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Technical Memorandum

To: Erik Carlson, MDNR
From: Greg Williams
Subject: Summary of Water Related Model Calibrations and Plant Site Corroboration
Date: July 24, 2012
Project: NorthMet EIS 23690862.00 042
c: Jim Scott, PolyMet

This memorandum presents a summary of the various model calibrations that have been completed as part of the water quality modeling being conducted for the NorthMet SDEIS. These calibrations have been presented in other documents, which are referenced. This memo presents the calibration statistics associated with each calibration, as well as other informal criteria that were used as part of the calibration processes. Where applicable, references to standard or commonly accepted error metrics are included. The level of error deemed "acceptable," however, varies according to model type and purpose, limiting the availability or applicability of standard metrics. Evaluating the impact of calibration accuracy on probabilistic model output requires detailed sensitivity analysis, which is beyond the scope of this report.

The corroboration of the Plant Site model to measured concentrations in the Embarrass River and associated tributaries is also presented in this memo. The Plant Site model corroboration has not been presented elsewhere.

1.0 Model Calibrations

1.1 Mine Site MODFLOW Model

The calibration of the Mine Site MODFLOW Model is documented Attachment B to the Water Modeling Data Package Volume 1 – Mine Site (PolyMet, 2012d). All of the information presented below is provided in that document.

1.1.1 Calibration Targets

The local scale model was calibrated using the following calibration targets:

- Water level measurements in the unconsolidated deposits (45 observations);

- Water level measurements in bedrock (29 observations); and
- Estimated baseflow in the Partridge River at SW002, SW003, and SW004 from the XP-SWMM model (3 observations).

1.1.2 Calibration Objectives

The objective of the model calibration was to minimize the difference between the observed and simulated values for each of the calibration targets. Calibration was conducted using the inverse modeling code PEST (Watermark Numerical Computing, 2005, 2009). When using PEST, the difference between observed and modeled values is quantified as the sum of squared weighted residuals and is termed the “objective function”. Therefore, the goal of calibration was to minimize the objective function. The techniques used to evaluate the MODFLOW calibrations are consistent with the guidance presented in ASTM D5490-93(2002) - Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information and ASTM D5981-96(2002) - Standard Guide for Calibrating a Ground-Water Flow Model Application. Specific numeric measures for evaluating calibrations are not provided in the guidance documents referenced above.

The acceptability of the model calibration was assessed by comparing the absolute residual mean of the head targets to the range in observed heads. The model calibration was considered acceptable if the absolute residual mean was less than 15% of the observed range in heads. In addition, simulated flows at SW002, SW003 and SW004 should be within 5% of the flow estimated by the XP-SWMM model in order for calibration to be considered acceptable. These criteria consider the intended uses of the model. The model is a simplification of the actual system and was not intended to represent the complex small-scale, heterogeneity present within the Mine Site. Therefore, some degree of mismatch between the model results and observations is expected and acceptable.

1.1.3 Calibration Results

A scatter plot of simulated and observed head values is presented on Figure 1. The absolute residual mean was 0.99 meters, which is 4% of the range of observed heads (25.76 meters). The absolute residual mean was less than 15% of the observed range in head, satisfying one part of the calibration objective. The modeled values of baseflow to the Partridge River are summarized in Table 1 along with their target values. Baseflow estimates at all three locations satisfy the calibration objective of having the MODFLOW-simulated flow within 5% of the XP-SWMM simulated flow.

Attachment B of the Mine Site Water Modeling Package notes that the modeled hydraulic gradient in the bedrock is flatter than the gradient that would be expected based on measured heads (see page 12 of Attachment B). This is apparent in Figure 1. In the MODFLOW model, each bedrock type is simulated as a separate zone with homogeneous hydraulic conductivity. In reality, there is likely localized heterogeneity within each type of bedrock that results in the range of heads observed. Due to the simplifying assumptions that have been made in constructing the MODFLOW model, this localized heterogeneity is not simulated. In the current probabilistic model, separate predictions of groundwater quality are made for the unconsolidated deposits and bedrock for the groundwater flow paths that originate at the mine pits.

