within the aquifer system, to evaluate the potential for concentrations of chloride to exceed the Ontario Drinking Water Standards (ODWS), and to provide recommendations on potential Beneficial Management Practices (BMPs) and/or operation of the well field with the objective of reducing chloride concentrations at the wells.
  Sources of chloride included point (water softeners, salt water pools) and non-point (road salting) sources. Residential surveys were conducted to gather information on septic systems and water softener use to evaluate potential loading from point sources. Road salt usage was detailed by the Township and private contractors. A spreadsheet model was developed to estimate potential chloride loading to groundwater and evaluate potential BMPs.

EXPERT TESTIMONY / WITNESS

- **Evaluation and Peer Review of Dewatering Estimates for Construction of a Deep Sanitary Sewer, Ontario (Senior Peer Review)****
  A review of dewatering estimates was completed to determine if estimates and assumptions were reasonable based on available data in support of a construction claim. The review included independent dewatering estimates considering the original data and new data available at the site to allow development of a dewatering plan to address construction issues.
- **Hydrogeology Peer Review, Durham, Ontario (Senior Peer Review)****
  A hydrogeology peer review of a proposed 5 lot development on private services adjacent to Lake Scugog was completed.
- **Expert Witness Support, Waterloo West Side Development, Waterloo, Ontario (Senior Peer Review)****
  Expert witness support was provided for a controversial development within the Waterloo Moraine. A review of the development application and hydrogeological data was completed and strategies were developed to maintain recharge in lower permeability soils, and to evaluate the potential impacts of winter road salting on adjacent municipal production wells. A third pipe collector system was developed and the concepts presented and support was obtained from Region of Waterloo. In support of the development and Ontario Municipal Board Hearing presentations were made to Waterloo Council and technical support was provided during the hearing.
- **Hydrogeology Peer Review and OMB Support, Township of East Luther Grand Valley, Ontario (Senior Peer Review)****
  Hydrogeology review services were provided for a proposed zoning by-law amendment for an explosives facility. The review focused on hydrogeologic issues and potential impacts to groundwater resources and supplies related to the storage and handling of ammonium nitrate. Support was provided for the Ontario Municipal Board Hearings where all hydrogeological issues were resolved and an agreed statement of facts were provided
- **Hydrogeology Peer Review and OMB Support, Township of Amaranth, Ontario (Senior Peer Review)****
  Hydrogeology review services were provided for residential and commercial/institutional development applications. For the residential application support was provided for the Ontario Municipal Board Hearings where all hydrogeological issues were resolved and an agreed statement of facts were provided. On-going support is being provided to the Township on Source Water Protection issues and its impact on development lands within the Township.
- **Hydrogeology Peer Review, Hamilton, Ontario (Senior Peer Review)****
  Provided hydrogeology peer review services for development applications with respect to impacts to municipal water supplies. The reviews focused on confirming potential impacts from proposed developments on groundwater quantity and quality at the municipal wellfields.
- **Hydrogeology Peer Review, County of Haldimand- Norfolk, Ontario (Senior Peer Review)****
  Provided hydrogeology peer review services for development applications. Reviews typically were related to private water and sanitary servicing impacts from proposed industrial and commercial developments.
- **Peer Review of Golf Course Development (Peer Reviewer)****
  Peer review of hydrogeologic studies related to golf course development and comment on potential concerns with respect to fertilizer and pesticides use.

CEMENT / AGGREGATES

- **Water Level Monitoring Program, Wellington Pit, No. 5, Capital Materials (Project Manager)****
  Long-term monitoring of water levels in groundwater and surface water features at an active aggregate extraction operation using a trigger based monitoring program to identify if any impacts to the natural systems occur as a result of below water table extraction.

- **Hydrogeologic Assessment for Proposed Aggregate Extraction, Wellington Pit No. 5, Township of Puslinch, Ontario (Hydrogeologist)****
  A study was completed to determine the hydrogeological setting, groundwater flow conditions, and potential impacts resulting from aggregate extraction on the groundwater system and on a near-by Provincially Significant Wetland. The study was completed in support of an application for an aggregate extraction license.

- **Hydrogeologic Assessment of Floodplain Area, Grand River Conservation Authority (Hydrogeologist)****
  Assessment of hydrogeologic setting with respect to gravel extraction options and potential improvements to the flood plain ecosystem along the Grand River.

- **Hydrogeologic Evaluation of Dewatering Operations at a Sand and Gravel Pit, Uxbridge, Ontario (Hydrogeologist)****
  A pumping test was completed to evaluate the potential impacts associated with below water table extraction and pumping at a sand and gravel pit within the Oak Ridges Moraine. A permit to take water for the pumping was obtained.

- **Proposed Aggregate Extraction, Nigro Pit, Township of Puslinch, Ontario (Hydrogeologist)****
  A study was completed to determine the hydrogeological setting, groundwater flow conditions, and potential impacts resulting from aggregate extraction on the groundwater system and on a near-by Provincially Significant wetland. The study was completed in support of an application for an aggregate extraction license.

- **Horst Property Hydrogeologic Assessment, Township of Woolwich, Ontario (Hydrogeologist) ****
  An assessment of hydrogeological conditions was completed with respect to gravel extraction options and potential improvements to the flood plain ecosystem along the Grand River. The study also assessed the potential impacts of the proposed aggregate extraction on local private wells using a 3-D groundwater flow model (MODFLOW).

TRANSPORTATION PLANNING

- **Hydrogeology Study for Proposed River Road Extension, King Street to Manitou Drive, Kitchener, Ontario (Project Manager / Senior Hydrogeologist)****
  An assessment of groundwater conditions along the proposed alignment of the River Road Extension was completed. The evaluation focused on the impacts to Provincially Significant Wetlands, regulated Jefferson Salamander habitat, surface water features and the Region of Waterloo's Hidden Valley intake on the Grand River, and the Parkway Well Field. The results of the initial impact assessment have been used to refine the road alignment and potential mitigation measures to be considered during detailed design. A pre-construction baseline monitoring program has been developed and is currently being implemented.

SPORTS, RECREATION & LEISURE

- **Permit To Take Water, Westmount Golf & Country Club, Kitchener (Project Manager)****
  An evaluation of permit requirements was completed and an application submitted to support the water taking from the irrigation holding pond.

- **Permit to Take Water and Golf Course Monitoring Program, Guelph, Ontario (Senior Hydrogeologist)****
  A hydrogeological assessment to support a PTTW renewal. Due to public opposition related to concerns of the potential to impact adjacent wetlands, a groundwater monitoring program was developed and implemented as a condition of the PTTW. The monitoring was completed and a longer term PTTW was issued by the MOE. In support of the permit, monitoring and annual reporting for the golf course was completed.

- **Permit to Take Water Brantford Golf and Country Club, Brantford, Ontario (Project Manager)****
  An evaluation of water supply options and the potential for increased water taking was completed for the golf course. Through meetings with the MOE, an assessment of current water supply requirements was completed and a permit application completed to increase the water taking to meeting current irrigation and supply needs.
- **Permit to Take Water For Golf Course Irrigation, Turnberry Golf Club, Brampton, Ontario (Project Manager)****
  Characterization of the geology and hydrogeology of the site was completed in support of a Permit To Take Water (PTTW) application. The water supply source was a groundwater fed pond created as part of the rehabilitation of a former gravel pit. An assessment of the groundwater and surface water sources to the pond was completed and a PTTW obtained for both irrigation and stormwater controls.
- **Irrigation System, Grey Silo Golf Course, Waterloo, Ontario (Hydrogeologist)****
  Evaluated, designed and obtained a permit to take water for the Grey Silo Golf Course irrigation system.
- **Water Supply and Irrigation System, Golf Course and Residential Community, Ontario (Project Manager)****
  A detailed hydrogeologic assessment was completed to develop a water and irrigation supply system for a championship golf course and adult lifestyle community. Due to concerns related to potential impacts to groundwater quality and quality, innovative techniques including the use of treated sewage effluent and stormwater to reduce irrigation requires were developed, and a cumulative impact assessment of the potential impacts to a cold water trout fishery were completed.

ENVIRONMENTAL SITE MANAGEMENT

- **Ex-Situ Bioremediation of Diesel Impacted Soil, Northern Ontario (Project Manager)****
  Design of soil management facility for 2,000 m^3 of petroleum impacted soil and implementation of an ex situ bioremediation program, including obtaining a Certificate Approval for waste processing.
- **Phase II ESA of Active Rail Yard, Northern Ontario (Project Manager)****
  Supplementary investigation and remediation of impacts to groundwater quality from a historical diesel fuel release at an active rail yard. As part of the investigation the risks to private and public water supplies were evaluated and replacement water supply was constructed for the rail yard.
- **Environmental Management of Train Derailment, District of Chapleau, Ontario (Project Manager)****
  Emergency response and supervision of site clean-up at a derailment site. Clean-up measures included the pumping and containment of oil that was released from two tank cars to a nearby water body, removal of impacted snow, ice, and soil and in-situ bioremediation.
- **Landfill Monitoring, Closed Landfill Sites, Regional Municipality of Peel, Ontario (Project Manager)****
  Regional Municipality of Peel – Hydrogeologic assessment and review of annual monitoring data for three closed municipal landfill sites.
- **Peer Review of Groundwater Management Plan, Former Rail Yard, Township of Tay, Ontario (Project Manager)****
  Peer review of a soil and groundwater management plan for the decommissioning of a former rail yard and redevelopment for residential land use.
- **Soil and Groundwater Management Plan, Active Rail Yard, Northern Ontario (Project Manager)****
  Preparation of a preliminary soil and groundwater management plan for the decommissioning of an active rail yard. Study included a detailed assessment of metal and petroleum impacts to soil and groundwater, as well as volume estimates of debris, impacted soil and groundwater.
- **Free Product Remediation, Active Rail Yard, Northern Ontario (Project Manager)****

Design and implementation of a remedial program to contain and collect free phase petroleum product associated with historical diesel fuel releases at a northern Ontario rail yard. The remedial system included a containment wall and horizontal trench system with groundwater and product recovery pumps.

- **Environmental Data Management, Active Rail Yard, Northern Ontario (Project Manager)****
  Development of a GIS based database system for environmental and infrastructure data associated with an active rail yard.
- **Peer Review of Environmental Investigation, Confidential Site, Ontario (Project Manager)****
  Peer review of Phase I and II ESA and preliminary remedial options related to benzene impacts to groundwater.
- **Environmental Investigation and Remediation, Former Gasoline Station, County of Bruce, Ontario (Project Manager)****
  Preliminary investigation of soil and groundwater quality for an abandoned gasoline station and subsequent removal of the underground storage tanks and impacted soils.
- **Assessment of Former Mine Shipment Facility, Northern Ontario (Hydrogeologist)****
  Review and assessment of long term groundwater and surface water quality data at a former mine shipment facility. As part of the review potential remedial options were considered to further reduce impacts from the facility associated with metal leaching and acid mine drainage.
- **Phase II ESA of Solvent Storage Site, Toronto, Ontario (Project Manager)****
  Project manager and principal investigator for a detailed Phase II ESA of soil and groundwater impacts associated with chlorinated solvents, including TCE and PCE, beneath a former industrial lease site. Remedial options were evaluated to address soil, groundwater and vadose zone impacts.

MEMBERSHIPS & ASSOCIATIONS

- Member, National Ground Water Association.
- Member, International Association of Hydrogeologists.

PUBLICATIONS

Blackport, R.J., J.W. Robinson, C.T. Johnston. Recent investigations of the hydrogeology of the Waterloo Moraine. Abstract, GAC/MAC Annual Meeting, Waterloo, Ontario. 1994.

Fritz, S.J., F.E. Harvey, R.J. Drimmie, C.T. Johnston, and S.K. Frape. Tritium variability of repeated samplings of well water in southern Ontario. Abstract, V.M. Goldschmidt Conference, Edinburgh, Scotland. 1994.

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Rudolph, D.L., T. Svensson, R.J. Blackport, and C.T. Johnston. Impacts of municipal groundwater quality from rural land use practices. OWWA/OMWA Joint Annual Conference, London, Ontario. 1996.

Sarwar, G., D.L. Rudolph, J.D. Campbell, C.T. Johnston. Field characterization of road salt impacts on groundwater resources in an urban setting: Kitchener, Ontario. 55th Canadian Geotechnical Conference, 3rd joint IAH-CNC/CGS Conference, Niagara Falls, Ontario. 2002.

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CHRISTOPHER D. WREN, B.Sc., Ph.D.

EDUCATION
B.Sc. Marine Biology, University of Guelph, 1977
Ph.D. Fisheries, and Aquatic Science, University of Guelph, 1983
1983-1985: Postdoctoral Research Fellow. Institute for Environmental Studies, University of Toronto
1986-1987: Postodoctoral Research Fellow, University of Trondheim, Norway,

PROFESSIONAL AFFILIATIONS
Trout Unlimited Canada
Society of Environmental Toxicology and Chemistry
Canadian Land Reclamation Association

POSITIONS HELD

2013 to present	Senior Environmental Consultant, LRG Environmental,
2015 -2018:	Chairman, Board of Directors, RWDI Group Inc., Guelph, Ontario.
2009-2012:	Technical Director, Risk Assessment, MIRARCO, Laurentian University. Adjunct Professor, Department of Biology, Laurentian University Partner LRG Environmental Consulting
2006 – 2009:	Senior Environmental Scientist, AECOM Canada (formerly Gartner Lee Limited)
2003 – 2006	President, C. Wren and Associates Inc.,
1989-2003:	ESG International, Partner, Senior Scientist for Water Quality, Fisheries and Risk Assessment
1987-1989:	B.A.R. Environmental, Guelph, Ontario, Scientific consultant
1985-1986:	Canadian Wildlife Service, Ottawa, Contract Research
1976-1983:	Summer Technician positions, MNR, Environment Canada

Primary Areas of Environmental Impact and Risk Assessment
Mining (Canada and international)
Pulp and Paper ; Aggregate extraction
Energy – oil and gas, hydroelectric, fossil fuel

Broad Interests
Human and Ecological risk assessment,
Environmental Impact Assessment review,
Risk communication
Fisheries Science, Water Quality

Previous Academic Affiliations and Activities
Past Associate Editor for Jounal; Science of the Total Environment (2002-2003)
Past Adjunct Faculty member at Universities of Guelph, Trent, Laurentian and Waterloo
Member of Organizing Committee for Sixth International Conference on Biogeochemistry of Trace Elements
Guest Lectures: University of Guelph; University of British Columbia, Queens Universty, Trent University, University of Toronto, University of Waterloo, Western University (London, Ontario)
Supervised two NSERC Industrial Postdoctoral Research Fellow; One NSERC Industrial Summer Student
External examiner and committee member on several M.Sc. and Ph.D thesis

SELECTED PROJECT EXPERIENCE

Training and Select Lectures

- Training workshop to Environment Canada staff on Ecological Risk Assessment to support technical reviews of applications under Canadian Environmental Assessment Act, March, 2014.
- Delivered keynote address "Communicating Risk Information to Stakeholders" to Husky Energy, Calgary, October 2013, to Corporate Responsibility Group,
- Lecture on risk assessment and risk communication at University of Guelph as part of a graduate course "Advanced Principles of Toxicology" (2009-2017 inclusive),
- Developed and taught a graduate level credit course at Laurentian University: Fundamentals of Risk Assessment, February, 2010, 2011,
- Provided 2 day workshop on fundamentals of risk assessment to Hutchinson Environmental Sciences Limited, Bracebridge, Ontario, 2011,
- Guest lecture at Laurentian University, 2013,
- Invited guest lecturer at Queens University in risk assessment and risk communication, 2009, 2011,
- Invited lecturer to different classes University of Guelph, 2010, 2011,
- Role of risk assessment in mine closure. Invited talk at Mine Closure 2010, Santiago, Chile, 2010,
- Provided full day course on risk assessment to 30 international attendees at Mine Closure 2010, Santiago, Chile, November 2010.

Risk Assessment

- Edited and produced text book on human and ecological risk assessment, January 2012 (see publications).
- Senior advisor to AngloGold Ashanti, Johannesburg, South Africa, for environmental and human health studies at gold mine site in Ghana, West Africa. 2011 to 2014.
- Senior project director for the Human Health Risk Assessment (HHRA) and Ecological Risk Assessment (ERA) for the Greater City of Sudbury. Vale INCO and Xstrata Nickel as primary clients. 2003 to 2009. Responsible for technical oversight and public communication of information.Budget in excess of $12M.
- Development of guidance document for reviewing applications to remediate contaminated sediments, for Fisheries and Oceans Canada, Federal Contaminated Sites Action Plan (FCSAP) program, 2010.
- Senior director for HHRA and ERA for Fort York, Toronto, Canadian Department of Defense. 2009.
- Direction of field program and Screening level risk assessment for decommissioned Cullaton Lake mine. Barrick Gold. 2008-2009.
- Provided Senior Peer Review of proposed Darlington Nuclear Generating Station Ecological Risk Assessment prepared by Senes Consulting for Ontario Power Generation. 2009.
- Direction of field program for ecological risk assessment for proposed IZOK mine in Nunavut, for OZ Minerals. 2008.
- Assisted with development of Problem Formulation for aquatic risk assessment for the proposed High Lake copper/zinc mine in NWT on behalf of Wolfden Mines (now part of OZ Minerals). 2007.
- Tier One screening level risk assessment for Camp Fernie for Greater Region of Vancouver. 2006-2007.
- Human Health risk assessment for mercury at the closed Discovery Lake mine, Northwest Territories. Environment Canada. 2006-2007.
- Public liaison and technical oversight for urinary arsenic study in Town of Falconbridge, Ontario, for Falconbridge, Ltd., 2004-2005.
- Screening Risk Assessment for possible use of EDTA to ameliorate effluent (copper) toxicity in mine effluent for Placer Dome North America, 2002-2003.
- Ecological Risk Assessment and Monitoring of sediments, soil and aquatic biota at Crompton (formerly Uniroyal), Elmira, Ontario.

- Ecological Effects Review and ecological risk assessment of the Chalk River Laboratory nuclear facility for the Atomic Energy Commission Ltd. (AECL); 2002-2003.
- Fisheries assessment; ecological risk assessment and development of remediation options of diesel hydrocarbon fuels in a northern Ontario lake, CP Rail. 2002.
- Participated on expert panel to assess potential risk of PCB contamination in the Hudson River for State of New York. Feb. 2002. Retained by State of New York.
- Ecological risk assessment and ecological effects review of the Darlington Nuclear Station. Ontario Power Generation. 2001-2002.
- Ecological Risk Assessment and ecological effects review for Bruce Nuclear Station, Ontario Power Generation. 1999-2000
- Screening level risk assessment of copper and nickel to aquatic biota at Sudbury, CP Rail, 1999
- Peer review of ecological and human risk assessment of contaminated soils, Toronto. CP Rail, 1998
- Peer review of ecological and human health risk assessment of former coal gasification site. London Hydro, 1998 for M.M. Dillon Consulting
- Terrestrial toxicity tests and ecological risk of contaminated soils at Toronto waterfront. Waterfront Regeneration Trust, 1997-1998
- Ecological assessment of landfill leachate to coldwater fishery in the Credit River. Regional Municipality of Peel, 1997-1998
- Potential risk to wildlife using contaminated stormwater ponds and constructed wetlands for habitat. Study for Environment Canada, 1996-1997
- Critical review of PAH soil quality guidelines. CP Rail, 1997
- Ecological and human health Risk Assessment of benzene in the St. Clair River, for Bayer Rubber, Sarnia, 1996. Provided expert testimony in court proceedings.
- Risk assessment of diazinon to earthworms and passerine birds. Ontario MOE, 1995
- Human health and ecological risk assessment of crude oil spill at St. Leons, Manitoba. Interprovincial Pipe Line Ltd., 1995-96
- Occupational risk of workers at a gold processing facility exposed to mercury vapours, Indonesia, for Hatch Associates, 1995
- Exposure and risk assessment of personnel in the natural gas industry exposed to mercury in the workplace. Centra Gas Ontario, 1995
- Risk assessment of wildlife exposed to Lindane. Canadian Wildlife Service, 1993

Mining and Resource Extraction

- Provided peer review of Environmental Impact Statement of Eastern Offshore Exploration Drilling by Exxon Mobil on behalf of Elsipogtog First Nation, New Brunswick, 2018,
- Provided peer technical review of Environmental Impact Study (EIS) for proposed gold mine by Greenstone Gold, Geraldton, Ontario, on behalf of Long Lake 58 First Nation. 2015-2018
- Provided peer technical review of Environmental Impact Study (EIS) for proposed gold mine by Prodigy Gold, Wawa, Ontario, on behalf of Batchewana First Nation. 2016-2018.
- Conducted natural environment baseline studies and prepared Natural Heritage reports under Aggregate Resources Act (ARA) to support application for proposed Alliston aggregate pit for Nelson Aggregates. 2014-2017. Provided expert testimony at Ontario Municipal Board (OMB) September, 2017.
- Senior advisor to AngloGold Ashanti, Johannesburg, South Africa, for environmental and human health studies at gold mine site in Ghana, West Africa. 2011 to 2014.
- Senior project director for the Human Health Risk Assessment (HHRA) and Ecological Risk Assessment (ERA) for the Greater City of Sudbury. Vale INCO and Xstrata Nickel as primary clients. 2003 to 2009. Responsible for technical oversight and public communication of information.Budget in excess of $12M.
- Conducted technical review of aquatic effects monitoring program (AEMP) for Diavik Diamond Mine on behalf of Wek' eezhii Land and Water Board, 2011.