Table 1 Mine Site MODFLOW model calibration statistics – comparison between estimated and modeled baseflow

Location	XP-SWMM Estimated Baseflow (cfs)	MODFLOW Modeled Baseflow (cfs)	Percent Error
SW002	0.41	0.42	2%
SW003	0.51	0.51	0%
SW004	0.92	0.94	2%

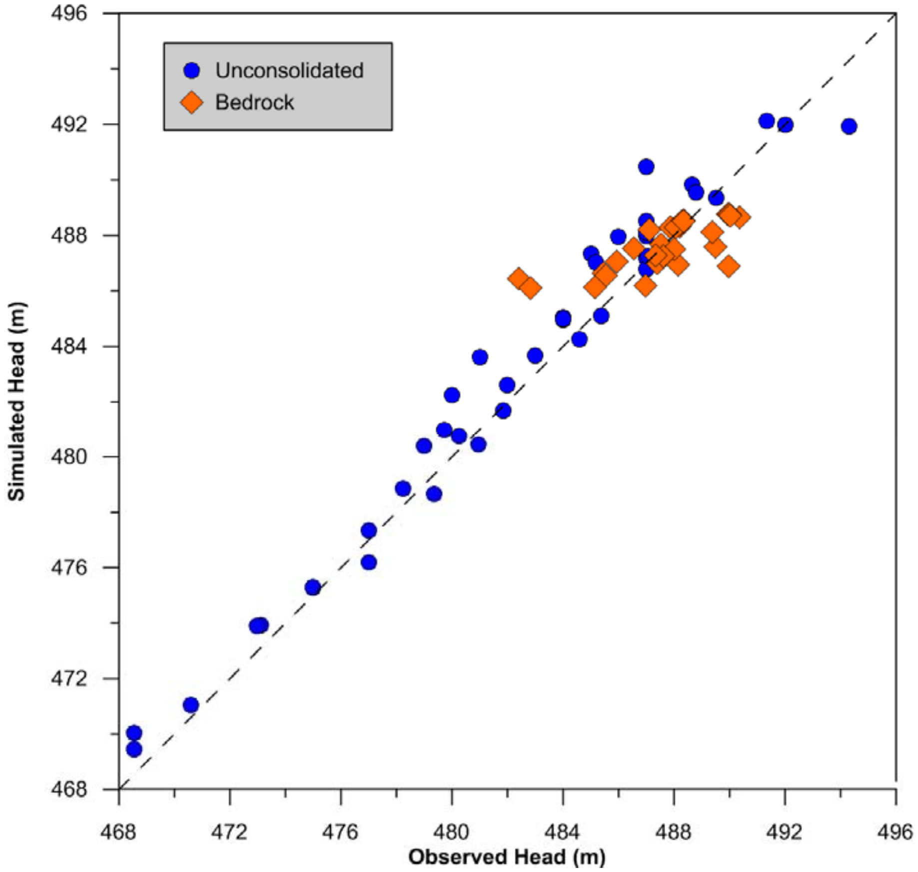

Figure 1 Simulated versus observed heads - Mine Site local-scale model

1.2 Mine Site XP-SWMM Model

The calibration of the Mine Site XP-SWMM model is documented in RS73A Streamflow and Lake Level Changes – Model Calibration Report (PolyMet, 2008). The surface water IAP process determined that re-calibration of the Partridge River XP-SWMM model was not necessary after adjusting the USGS gage data for Peter Mitchell Pit dewatering or updates to the model watersheds based on more accurate topographic data. Model calibration metrics, however, were updated to reflect the updated XP-SWMM model and the adjusted observed flow record. That update is described in the Water Modeling Data Package – Volume 1, Mine Site (PolyMet, 2012d). All of the information presented below is provided in the documents referenced above.

1.2.1 Calibration Targets

The XP-SWMM model calibration considered three target statistics (utilized for both calibration and validation), including:

- Total volume of runoff
- Daily flows
- 30-day annual low flow

The XP-SWMM model developed for the study area was calibrated to data corresponding to the water year 1984-1985 at USGS gaging station #04015475 (Partridge River above Colby Lake at Hoyt Lakes). This water year was selected because the ratio of the average gaged runoff to precipitation is about the same as the mean value of 0.40-0.45 suggested by Baker et al. (1979) for this region of Minnesota.