- Provided expert testimony at Ontario Municipal Board (OMB) hearing, Aut.-Sept 2011, for quarry application. Conducted natural environment baseline studies, prepared reports under Aggregate Resources Act (ARA) to support application for proposed Limestone Quarry, Osprey Township, Ontario. MAQ Ltd. 2005- 2011. Application approved summer of 2012.
- Providing support and expert opinion regarding quarry dewatering at Keppel Quarry, Harold Sutherland Construction, 2011-2012.
- Provided confidential environmental screening assessment at greenfield sites for potetential aggregate and quarry developments for major Aggregate companies in Ontario.
- Senior fisheries scientist for annual monitoring and reporting of trout populations in Mill Creek, Puslinch Township for Dufferin Aggregates. 1993 – present.
- Conducted natural environment baseline studies, prepared reports under Aggregate Resources Act (ARA) and provided expert testimony to support successful application for Reeb Limestone Quarry, Port Colborne, Ontario. MAQ Ltd. 2005-2009.
- Development of Biodiversity Strategy for Xstrata Nickel smelter site. 2007-2009.
- Development of Toxicity Identifification and Evaluation program for INCO Port Colbourne effluent discharge. 2002- 2003.
- Review of water quality monitoring data for the closed Cullaton Lake mine, Northwest Territories, Barrick Gold. 2007.
- Provided expert testimony on behalf of mine in Northern Ontario for charges under the *Fisheries Act* for release of a deleterious substance. November, 2006.
- Review and input to the proposed High Lake Copper/Zinc mine in Northwest Territories Environmental Assessment document for Wolfden Mines. 2006.
- Prepared preliminary environmental constraints analysis for two potential quarry developments in southern Ontario. Dufferin Aggregates.
- Retained by Hudson Bay Mining and Smelting (HBMS) Ltd. To develop Environmental Effects Monitoring Study Desgin for 6 effluent discharge points/mine sites at Flin Flon, Manitoba. 2002-2003.
- Biological assessment of effluent discharge for proposed copper/nickel mine at the Montcalm project, Falconbridge. 2003
- Senior advisor to desing baseline flora and fauna survey, LaGranja project, Peru. Billiton Minerals. 2001.
- Development of Toxicity Identification and Evaluation Guidance Document. Environment Canada and Mining Association of Canada. 2000-2001.
- Predicting biological recovery for Closure Planning at the Detour Lake mine. Placer Dome. 2001.
- Kidd Creek Aquatic Impact Assessment Survey. Falconbridge, Timmins. 2001.
- Lake assimilation capacity modeling for Golden Giant Mine. 2001.
- Retained by Independent Finance Corporation (IFC of the World Bank), Washington, as part of a Commission to investigate a mercury spill related to a gold mine operation, Peru, 2000
- Retained by Falconbridge to investigate a fish kill, downstream of a nickel operation, Dominican Republic. February, 2001
- Development of site remediation options for Kam Kotia tailings site, Timmins, for the Ministry of Northern Development and Mines (MNDM), 2000
- Review of post-operational monitoring assessment study at Golden Patricia mine for Barrick Gold, 2000
- Provide expert testimony at Ontario Municipal Board hearing for proposed quarry application, Formosa Aggregates, fall 1999
- Retained by Mining Association of Canada (MAC) to provide scientific and technical guidance on proposed Environmental Effects Monitoring (EEM) legislation, 1999 – 2002.
- Developed rehabilitation and remediation plans for aquatic and wetland resources for numerous pits and quarries in Ontario
- Retained by Ontario Mining Association (OMA), Ministry Northern Mines and Development (MNMD) and Ontario Ministry of Environment (MOE) to review Ontario mine effluent toxicity data and causes of toxicity, 1999
- Review and assessment of simulated effluent chemistry and toxicity for Voisey's Bay Nickel Co., 1999

- Assessment of mercury levels in fish and effects from a gold mine operation. Barrick Gold Corp., 1999
- Environmental monitoring study design and fish telemetry tracking studies. Placer Dome North America, Campbell Mine. 1999
- Preparation of environmental monitoring study design for three mines at Hemlo gold comp. 1999
- Primary Author of Final Synthesis Report for the Aquatic Effects Technology Evaluation (AETE) program. Natural Resources Canada and Mining Association of Canada, 1999
- Environmental assessment of arsenic effects with field and laboratory studies. Placer Dome, 1999
- Modeling and prediction of water quality changes in receiving waters under different discharge scenarios. Williams Operating Corp., 1999
- Effluent Toxicity Identification and Evaluation (TIE) studies for Inco Ltd., 1998-2000
- Development of Technical Guidance document for collecting water and sediment samples for Environmental Effects Monitoring (EEM), Environment Canada, 1998-1999
- Study design and impact assessment survey at Detour Lake gold mine. Placer Dome Canada, 1998-1999
- Retained by Environment Canada to provide scientific advice to EIS Review Panel for Voisey's Bay Project, February, 1998
- Predictive impact assessment of pit dewatering on receiving waters. Placer Dome Canada, 1997
- Impact assessment of pit dewatering for Certificate of Approval application for a proposed open pit near Rapid River. Sudbury. INCO, 1997
- Benchtop experiments to examine efficacy of peat moss to remove metals from mine wastewater. Falconbridge Ltd., 1997
- Baseline water quality, benthos and fisheries environmental impact assessment in Night Hawk Lake, Timmins, Ontario, for a proposed gold mine operation for Royal Oak Mines Inc., 1996-1997
- Impact assessment and fisheries compensation for a proposed gold mine expansion in Three Nations Lake, Timmins, Ontario, for Royal Oak Mines Inc., 1996-Present
- Aquatic effects monitoring of Placer Dome Ltd. Gold Mine on the Porcupine River for the Aquatic Effects Technology Evaluation Program, Natural Resources Canada and Mining Association of Canada, 1996
- Aquatic effects monitoring of Inco Ltd. and Falconbridge Ltd. Mines on the Onaping River for the Aquatic Effect Technology Evaluation Program, Natural Resources Canada and Mining Assoc. of Canada, 1996
- Fisheries and water quality assessment and rehabilitation plans for Caledon Sand & Gravel, 1996-1997
- Aquatic impact assessment of mine operation for Placer Dome Canada, Detour Lake mine, 1995
- Retained by Mining Association of Canada (MAC) to synthesize AQUAMIN (Aquatic Effects of Mining in Canada) documents into a Final Report, 1996
- Fisheries and water quality inventory at West Morgan Lake for Falconbridge, Sudbury Division, 1995
- Development of soil transport model for cadmium and other metals. Ministry of Environment, 1995
- Aquatic impact assessment of Porcupine River for Kidd Creek Mines, Timmins, Ontario, 1995
- Aquatic impact assessment of three gold mines in N.W. Ontario for Hemlo Gold Mines, Williams Operating Corporation and Tech Operating Corp., 1992-1993
- Screening of over 600 mining studies and development of a database for the AQUAMIN program. Environment Canada, 1993. Database now at Laurentian University
- Representative for Mining Association of Canada (MAC) in discussions for Accelerated Reduction of Environmental Toxics, 1993
- External expert for study design and impact assessment at the Anaconda smelter, Montana, a U.S. Super Fund site under CERCLA and NRDA legislation, 1992
- Fish habitat and impact assessment for proposed Mardon limestone quarry in Mara Township for Dufferin Aggregates, 1990-1994
- Aquatic impact assessment of ERG tailings spill into the Porcupine River, Timmins. Ministry of Natural Resources, 1993
- Evaluation of aggregate removal on brown trout habitat in Brantford County in southern Ontario for Oxford Sand and Gravel, 1993
- Environmental impact assessment of dredging and aggregate removal in Lake Superior on fish habitat for A.B. McLean Ltd., 1989-1993
- Evaluation of techniques to reduce effluent toxicity for Ontario Mining Association, 1988

Fisheries and Fish Habitat (involved in excess of 150 fisheries habitat studies - select examples provided)

- Assessment of brook trout habitat and stream realignment for proposed road widening, Niagara Escarpment, Clearview Township.2016-2017.
- Peer review of proposed fish habitat rehabilitation in St. Mary's River, Ontario. For Batchewana First Nation, Sault Ste. Marie.
- Regulatory review of 2012 changes to the *Fisheries Act* and comments to Parliamentary Secretary on behalf of Long Lake 58 First Nation, Long Lac, Ontario.
- Working with Stantec to delevelop a Best Management Practices Guideline document to methodologies for development of ecological flows for Ontario Waterpower Association, 2014.
- Regularily retained by lawyers to provide expert testimony on matters related to the *Fisheries Act* and *Water Resources Act* at Ontario Municipal Board hearings,
- Retained to review chemical data and receiving environment assessment for potential impacts of accidental discharge at Bruce Nuclear facility, 2011.
- Development of numerous water quality monitoring and fish habitat assessment programs for natural gas pipeline crossing, bridge replacements, aggregate operations and industrial discharges for variety of engineering firms and internal (AECOM, ESG projects) 1995-2009.
- Preparation of detailed Fisheries habitat atlas and water quality monitoring program for the PRISM pipeline project in southern Ontairo. 2001-2002.
- Remediation and restoration of disturbed wetland/stream ecosystem including design of new stream channel, and restoration monitoring, Puslinch Township, 1999
- Testimony and expert opinion provided at National Energy Board (NEB) hearing for proposed pipeline crossing of St. Clair River and other streams. Vector Pipeline Application, London, Ontario, January 1999
- Environmental Effects Monitoring (EEM) studies for over 20 pulp and paper mills, Ontario, 1997-2003
- Development of EEM program in Ottawa River for the Regional Municipality of Ottawa Carleton (ROC). Included toxicity assessment of wastewater and staff training workshops, 1999
- Provided input regarding potential effects of barnyard runoff on water quality of nearby streams. Agricultural operation near London, Ontario, 1999
- Water quality and benthic assessment of discharge from corn syrup processing facility, London, 1999
- Assessment of impacts of seepage from Caledon Landfill on fisheries of the Credit River: for Region of Caledon, 1996-1998.
- Impact assessment of manure spill on water quality and biota in tributary to Sixteen Mile Creek, 1998
- Fisheries habitat survey and mitigation for proposed bridge replacement at Eden Mills for Triton Engineering, 1996
- Fisheries habitat and impact assessment for natural gas pipeline crossing of Nith River. Union Gas, 1996
- Fish habitat survey and habitat enhancement measures for proposed bridge replacement over the Grand River at Inverhaugh for K. Smart and Associates, 1996
- Environmental Effects Monitoring studies of fisheries habitat for DOMTAR Ltd. at Cornwall, Trenton and Red Rock, Ontario, 1993-1995
- Nipigon River: Development of a Water Management Plan. North Shore of Lake Superior Remedial Action Plan (RAP) Technical Report Series No. 20. 1994.
- Development of fish habitat replacement model for Ontario Ministry of Transportation, 1993
- Detailed fisheries habitat assessments in Northern Ontario for proposed pipeline construction for TransCanada Pipelines Ltd., 1991-1993
- Fish habitat impact assessment of log transportation on the Kapuskasing River and development of habitat restoration techniques for Spruce Falls Inc. Pulp and Paper, 1991-1992
- Fish habitat mapping study in Lake Simcoe for City of Barrie, 1991
- Habitat mapping in Fathom Five National Park for Parks Canada, 1992
- Assessment of growth and reproduction of lake trout stocked in an acidic lake after neutralization for Ontario Ministries of Environment and Natural Resources, 1987
- Efficiency of site-specific shoal liming for lake trout egg survival in an acid-stressed lake, 1988

Site Assessment and Remediation

- Routinely retained to provide expert opinion, data interpretation and guidance for Phase 1 through 3 site assessments for private properties and developments. Contaminants range from standard petroleum hydrocarbons, BTEX, metals, PCBs, pesticides and dioxins.

Planning and Development

- Assessment of stream re-alignment, culvert installations and stream crossings for several residential developments Collingwood-Blue Mountain areas. 2016-2017.
- Input to Environmental Impact Study (EIS) for stormwater pond adjacent to a coldwater stream, Markdale, Ontario. 2016.
- Provide expert testimony at Ontario Municipal Board hearing regarding potential agricultural runoff into a coldwater stream. Collingwood, Ontario. June 2007.
- Provided expert testimony under *Water Resources Act* regarding input of sediments to a stream from construction site, Toronto area. 2006.
- Provided expert testimony on water quality issues related to road salts and other chemicals at Oak Ridges Morraine Ontario Municipal Board hearing, Richmond Hill, 2001.
- Studies and expert testimony relating to water taking permit for Mansfield Ski Club under Environmental Assessment Appeals Board, 2000
- Expert testimony at Ontario Municipal Board Hearing regarding proposed development on Lake Muskoka. December, 1997
- Expert testimony at OMB hearing regarding potential impacts of nutrients from proposed rural subdivision development on wetland and coldwater fisheries at Erin. Proposed Gulia Subdivision, September, 1997
- Fisheries habitat assessment of a proposed marina at Jackson’s Point, Lake Simcoe, 1995-1996
- Fisheries habitat assessment for regional Wilmot Centre groundwater withdrawal. Regional Municipality of Waterloo, 1997-1998
- Fisheries habitat and sediment quality assessment for proposed natural gas pipeline at Talfourd Creek, Sarnia Interprovincial Pipelines.
- Fisheries habitat enhancement plan for Orpen Lake and tributaries to Credit River. Soga Gakki International, 1997-1999
- Expert testimony at Ontario Municipal Board Hearing regarding potential impacts of nutrients and sewage on coldwater fisheries. Buffalo Springs Rural Estate - Seeley and Arnill, 1995
- Assessment of potential impacts of cottage development on the Grass Lake lake trout populations, Muskoka. M. Michaelski and Associates, 1995
- Expert testimony at Ontario Municipal Board Hearing regarding potential impacts of septic systems on coldwater fish and aquatic habitat. Soga Gakki International, 1995
- Fisheries habitat assessment for proposed natural gas pipeline in S. Ontario for IPL, 1993.
- Survey and investigation of mercury contamination of soils at natural gas compressor sites - TransCanada Pipelines Ltd., 1994
- Investigation of mercury contamination of soils at natural gas compressor sites - Consumers Gas, 1993
- Environmental impact assessment and 600km route selection for 500kv transmission line in Northwestern Ontario for Ontario Hydro, 1992
- Environmental impact assessment and route selection for proposed Hwy 407 extension for Ontario Ministry of Transportation and Parker Engineering, 1990
- Aquatic impact assessment and route selection for K-W Loop natural gas pipeline for Union Gas, 1991
- Natural resources impact assessment and site selection for new landfill site for City of Guelph and Wellington County, 1993
- Environmental survey and study report for proposed hydroelectric development on the Abitibi River for Ontario Hydro, 1990
- Fish habitat assessment of the Pine Ridges rural estate development near Newmarket on a cold water stream, 1990

Toxicology and Chemical Substance Hazard Evaluation

- Project director to assess methods to extrapolate acute aquatic toxicity data to chronic data. Environment Canada. Ottawa, 2008.
- Senior scientist on study to review existing Canadian agricultural water quality guidelines and recommend updates and revisions. Environment Canada. Ottawa, 2008.
- Review of proposed water quality guideline for nitrate in effluent discharge from an existing diamond mine on behalf of Wek'eezhii Land and Water Board. June 2007.
- Review and input to proposed sediment and shoreline remediation plan to address arsenic contamination at Long Lake First Nations. 2007.
- Review of air quality monitoring data for Iron Ore Company of Canada Ltd. 2007.
- Input to soil remediation program and assess possible human health hazard related to arsenic in soil from herbicide use at Whitefish First Nations. 2006.
- Review of aquatic toxicity of arsenic. Ontario Mining Association, 1999-2000
- Critical evaluation of potential impacts of demineralized water discharges and aquatic toxicity test methodologies. On behalf of Ontario Power Generation in discussions with Ontario Ministry of Environment.
- Review of World Health Organization Environmental Health Criteria document (EHC) on Copper for Environment Canada, Toxic Substance Branch, 1996
- Review of World Health Organization Environmental Health Criteria document (EHC) on Nickel for Environment Canada, Toxic Substances Branch, 1996
- Development of toxicity profile on Polychlorinated BiPhenyls (PCBs) for Priority Substance List assessment for Environment Canada, 1996
- Retained to provide expert advise on mercury in fish by MacLaren Hart, California, for the Oak Ridge Superfund Site, Tennesee, 1995-1996
- Field and laboratory stories of diazinon uptake and toxicity to earthworms, 1993
- Investigation of sources and chemistry of dioxins on industrial property in Sault Ste. Marie, Ontario. Praxair Ltd., 1993
- Hazard assessment of eight organic chemicals found in pulp and paper effluent for Ontario Ministry of the Environment, 1993
- Development of soil quality guidelines for Toluene, Ethylbenzene and Xylene for Env. Canada, 1992
- Development of soil quality guideline for mercury for Environment Canada, 1992
- Development of Federal water quality criteria for Linuron and Chlorothalonil, for Env. Canada, 1993
- Development of water quality guidelines for 12 organic chemicals for Ontario Ministry of the Environment. 1991-1992
- Technical review of aquatic toxicity data for Noranda Research Centre, 1988
- Development of water quality criteria for arsenic, thallium, vanadium and antimony for Ontario Ministry of the Environment, 1988
- Development of water quality criteria for methylated naphthalenes for Ontario Ministry of the Environment, 1988
- Development of water quality objectives for lead, cadmium, copper and zinc for the Ontario Ministry of the Environment, 1989
- Development of background data for establishing tissue contaminant guidelines in aquatic biota - Ontario Ministry Environment, 1988
- Data reviews for As, Cr, Ni, Sn, F for Health and Welfare, Canada, 1989
- Experimental study on the effects of PCBs and methylmercury on mink reproduction for National Research Council, 1985

AWARDS

Ontario Graduate Scholarship, 1979-1980; 1981-1982
Postdoctoral Fellowship, Royal Norwegian Council for Industrial and Scientific Research, 1986-1987
NATO Travel Grant, 1987
Coauthor of "Best Paper of the Year" Award presented by American Fisheries Society. 1993.

PUBLICATIONS

Dr. Wren has over 40 publications in peer reviewed journals, textbooks and documents. He has presented papers at over 30 conferences and workshops, and has authored well over 200 reports for consulting projects. In addition he has acted as facilitator at workshops and meetings. Dr. Wren has also appeared as expert witness in Ontario Municipal Board hearings, National Energy Board proceedings and court cases.

Wren, C.D. (ed). 2012. Risk assessment and environmental management: A case study in Sudbury, Ontario. Maralte Publishers, Netherlands. 454 pgs. www.maralte.org.

Wren, C.D. and L.R. Guenther. 2003. Open pit mining and the Fisheries Act: Potential effects and mitigation. Canadian Reclamation. Spring 2003, p. 31.

Mason, C. and C.D. Wren. 2001. Organochlorine and metal contaminants in Carnivora. Chapter in Ecotoxicology of Mammals. R.F. Shore and B. Rattnor (ed.) pps 315-370.

Wren, C.D., N.A. Harttrup, B. Michelluti and G. Hall. 1997. Recovery of a river ecosystem receiving 80 years of mine effluent. Proceedings Aquatic Toxicity Workshop, Niagara Falls. October 1997. Can. Fish. Aquatic Science Technical Report. #2192.

Wren, C.D., C.A. Bishop, D.L. Stewart and G.C. Barrett. 1997. Wildlife and contaminants in constructed wetlands and stormwater ponds: current state of knowledge and protocols for monitoring contaminants levels and effects in wildlife. Canadian Wildlife Service Tech. Rep. Series Nº. 269. Burlington.

Fletcher, T., G.L. Stephenson, J. Wang, C.D. Wren and B.W. Muncaster. 1996. Scientific criteria document for the development of an interim provincial water quality objective for antimony. Ontario Min. Environ. and Energy. Queens Printer, Toronto. 32 pp.

Stephenson, G.L., D.J. Spry, B.W. Muncaster, C.D. Wren and T. Fletcher. 1996. Scientific criteria document for the development of an interim water quality objective for thallium. Ont. Min. Environ. and Energy. Queens Printer, Toronto. 29 pp.

Stephenson, G.L., C.D. Wren, I.C.J. Middelraad, and J. Warner. 1997. Exposure of the earthworm, *Lumbricus terrestris*, to diazinon and the relative risk to passerine birds. Soil Biology and Biochemistry. 29: 717-720.

Wren, C.D., and C.W. Farrell. 1995. Mercury in the natural gas industry in Canada. Water, Air, Soil Pollut. 80:1203-1206.

Wren, C.D., N. Harttrup and S. Harris. 1995. Ecotoxicology of mercury and cadmium. *In:* Handbook of Metals Ecotoxicology, Lewis Pub. D.J. Hoffman (ed.) pp.392-423.

Lanno, R.P., G.L. Stephenson, and C.D. Wren. 1997. Application of toxicity curves in assessing the toxicity of diazinon and pentachlorophenol to *Lumbricus terrestris* in natural soils. Soil Biology and Biochemistry. 29: 689-692.

Stephenson, G.L., C.D. Wren, I.C.J. Middelraad and J. Warner. 1994. Toxicity and bioaccumulation of diazinon in the earthworm, *Lumbricus terrestris*, and an assessment of the relative risk to worm-eating birds. Proceedings Ontario Environment and Energy Conference, Ontario Ministry of the Environment and Energy, Toronto, Ontario.

Wren, C.D. and E. Steinnes. 1994. Use of willow grouse as biological indicators of metal levels in Norway. Environ. Pollut. 85:291-295.

Lanno, R. and C. Wren. 1992. Predictive modeling of fisheries habitat loss and replacement. Research and Development Branch, Ontario Ministry of Transportation MAT-92-01, Downsview, Ontario. 36 pp.

Wren, C.D., G.L. Stephenson and R. Lanno. 1993. The use of biological testing for contaminated soil assessment. Environmental Science and Engineering. September 26-27.

Gunn, J., C.D. Wren and G.M. Booth. 1993. Site specific efficacy of shoal liming on lake trout egg survival in acidic lake. Trans. Am. Fish. Soc. 13:766-774. (*Won Best Paper of the Year Award from American Fisheries Society).

Wren, C.D., I. Gray, B. Muncaster, W. Scheider and D. Wales. 1991. Relationship between mercury levels in walleye and northern pike in Ontario lakes and influence of environmental factors. Can. J. Fish Aquat. Sci. 48:132-139.

Wren, C.D. and G. Stephenson. 1991. The effect of acidification on the accumulation and toxicity of metals to invertebrates. Environ. Pollut. 71:205-241.

Wren, C.D., 1991. Relationship between chemicals in the Great Lakes and mink and otter populations. J.Environ. Toxicol. 33:549-585.

Gunn, J.M., J. Hamilton, G.M. Booth, C.D. Wren and G. Beggs. 1990. Survival, growth and reproduction of lake trout and yellow perch after neutralization of an acidic lake near Sudbury, Ontario. Can. J. Fish. Aquat. Sci. 47(2):446-453.

Steinnes, E., Solberg, W., Petersen, H., and C.D. Wren. 1989. Metal levels in soils of Norway in relation to Long Range transport of atmospheric deposition. Water, Air, Soil Pollution. 45:207-218.

Wren, C.D., K.L. Fischer and P.M. Stokes. 1988. Levels of lead, cadmium and other elements in mink and otter from Ontario, Canada. Environ. Pollut. 52:193-202.

Wren, C.D. and P.M Stokes. 1988. Depressed mercury levels in biota from acid and metal stressed lakes near Sudbury, Ontario. Ambio 17: 28-30.

Richman, L.A., C.D. Wren and P.M. Stokes. 1988. Facts and fallacies concerning mercury uptake by fish in acid stressed lakes. Water, Air and Soil Pollution. 37: 465-473.

Wren, C.D., D.B. Hunter, J.F. Leatherland and P.M. Stokes. 1987a. The effects of Polychlorinated biphenyls and methylmercury, singly and in combination, on mink, 1: Uptake and toxic responses. Arch. Environ. Contam. Toxicol. 16:441-447.

Wren, C.D., D.B. Hunter, J.F. Leatherland and P.M. Stokes. 1987b. The effects of Polychlorinated biphenyls and methylmercury, singly and in combination, on mink, 2: Reproduction and kit development. Arch. Environ. Contam. Toxicol. 16:449-454.

Wren, C.D., N. Cloutier, T.P. Lim and N.K. Dave. 1987. Ra-226 concentrations in otter (*Lutra canadensis*) trapped near uranium tailings at Elliot Lake, Ontario. Bull. Environ. Contam. Toxicol. 38:209-212.

Wren, C.D. 1987. Toxic substances in furbearing animals. Chapter In Fur Management and Conservation in North America. M. Novak (ed) Ministry of Natural Resources and Ontario Trappers Assoc. pp. 930-936.

Wren, C.D., P.M. Stokes and K. Fischer. 1986. Mercury levels in Ontario mink and otter relative to dietary levels and watershed acidification. Can. J. Zool. 64(12): 2854-2859.

Wren, C.D. 1986. Metal accumulation and toxicity in wild mammals, 1: Mercury. Environ. Res. 40:210-244.

Wren, C.D., and H.R. MacCrimmon. 1986. Comparison of the distribution and accumulation of mercury in two adjacent freshwater ecosystems. Water Res. 20(6):763-769.

Wren, C.D. 1986. Mammals as biological indicators of environmental metal loading. J. Environ. Monitor. and Assess. 6:127-144.

Stokes, P.M., and C.D. Wren. 1986. Bioaccumulation of mercury by aquatic biota in hydroelectric reservoirs: A review and consideration of mechanisms. In Occurrence and Pathways of Lead, Mercury, Cadmium and Arsenic in the Environment. T.C. Hutchinson and K.M. Meema (eds), pp. 255-277. John Wiley and Sons Ltds. Toronto.

Wren, C.D. 1985. Probable case of mercury poisoning in a wild otter, *Lutra canadensis*, in Northwestern Ontario. Can. Field Naturalist. 99(1):112-114.

Wren, C.D. 1984. Distribution of metals in tissues of beaver, racoon and otter from Ontario, Canada. Sci. Total Environ. 34:177-184.

Wren, C.D., and H.R. MacCrimmon. 1983. Mercury levels in sunfish (*Lepomis gibbosus*) relative to pH and other environmental variables of Precambrian shield lakes. Can. J. Fish. Aquat. Sci. 40:1737-1744.

Wren, C.D., H.R. MacCrimmon and B. Loescher. 1983. Examination of biomagnification and bioaccumulation of metals in a freshwater ecosystem. Water, Air Soil Poll. 19(3):277-292.

MacCrimmon, H.R., C.D. Wren and B.L. Gots. 1983. Mercury accumulation in lake charr (*Salvelinus namaycush*) in an undisturbed Precambrian shield lake. Can. J. Fish. Aquat. Sci. 40(2):114-120.

Wren, C.D. 1982. Potential effects of metals on benthic organisms after liming acid-stressed lakes. Water Poll. Res. J. Canada 17:149-151.

Wren, C.D., H.R. MacCrimmon, R. Frank and P. Suda. 1980. Total and methylmercury levels in wild mammals from the Precambrian shield area of south central Ontario. Bull. Environ. Contam. Toxicol. 25:100-105.

CONFERENCE PRESENTATIONS, NON-REFEREED PUBLICATIONS AND REPORTS

Wren, C.D. 2010. Role of risk assessment in mine closure. Invited paper presented at Mine Closure 2010, conference in Santiago, Chile, November, 2010.

Wren, C.D. 2010. Human health and ecological risk assessment in mine closure. Full day course presented to 30 international attendees at Mine Closure 2010 conference in Santiago, Chile, November 2010.

Wren, C.D. and C. Wardlaw. 2010. Guidance document for reviewing applications to remediate contaminated sediments. Report prepoared for Department of Fisheries and Ocean, Federal Contaminated Sites Action Program. Burlington, March, 2010.

Wren, C.D., G. Watson and M. Butler. 2009. The Sudbury Soils Study; a significant case study in risk assessment. Laurentian SETAC, June, Otttawa.

Wren, C.D. and G. Watson. 2008. Overview of risk assessment in the mining industry and case study presentation. National Orphaned Abondoned Mines Initiative (NOAMI) workshop. November 12-13. Vancouver.

Wren, C.D. 2005.Overview of the Sudbury Soils Study: risk assessment case study in Canada. Securing the Future. International Mining Conference; ICARD #7. June. Skeleftea, Sweden.

Wren, C.D. 2005. Ths Sudbury smelter risk assessment: overview and key issues. Invited papter presented at International workshop on metals in soils. Natural Resources Canada. Ottawa. Feb. 14-15.

Wren, C.D. and L. Guenther. 2005. Insight into the defense for charges under the *Fisheries Act.* Training session to Department of Fisheries and Oceans. Talisman Resort. Ontario.

Taylor, L.N., A.J. Martin, L.J. Novak and C.D. Wren. 2004. Fate and behaviour of EDTA in a metal-mining polishing pond. Paper presented at SETAC Confererence. November. 2004. Oregon.

Wren, C. D., N. Harttup, R. Van Ooteghem, S. Lowe and A. Hims. 2003. Relationship between aggregate extraction, groundwater and trout populations in a southern Ontario stream. Paper presented at the Sudbury 2003 Mining and the Environment Conference. May, 2003.

Wren, C.D., G. Watson, M. Butler and G. Ferguson. 2003. The Sudbury Soils Study: A community based risk assessment. Paper presented at the Sudbury 2003 Mining and the Environment Conference. May, 2003.

Orr, P., D. Zaranko, I. Martin, A. Burt, D. Ferrara and C. Wren. 2002. Are proposed requirements for benthic community assessments at Canadian mine sites progressive or regressive? Paper presented at 29th Annual Aquatic Toxicity Workshop, Whistler, B.C.

Wren, C.D. 2001. Ecological risk assessment at contaminated sites. Invited panel presentation at Managing Contaminated and Brownfield Development workshop. Waterloo, Ontario. November, 2001.

Wren, C.D. 2001. Soil contamination from a mercury spill in the Andes Mountains: Environmental and human health implictations. Presented at Sixth International Conference on the Biogeochemistry of Trace Elements. July 28-August 2, University of Guelph. 2001.

Wren, C.D., B. Muncaster and K. Cover. 2000. Environmental impact assessment of two water purification plants and a sewage treatment plant discharging to the Ottawa River. Paper presented at 27th Aquatic Toxicity Workshop, Oct. 1-4, St. John's, Nfld.

Wren, C.D., N. Harttrupp and K. Ferguson. 2000. Aquatic environmental assessment of a gold mine in Northern Ontario. Paper presented at 27th Aquatic Toxicity Workshop, Oct. 1-4, St. John's, Nfld.

Wren, C.D. 2000. Environmental and human health implications of mercury spill from gold mine in the Andes Mountains, Peru. Paper presented at 27th Aquatic Toxicity Workshop, Oct. 1-4, St. John's, Nfld.

Wren, C.D. and N. Harttrupp. 2000. Fish habitat and water quality considerations in planning and design of open pit mining. Invited paper presented at Sudbury Restoration Workshop, Laurentian University. February 22, 2000.

Wren, C.D., 1999. The ABC's of the aquatic impact assessment "toolbox". Short course presented at Sudbury '99 Conference with other ESG staff. Sudbury, September. 1999.

Wren, C.D., L. Trudel, D. Campbell and J. Papineau. 1998. Overview of Aquatic Effects Technology Evaluation (AETE) program. Presented at 25th Aquatic Toxicity Workshop. October 19-21. Quebec City.

Wren, C.D., N.A. Harttrup, B. Michelluti and G. Hall. 1997. Ecosystem recovery in the Onaping River. Paper presented at the 8th annual Sudbury Restoration Workshop. Laurentian University, February 18, 1997.

Wren, C.D. 1997. Aquatic ecological research outside of academia. Invited paper presented at Ontario Ecology and Ethology Colloquium. University of Western Ontario. May 13.

Wren, C.D. and C.R. Bishop. 1996. Risk of chemicals in stormwater ponds and constructed wetlands to fish and wildlife. Paper presented at 31st Canadian Symposium on Water Pollution Research. Feb. 8, 1996. Burlington, Ontario.

Wren, C.D. 1996. Presentation to government-industry panel on environmental effects monitoring in Ontario pulp and paper mills. September, Toronto.

Wren, C.D. and C.W. Farrell. 1995. Mercury contamination in the natural gas industry. Presented at Conference on Mercury as a Global Pollutant, Whistler, B.C. July.

Stephenson, G.L., C.D. Wren, I.C.J. Middelraad and J. Warner. 1994. Toxicity and bioaccumulation of diazinon in the earthworm, *Lumbricus terrestris*, and an assessment of the relative risk to worm-eating birds. First Ontario Environmental and Energy Conference, Toronto, Ontario. Nov.15-16, 1994.

Wren, C.D., G.L. Stephenson and I. Middelraad. 1994. Risk assessment of Diazinon to earthworms and passerine birds. Paper presented at 15th Annual Meeting: Society of Environmental Toxicology and Chemistry. November. Boulder Colorado.

Stephenson, G.L., I.C.J. Middelraad, C.D. Wren and J. Warner. 1994. The exposure of earthworms (*Lumbricus terrestris)* to diazinon and risk assessment to passerine birds. Fifth International Symposium on Earthworm Ecology. Ohio State University, Columbus, OH. July 4-9, 1994.

Lanno, R.P., C.D. Wren, and G.L. Stephenson. 1994. The use of acute lethality thresholds in assessing the toxicology of four chemicals to the earthworm, *Lumbricus terrestris,* in three natural soils. Fifth International Symposium on Earthworm Ecology. Ohio State University, Columbus, OH. July 4-9, 1994.

Lanno, R.P., C.D. Wren and G.L. Stephenson. 1993. Earthworm and seed germination toxicity tests to assess the efficacy of bioremediation of chlorophenol and PAH-contaminated soils. Society of Environmental Toxicology and Chemistry, Houston, Texas, Nov. 14-18, 1994.

Lanno, R.P., C.D. Wren and G.L. Stephenson. 1993. The toxicity of four chemicals to the earthworm *Lumbricus terrestris* in three natural soils. Society of Environmental Toxicology and Chemistry, Houston, Texas. Nov. 14-18, 1994.

Wren, C.D. 1993. The cost of conducting Environmental Effects Monitoring (EEM) studies in the pulp and paper industry. Invited paper. Presented at 20th Aquatic Toxicity Workshop. October 21, 1993. Quebec City.

Wren, C.D. and Welbourn, P.M. 1991. Technical Review of Environmental Assessment, Little Jackfish River Hydroelectric Project: Reservoir Preparation and Management, Mercury Methylation, Nutrient and Sediment Cycling. Prepared for Dept. Fisheries and Oceans. 38 pp.

Wren, C.D. 1990. Wildlife as biological indicators of Ecosystem Health. Invited paper. International conference on Aquatic Ecosystem Health and Management. August 23-26. Waterloo, Ontario.

Wren, C.D. 1989. Viewpoints on MISA - the Ontario Municipal Strategy for Abatement Program - from a biologist's perspective. Invited paper to the Annual Meeting of the Canadian Water Resources Association, April 25, Black Creek Pioneer Village, Toronto.

Wren, C.D. 1989. An epidemiological approach to examining the effects of chemicals in the Great Lakes to wild mink and otter populations. Invited paper presented at Workshop on Cause-Effect Linkages. Council of Great Lakes Research Managers. March 28-31. Chicago.

Wren, C.D. 1989. Aquatic bioassays in MISA. Water Pollution Control magazine. April issue.

Wren, C.D. 1988. Relationship of mercury levels in sportfish to water quality and lake sediment characteristics. Proc. Ont. Min. Environ. Technol. Transfer Conference. November 28-29, Toronto.

Wren, C.D. 1988. Influence of water chemistry on food chain transfer of lead, cadmium and mercury. Invited review paper presented at Society Environmental Toxicology and Chemistry, Ninth Conference. Arlington, VA, November 14-18.

Booth, G.M., W. Keller, J. Gunn and C. Wren. 1988. The effect of whole lake neutralization on a lake trout community in Ontario, Canada. Paper presented at 118th Annual Meeting American Fisheries Society. September 9-15, Toronto.

Wren, C.D. 1988. Opportunities and issues for biological testing laboratories in pollution abatement programs. Invited paper. Proceedings of Workshop on Biology in the New Regulatory Framework for Aquatic Protection. Sponsored by Environment Canada. April 26-28, Alliston, Ontario.

Wren, C.D. 1987. Contaminant Research in Canadian otters. U.U.C.N. Otter Specialist Group, Bulletin Number 2.

Wren, C.D. and P.M. Stokes. 1986. Mercury release in hydroelectric reservoirs. Paper presented to Canadian Electrical Association. Harbour Hilton, Toronto, March 25.

Wren, C.D., D.B. Hunter and P.M. Stokes. 1985. Effects of methylmercury on mink: an integrated field and lab study. Paper presented at Sixth Annual Meeting, Soc. Environ. Toxicol. and Chem., St. Louis, Mo. November 9-12.

Wren, C.D. and P.M. Stokes. 1985. Facts and fallacies concerning mercury uptake in fish from acid stressed lakes. Poster, Internat. Sympos. on Acid Precipitation, Sept. 15-20. Muskoka, Ont.

Wren, C.D., P.M. Stokes and K. Fischer. 1985. Mercury levels in piscivorous furbearers relative to environmental loading and availability in Ontario. Poster, Internat. Sympos. on Acid Precipitation, Sept. 15-20. Muskoka, Ontario.

Wren, C.D. and P.M. Stokes. l986. Mercury release in hydroelectric reservoirs. Presented at Canadian Electrical Association meeting in Toronto, March, l986.

Wren, C.D. and P.M. Stokes. 1985. Evaluation of environmental mercury hazard to mink: an integrated field and lab approach. Presented at Sixth Annual Conference of the Society of Environmental Toxicology and Chemistry, St. Louis, Mo., November 10-13, 1985.

Wren, C.D. 1984. Potential effects of acid rain to wildlife and furbearing animals. Presentation to the Sudbury Trappers Association. June 24, Sudbury, Ontario.

Wren, C.D. and P.M. Stokes. 1984. Metal accumulation and potential toxicity to wild mammals in Ontario. Presented to the Royal Society of Canada peer review of the Federal Government of Canada research programs on Long Range Transport of Atmospheric Pollutants (LRTAP). Feb. 21-22. Toronto.

Wren, C.D. 1984. The Institute for Environmental Studies. University of Toronto, Bull. Canadian Society of Zoologists 15:10-11.

Wren, C.D. and H.R. MacCrimmon. 1983. Relationship of mercury levels in sunfish to environmental conditions of acid- stressed lakes. Presented at Canadian Society of Environmental Biologists Annual Meeting, Winnipeg. Manitoba.

Wren, C.D. and H.R. MacCrimmon. 1982. Growth rate and mercury levels in pumpkinseed sunfish relative to pH in south central Ontario lakes. Presented to Acid Rain workshop, Ontario Ministry of the Environment. Toronto, April 2-4.

Wren, C.D. and H.R. MacCrimmon. 1981. Distribution of metals in an aquatic ecosystem. Paper presented at the 8th Aquatic Toxicity workshop. University of Guelph, November 2-4.

Wren, C.D. and H.R. MacCrimmon. 1981. Mercury accumulation in Precambrian shield lake ecosystems relative to local environmental conditions. Presented at the Plains Aquatic Research Conference, Calgary, Alberta. August 25-26.

January 2018

MICHAEL G. JONES

B.Sc., M.Sc., P.Geo.
Senior Hydrogeologist/Hydrogeochemist
President

PROFILE

1995-Present	President, Azimuth Environmental Consulting, Inc.
2003-2005, 2008-2012	Faculty (part time), Georgian College (Professional Golf Management Program)
1987-1995	Hydrogeochemist, Senior Consultant, Gartner Lee Limited
1985-1987	M.Sc., University of Waterloo, Geology/Geochemistry
1985-1987	Research Assistant, University of Waterloo, Geology Dept.
1983-1985	Technician, University of Waterloo Isotope Research Laboratory
1983	Geophysical Exploration Technician, UMEX Inc.
1980-1985	B.Sc. (Honours Co-op), University of Waterloo, Geology

EXPERIENCE

1995 – Present President, Azimuth Environmental Consulting, Inc.

Mr. Jones is a founding member of Azimuth Environmental Consulting, Inc. Mr. Jones' areas of specialty include water supply and wastewater treatment, ground water geochemistry and contaminant hydrogeology. He provided expert testimony before the Joint Board, the Ontario Municipal Board, the Environmental Review Tribunal and civil court.

He has undertaken a variety of projects, including:

- Lead hydrogeologist for construction of Highway 407 Phase 2. This project includes assessment of construction dewatering requirements at more than 100 structures and obtaining Permits to Take Water for all activities that may reach the water table. It also includes an active monitoring programme for ground water levels at an extensive well network and at major stream crossings and terrestrial ecology sites to evaluate the potential and actual changes caused by the highway. Participation with BBC staff and in working group meetings, and liaison with key staff at regulatory agencies is required to address potential issues as they arise.
- Lead investigator and environmental consultant for ClubLink Corporation at 28 of their properties. These studies have focused on aspects of water management, from supply for irrigation and potable needs to sewage treatment. Water management is a central requirement for a successful golf facility, so water issues are incorporated at the beginning of development plans. We have succeeded in finding innovative solutions where site limitations would have precluded a golf facility. Monitoring of potential impacts from chemical products and treated effluent applications is completed routinely and environmental impacts are evaluated. ClubLink is obtaining Audubon Signature designation at their courses so stewardship programs for water management and environmental practices have been developed. Azimuth has assisted ClubLink in obtaining MOE permits to take water, sewage system permitting and to operate potable water treatment systems. Similar work has also been completed for several other golf properties.
- Lead investigator for water supplies and more than 200 Permits to Take Water. Water-takings have included those for irrigation, potable water, quarries, construction dewatering and commercial taking for spring water, bottled water and beverage

production. Work has included hydrogeological evaluations to document the ground water regime for proposed water supplies and consideration of potential impacts from the proposed taking to other users and natural heritage features. For complex environments or large takings, Modflow is used to simulate the takings and predict the potential drawdown for specific receptors.

- The annual ground water, surface water and leachate monitoring programs at approximately 15 landfills in central and northern Ontario. These programs involve the collection and analysis of samples and site data throughout the year to evaluate the performance of the site. Most of the sites have been designed to naturally attenuate contaminants, so that routine monitoring is important in assessing regulatory compliance. Since 1995, more than 100 annual investigations have been completed.
- Design and approvals for leachate collection and treatment systems at four rural landfill sites. The systems include on-site treatment using a tertiary treatment system and discharge of treated effluent to either a leaching field or direct discharge to wetlands or a small creek. The systems provide contingency mitigation in the event that predicted impacts from natural attenuation become unacceptable. At one site, the LTS provides the main leachate control and has resulted in the reduction of environmental discharges by 95%.
- Project manager and hydrogeologist for the Ministry of Transportation providing an assessment of road salt or construction blasting impacts. These investigations include an assessment of the physiographic setting, surface drainage and hydrogeology. An assessment is made of potential contaminant sources, pathways to the contaminated well and well status. Recommendations are made regarding possible remedial measures. This work has included a broad spectrum of investigations over more than two decades, including regional studies of the Highway 11 and 118 corridors to evaluate at whole communities, investigations at salt storage yards and works yards, a review of potential salt impacts in Emsdale pertaining to whole community, which has become a class action lawsuit and approximately 400 well assessments to consider causal relationships for water quality and quantity problems. From this work, Azimuth prepared the MTO protocol for pre-construction well testing and baseline evaluations.
- Phase I/II assessments of commercial and industrial properties. These assessments focus on previous and current land use and the potential for contaminant impact. Assessments typically include test pitting, visual assessment of the lands and premises and the collection of soil and water samples for analysis.
- Lead investigator and environmental consultant for the Township of Oro-Medonte. Initiated long-term watershed management plan for Oro Moraine. Goal of project was to provide long-term protection of this resource through the planning process. On behalf of the Township, Azimuth has maintained an on-going water monitoring program using the installation of pressure dataloggers in key locations. A second project involved an inventory of the natural heritage features and developed a methodology for establishing the levels of constraint for development based on natural heritage features/functions and hydrogeology. Continue to provide third-party review of hydrogeologic submissions to the Township.
- Project director and environmental consultant for M.A.Q. Quarries. Conducted Level 2 hydrogeologic investigations at prospective quarry sites in Severn, Ramara (Carden Plain), Duntroon and Port Colborne. Work program involves fracture network evaluation using packer testing system, continuous water monitoring using dataloggers,

geochemical profiling, surface water monitoring and numerical modeling of the environmental setting. Program provided represent contemporary standards for fractured rock site evaluation as recommended and accepted by the client.

- Project manager and lead investigator for water and wastewater system implementation for approximately thirty rural and communal facilities. These projects have included public systems (EAA, EPA and OWRA approvals) as well as private systems (EPA and OWRA approvals). The projects offer complete assessments, from delineation of available water supplies, appropriate potable water treatment needs, sewage and wastewater collection and treatment, and discharge of treated effluent. Opportunities are defined and then approvals are sought to meet provincial and municipal requirements. At several sites, treated effluent has been incorporated into irrigation supply to allow re-use and recognize the additional treatment benefits when treated effluent is applied to turf. The systems have been designed to satisfy water demand from 10 to 2,200m^3/day. Sewage treatment systems have been designed for 10 to 650m^3/day. Examples of these systems include golf clubhouses (e.g. The Rock and Mad River Golf Club), rural subdivisions (e.g. Balsam Lake), new urban subdivisions (e.g. the Greenwood expansion, Westhill (Aurora), Villages of Shakespeare and Minett) and resorts with mixed waste streams (e.g. Red Leaves in Minett, the Muskokan Resort, Lakeside at Rocky Crest).
- Project manager and lead investigator for Class EA approvals for water and wastewater. These projects have included new supplies for Minett, Aurora, Greenwood, Sebringville and Shakespeare. In a sixth project, I provided peer review of technical reports for Bradford – West Gwillimbury for the proposed Bradford-Bondhead expansion.
- Lead hydrogeologist for the peer review of two proposed gold mine sites in Northern Ontario (Federal Class EA). Our review was completed as part of a multi-disicplinary team on behalf of our clients, two First Nations communities where the mine sites are located within their historical use areas.
- Lead investigator for investigations regarding the alleged parasite (*Giardia*) contamination of the south municipal water supply for the City of Thunder Bay. These forensic investigations were undertaken as the municipality is the defendant in a number of on-going civil court cases. Our investigations identified that *Giardia* in the water source during the alleged period of contamination reflected background conditions consistent with those over the last 90 years, and that an outbreak did not occur.
- Reviewer for the MOE Ground water Under the Influence (GUDI) Water Supply Program. Following the Walkerton Inquiry, the MOE retained thirty individuals across the province to review GUDI reports on public water supplies. These reports assessed the minimum treatment requirements for public supplies that may be susceptible to surface water infiltration. Mike reviewed seven of these reports for the MOE.
- Lead investigator for a research project to evaluate chloride sources in a small rural watershed. This project was jointly funded by the National Research Council of Canada, MTO and Azimuth. Potential sources include road salt, water softener salt, septic discharge and agrichemicals. The study utilizes inorganic and isotopic analyses to differentiate chloride sources and determine the relative mass contribution from the various sources.
- Project manager for an investigation of bird risk to aviation. A census was undertaken over a complete season and statistical methods were employed to evaluate migration pathways, particularly in the vicinity of an airport.

PROFESSIONAL AFFILIATIONS, CERTIFICATION & TRAINING

- Association of Professional Geoscientists of Ontario
- Ontario Onsite Wastewater Association
- Drinking Water System Operator – Limited Ground Water Systems
- Association of Professional Geoscientists of Ontario Discipline Committee 2005 to current, Secretary for 2010-2012, Vice-chair 2012-2014, Chair 2014-2016
- Association of Ground Water Scientists and Engineers (NGWA) (1990 to present)
- Canadian Water Resources Association (2008 to present)
- International Association of Hydrogeologists - IAH Newsletter Editor from 1989 to 1992
- St. John Ambulance Standard First Aid and CPR
- safety training: WHMIS, confined space hazards, emergency preparedness

PUBLICATIONS AND PRESENTATIONS

Jones, M.G. Thermal Impacts and Mitigation Monitoring for a stormwater pond to protect aquatic species at risk, Presentation to TRCA/MNRF Thermal Mitigation Working Group – Workshop, March 2017

Jones, M.G. Guidelines and Standards for Environmental Site Audits, presentation at Georgian College, annually from 2013 to 2017

Ketcheson, D. and M. Jones, “Quarry Influences on Ground Water Systems in Limestone Environments of Southern Ontario” National Ground Water Association Conference on Ground Water in Fractured Rock and Sediments, September 23-24, 2013, Burlington, VT

Part-time Faculty, Environmental Law, Georgian College, 2003- 2005, 2008-2012 winter terms, teaching in the Professional Golf Management Program

Jones, M.G. Denitrification – the next step in sewage treatment. paper and presentation at Ontario On-Site Wastewater Association annual conference, March 2009.

Jones, M.G. Hydrogeology of the Oro Moraine, presentation to MPP Dunlop’s Community Awareness public forum, September 2008.

Jones, M.G. MOE Approvals for Large On-Site Sewage Treatment Systems. paper and presentation at Ontario On-Site Wastewater Association annual conference, March 2008.

Well Aware Seminars, APGO Community Programs in Durham and Haliburton, 2004

Jones, M.G. and McDonald, N. Natural Heritage Planning for the Oro Moraine (the Other Moraine). Presentation at the Power of Place Conference, OPPI/OPLA, Sept 2003

Wallis, P.M., D. Matson, M. Jones, and J. Jamieson. Application of monitoring data for *Giardia* and *Cryptosporidium* to boil water advisories. Risk Analysis. vol 21, no. 6, 2001

Jones M.G. Factors Controlling Leachate Quality and Quantity. Lecture for the MOE Landfill Design Course, 2001.

Jones M.G. Factors Controlling Leachate Quality and Quantity. Lecture for the MOE Landfill Design Course, 2000.

Wallis, P, Matson, D, Jones, M.G. and Jamieson, J., Risk of Waterborne Giardiasis Based on Monitoring Data, paper and presentation at 9th Drinking Water Conference, Regina, May 2000.

Jones, M.G., Descriptive Hydrogeology and Ground Water Issues in New Tecumseh, presentation at the New Tecumseh Environmental Conference 2000, March 2000 (televised)

Jones, M.G., Environmental Issues and Approvals for Golf Course Development, presentation at Georgian College, Barrie, Jan 2000.

Jones, M.G., Golf Course Development: Permitting Requirements, presentation at Georgian College, Barrie, Jan 1999.

Jones, M.G. and Ketcheson, D.R.., Chloride contamination of water supply wells and identification of chloride sources for sites located on the Canadian Shield, presentation and paper, Ground water in a Watershed Context conference, CCIW, December, 1998

Jones M.G. Hydrogeological Considerations, Leachate Quality and Quantity and Landfill Monitoring. Lectures and paper for the MOE Landfill Design Course, 1998.

Zaltsberg, E., Jones, M. and Gehrels, J.. A trigger mechanism for evaluating the landfill impact on water quality. Paper and presentation, GAC/MAC, Quebec, May 1998

Jones, M., Neals, P. and Van Barr, C.C.. "An ounce of prevention...can save a property transfer/ development/purchase" article in BBN Magazine Business and Leisure, June/July 1996

Kassenaar, D., Jones, M. and Gartner, J.. Wellhead Protection. WaterPower Magazine. Fall 1995.

Jones, M.G. Sanitary Landfill Leachate and Gas Management. Chair of seminar, University of Toronto, Educational Program Innovations Center, April 13-14, 1994.

Jones, M.G. Leachate Quality and Characteristics. Paper and Presentation for seminar on "Sanitary Landfill Leachate and Gas Management", University of Toronto, April 13, 1994.

Jones M.G. Factors Controlling Leachate Quality and Quantity. Lecture for the MOE Landfill Design Courses, 1993 and 1991.

Frape, S.K., Blyth, A.R., Jones, M.G., Blomqvist, R., Tullborg, E.L., McNutt, R.H., McDermott, F. and Ivanovich, M. A comparison of calcite fracture mineralogy and geochemistry for the Canadian and Fennoscandian Shields. Presentation and proceedings of the 7th International Symposium on Water-Rock Interaction, WRI-7, Utah, USA, July 1992.

Leech, R.E.J.L., Reynolds, G.W. and Jones, M.G. Protection of Thin, Low Yielding Aquifers through Considerate Landfill Design: The Result of Public Demand. Paper and presentation to the AWWA/OMWA 1992 Joint Annual Conference, April 1992.

Rowe, R.K. and Jones, M.G. Conceptual Design of the Halton Landfill, presentation to the Canadian Geotechnical Society, southern Ontario Section, at the MTO Atrium Tower, Toronto, January 1992.

Jones, M.G. Factors controlling the character of municipal landfill leachate in Ontario. Paper and Presentation for seminar on "Sanitary Landfill Leachate and Gas Management", Technical University of Nova Scotia, September, 1991.

McNutt, R.H., Frape, S.K., Fritz, P., Jones, M.G. and MacDonald, I.M. The $^{87}Sr/^{86}Sr$ values of Canadian Shield brines and fracture minerals with applications to ground water mixing, fracture history and geochronology. Geochimica et Cosmochimica Acta, January 1990.

McNutt, R.H., Frape, S.K., Jones, M.G. and MacDonald, I.M. The $^{87}Sr/^{86}Sr$ of Canadian Shield brines and fracture minerals with applications to ground water monitoring, fracture history and geochronology. Geochemical Cosmochemistry Association 1989.

Love, D., Frape, S.K., Gibson, I. and Jones, M.G. The ^{18}O and ^{13}C isotopic composition of secondary carbonates from basaltic lavas cored during the drilling of hole 642E, Ocean Drilling Program Leg 104. In press. "Part B of the Initial Report for Leg 104", Ocean Drilling Program, 1987.

Jones, M.G., Frape, S.K., Fritz, P., and Gibson, I.L. A study of late-stage secondary fracture mineralogy at sites across the Precambrian Canadian Shield and at the Stripa, Sweden site. Internal publication and presentation for the Walker Mineralogical Club, Toronto, 1987.

Jones, M.G., Frape, S.K. and McNutt, R.H.. A study of the geochemistry and isotopic composition of late stage secondary fracture mineralization at the Underground Research Laboratory, Pinawa, Manitoba. Final Report to AECL, June 1987.

Jones, M.G. A study of the late-stage secondary fracture mineralization at sites across the Precambrian Canadian Shield, unpub. M.Sc. Thesis, University of Waterloo, 1987.

McNutt, R.H., Frape, S.K., Jones, M.G. and Fritz, P. The $^{87}Sr/^{86}Sr$ values of brines in rocks of Archean age, Matagami area, Quebec: a contrasting behavior to other Canadian Shield brines. International Association of Geochemistry and Cosmochemistry Fifth International Symposium on Water-Rock Interaction, Reykjavik, Iceland, August 1986. Extended abstract, poster session and presentation, 1986.

Jones, M.G. A study of the late-stage secondary fracture mineralization at sites across the Precambrian Canadian Shield, unpub. B.Sc. Thesis, University of Waterloo, 1985.

Greg Rose

Associate, Senior Water Resources Scientist

PROFESSIONAL SUMMARY

Mr. Rose is a water resources specialist with over 15 years of experience in the investigation and analysis of surface water systems. He has completed numerous multi-year, large-scale programs including watershed monitoring and modelling studies, hydrodynamic, water quality and contaminant transport modelling investigations, environmental assessments and development impact evaluations. He is well-versed in field sampling design, data management and analysis, model conceptualisation and construction and regulatory liaison.

Employment History

Golder Associates Ltd. – Mississauga, Ontario
Associate from 2016, Senior Water Resources Scientist (2006 to Present)

Metoc Plc. – Hampshire, England
Senior Scientist (2001 to 2006)

Education

M.Sc. Coastal Zone Management, Bournemouth University, Bournemouth, England, 2000

B.Sc. Zoology (Hons), University of Leeds, Leeds, England, 1999

Languages

English – Fluent
German – Fluent

RELEVANT EXPERIENCE

Bruce Power *Kincardine, Ontario, Canada*	Multi-year program management for ongoing Environmental Compliance Approval support including management of year-round hydrodynamic and water quality monitoring, thermal modelling, results visualisation, strategic advice and regulatory liaison, and development of MIKE3 model for Lake Huron.
Ram Coal *Alberta, Canada*	Baseline studies, water quality modelling and preliminary capital cost estimate development for water quality mitigation of a proposed metallurgic coal mine at a greenfield site. Responsibilities include coordination of multi-disciplinary aquatics team, development and delivery of water quality model to required regulatory standards.
Teck Coal *British Columbia, Canada*	Responsible for management of the water quality impact assessment modelling investigations component for a proposed metallurgic mine expansion in British Columbia, including integrated infrastructure and contaminant transport water quality modelling for multiple sub-watersheds, reporting and permitting.
Atlantic Innovation Fund / Applied Geomatics Research Group *Annapolis Basin, Canada*	Concept development, design and modelling of an integrated contaminant loadings, watershed runoff and estuarine transport modelling system of the Annapolis Basin to provide water quality forecasts at key sensitive receivers based on ongoing weather forecasting services using MIKE 11 and MIKE 21.
Client Confidential *Southwestern Ontario, Canada*	Baseline characterisation and impact assessment modelling of a proposed shale quarry in order to quantify and where necessary mitigate potential flow, water quality and thermal effects of the quarry on nearby watercourse and wetlands.

Client Confidential *Northern Ontario, Canada*	Mass balance modelling assessment of two lakes and a number of watersheds including surface water and groundwater influences based on flow monitoring and water quality sampling data to identify key contaminant sources at a remote decommissioned uranium mine site in northern Ontario. Model results resulted in targeted remediation program in order to provide long-term water quality control.
EWL *Former Coldstream Mine, Canada*	Development of a dynamic reservoir model of an existing tailings management pond to simulate the effects of meteorology on tailings exposure and turnover magnitude and frequency and develop an appropriate long-term dam design to manage water quality impacts at downstream environmental control points.
Xstrata Nickel *Kabanga, Tanzania*	Plume modelling assessment to quantify the risk of regulatory exceedances in the Ruvubu River resulting from proposed effluent streams. The study specifically focused on optimising discharge design in order to minimise the potential for regulatory non-compliance in Burundi waters, given that the watercourse is shared by both countries.
Ontario Power Generation *Darlington, Ontario, Canada*	Hydrodynamic, thermodynamic and water quality modelling of proposed new nuclear facility in support of Environmental Assessment using MIKE 3.
Bruce Power *Nanticoke, Ontario, Canada*	Execution of field data collection program to provide a characterisation of baseline conditions at Long Point Bay in Lake Erie. One-dimensional modelling assessments were conducted as part of the Environmental Assessment to evaluate water quality and thermal impacts on the receiving environment and recommend mitigation measures to support regulatory compliance.
AMEC NCL *Bruce Peninsula, Ontario, Canada*	Design and execution of model assessment required to evaluate potential water quality effects of restarting two nuclear units and associated cooling water systems that had been in lay-up for over a decade. The work included concept design and modelling to represent several kilometers of interconnected cooling water pipes and system elements to determine concentration magnitudes and durations within the receiving discharge channel and Lake Huron.
Hanson Brick *Halton Region, Ontario, Canada*	A Threats Assessment for a proposed drinking water supply intake was undertaken in support of a Municipal Class EA to provide and evaluate the reliability of alternative drinking water sources within the local area. The Threats Assessment was undertaken according to the Source Water Protection protocols identified as part of the MOE developed Guidance Modules, with significance of threat sources being identified through hydrologic modelling of the watershed.
Multiple Clients *England, Scotland, Wales in United Kingdom*	Multiple environmental design optimization modelling studies for a variety of clients (including Scottish Water Solutions, Anglian Water Services and Welsh Water / Dwr Cymru) to identify the economically sustainable and environmentally appropriate wastewater design solutions for over 60 Wastewater Treatment Schemes discharging to coastal systems in Scotland, Wales and England. Modelling of estuarine, open coastal and riverine discharges throughout the UK using MIKE21, Telemac, proprietary software and in-house statistical compliance tools to ascertain impacts, develop recommendations for design optimization and identify statistically-balanced solutions for environmental compliance and cost benefit.

PETER JOHN THOMPSON M.A.Sc., P.Eng.

GeoProcess RESEARCH ASSOCIATES

Knowledge
Research
Consulting

SENIOR HYDROLOGIST/HYDROLOGIC MODELLER

Education & Training

M.A.Sc., Environmental and Civil Engineering, University of Waterloo, 2013

Thesis: *Event Based Characterization of Hydrologic Change in Urbanizing Southern Ontario Watersheds via High Resolution Stream Gauge Data* (Received the 2014 Canadian Society for Civil Engineering (CSCE) Hydrotechnical Engineering Award)

B.A.Sc., Civil Engineering *(with Distinction),* University of Waterloo, 2007

Option in Water Resources, Certificate in Structural Engineering

Certifications & Affiliations

Professional Engineer, Professional Engineers Ontario

PERSONAL PROFILE

Pete is a specialist in surface water hydrology and hydraulics. Areas of focus include the analysis of groundwater/surface water interactions with numerical models, the effects of urbanization on the hydrologic regime, future impacts of climate change on a watershed scale, and in-stream ecological flow needs assessment. Pete was the lead hydrologic modeler in several studies delineating ecologically significant groundwater recharge areas on a watershed scale and has served as project manager in the development and application basin-scale, distributed, integrated surface water-groundwater models for Source Water Protection and cumulative impact studies. Pete has constructed, calibrated, and applied environmental numerical models in multiple domains including hydraulic (HEC-RAS, WaterCAD), hydrologic (PRMS, HEC-HMS, HBV), hydrogeologic (MODFLOW-NWT, FEFLOW) as well as integrated groundwater/surface water (GSFLOW) models.

RELEVANT EXPERIENCE

Co-Author, Low Impact Development Stormwater Management Guidance Manual, Ontario Ministry of the Environment and Climate Change (MOECC), Ontario

MOECC is currently updating its 2003 Stormwater Management Manual, with a focus on Low Impact Development (LID) methods. Pete's contributions to the revised manual include the Model Selection Framework and portions of the Modelling chapter text, a Province-wide analysis of precipitation patterns to support the selection of Runoff Volume Control Targets (RVC_T) for Ontario, and commentary related to the analysis of future climate change in urban design modeling.

Senior Hydrologist, Assessment of Long Term Hydrogeologic Conditions along the Eglinton Crosstown Transit Line, Crosslinx Transit Solutions, Ontario

The Eglinton Crosstown is a light rail transit project currently under construction in Toronto, Ontario. To aid in the design of the various underground stations that will service the line, Pete undertook an analysis of the long-term variability of groundwater levels under future climate conditions. The analysis employed an existing integrated groundwater/surface water model that he updated for this analysis.

Project Manager/Senior Hydrologist, Whitemans Creek Tier Three Local Area Water Budget and Risk Assessment, Grand River Conservation Authority, Ontario

Served as the project manager and lead hydrologic modeller on a Tier 3 Water Budget and Risk Assessment of the Whitemans Creek subwatershed. He constructed and calibrated the hydrologic component of an integrated groundwater/surface water model of the study area using the USGS GSFLOW model code. Pete oversaw an analysis of crop types, determined irrigation requirements, and simulated the irrigation demand across the subwatershed. He led the creation of three major project reports and the managed the subsequent peer review response process.

Lead Hydrologic Modeller, Phase 2 Review of Potential Cumulative Impacts to Surface Water and Groundwater from In-Situ Oil Sands Operations in the MacKay River Watershed, CEMA, Alberta

Served as the lead hydrologic modeller on a project to assess the impacts of numerous planned Steam Assisted Gravity Drainage (SAGD) oil sand developments on the water resources of the MacKay River watershed in northern Alberta. Pete constructed and calibrated the hydrologic component of an integrated groundwater/surface water model which required the development of a new frozen ground module to simulate the impact of cold climates on recharge and runoff. With the final model, Pete conducted an analysis of the cumulative impacts of the planned GW and SW takings on the instream flow needs of the MacKay Watershed.

Lead Hydrologic Modeller, Tier 2 Water Budget, Climate Change and Ecologically Significant Groundwater Recharge Area Assessment, Ramara Creeks, Whites Creek and Talbot River Subwatersheds, LSRCA, Ontario

Pete constructed the hydrologic component of an integrated groundwater/surface water model of several watersheds which drain the north-west side of Lake Simcoe using the USGS GSFLOW code. He calibrated the model with Monte Carlo techniques and evaluated the results with a custom set of tools. Pete managed the application of the model to evaluate droughts and to assess the long-term impacts of future climate change.

Hydraulic Modeller/Model Integration Specialist, Tier 3 Water Budget and Local Area Risk Assessment for the Kelso and Campbellville Groundwater Municipal System, Conservation Halton, Ontario

Pete developed the hydraulic submodel that was part of an integrated groundwater/surface water model created to analyze the Kelso and Campbellville municipal groundwater systems. He undertook final calibration of the completed integrated model (which was focused on reservoir/well interactions) and completed the water budget assessment of the wellfield as part of the Tier 3 Source Water Protection study.

SELECTED CONFERENCES AND PUBLICATIONS

Plumb BD, Annable WK, **Thompson P J**, & Hassan MA. 2017. The impact of urbanization on temporal changes in sediment transport in a gravel bed channel in Southern Ontario, Canada. *Water Resources Research*, 53.

Marchildon MA, **Thompson PJ**, Cuddy SE, Wexler EJ, Howson K. and Kassenaar JD. 2016. A methodology for identifying ecologically significant groundwater recharge areas. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, 41.4 (2016): 515-527.

Thompson PJ, Wexler EJ, Takeda MGS, Kassenaar DC. 2015. Integrated Surface Water/Groundwater Modelling to Simulate Drought and Climate Change Impacts from the Reach to the Watershed Scale. *Proceedings of the 2015 conference of the CNC-IAH.* October 2015. Waterloo, ON.

Thompson PJ and Annable WK. 2014. Characterizing change of high frequency return periods in urbanizing southern Ontario watersheds. *Proceedings of the CWRA 2014 Canada Water Resources Congress.* Hamilton, ON.

Annable WK, Watson CC, **Thompson PJ**. 2010. Quasi-Equilibrium conditions of urban gravel-bed stream channels in Southern Ontario, Canada. *River Research and Applications*, 28: 302–325.

EMPLOYMENT HISTORY

GeoProcess Research Associates Inc.
2017 - Present Hydrologist/Hydrologic Modeller

Earthfx Inc.
2011 - 2017 Senior Hydrologist, Project Manager

Water Survey Division, Environment Canada
2009 - 2011 Network Applications Engineer