The XP-SWMM model was validated against data corresponding to:

- USGS gaging station #04015475 (Partridge River above Colby Lake at Hoyt Lakes), for the period of record 1978-1988.
- USGS gaging station #04015455 (South Branch Partridge River near Babbitt), for the period of record 1978-1980.

1.2.2 Calibration Objectives

The objectives of model calibration vary according to the target statistics (total volume, daily flow, and 30-day low flow). Three calibration metrics (Deviation in Volume, Coefficient of Efficiency, and normalized RMSE) utilize the three calibration targets (annual flow, daily flow, and 30-day low flow), respectively. These calibration metrics are detailed below.

- **Deviation of Volume (D_v)** – Error between modeled and observed total volume is referred to as the deviation of volume runoff D_v. This calibration metric utilizes modeled and observed annual flow volume. Deviation of volume is defined as:

$$D_v = 100\left(\frac{V_{obs} - V_{mod}}{V_{obs}}\right)$$

…where V_{obs} = observed volume of runoff for the simulation period (i.e., water year)

V_{mod} = modeled volume of runoff for the simulation period (i.e., water year)

For model calibration, D_v was calculated for water year 1984-1985. During model validation, D_v was calculated for each water year and averaged over the entire period of analysis (1978-1988). The deviation of volume, D_v, computed on a water year basis, will vary between -40 and +40 for the model to be considered satisfactory (i.e., modeled values will be within ± 40 percent of the observed values). The criterion was based on the intended model use (James, 2005). The hydrologic/hydraulic model of the study area will be used to evaluate relative changes on the average, minimum and maximum flows; the model is not intended to predict instantaneous flow values.

- **Coefficient of Efficiency (*E*)** – Error between modeled and observed daily flows was quantified using the coefficient of efficiency (*E*). This calibration metric utilizes modeled and observed daily flows. The coefficient of efficiency is defined as:

$$E = 1 - \left[\frac{\sum_{i=1}^{N}(Q_{obs}^{i} - Q_{mod}^{i})^2}{\sum_{i=1}^{N}(Q_{obs}^{i} - \overline{Q_{obs}})^2}\right]$$

…where Q_{obs}^{i} = observed flow on day *i* of the simulation period

Q_{mod}^{i} = modeled flow on day *i* of the simulation period

$\overline{Q_{obs}}$ = average of observed flows during the simulation period

N = number of days during the simulation period

The possible theoretical value of *E* is from minus infinity to one. Motovilov et al. (1999) suggest that the coefficient of efficiency *E* has to be greater than 0.36 for a model to be considered satisfactory. A less strict interpretation is that negative values of the coefficient of efficiency *E* indicate a bad model performance, while values near to one indicate a very good model performance. It should be noted that the coefficient of efficiency is not directly analogous to the correlation coefficient, which ranges between -1 and +1 by definition.

- **Root mean squared error (RMSE)** – A dimensionless version of the RMSE (*RMSE'*) was used to quantify deviation between modeled and observed low flows, and utilizes the modeled and observed 30-day annual low flow. The *RMSE'* of the 30-day low flow is defined as:

$$RMSE' = \frac{1}{\bar{Q}}\sqrt{\frac{\sum_{i=1}^{N}\sum\left(Q_{obs}^{i} - Q_{mod}^{i}\right)^{2}}{N}}$$

…where Q_{obs}^{i} = observed flow on day i of simulation period (i.e., 30 days)

Q_{mod}^{i} = modeled flow on day i of simulation period (i.e., 30 days)

$\bar{Q}$ = observed 30-day average low flow

N = number of days in simulation period (30)

During model development, no references on acceptable ranges of *RMSE'* were found. Thus, the acceptable RMSE' was set at a value representing a discrepancy between observed and modeled flows of 0.10 inches in runoff over the 30-day period. [**Note:** during initial model calibration (see RS73A), this yielded a RMSE' of 1.62. When the USGS gage record was adjusted to account for Peter Mitchell Pit dewatering, the average 30-day low flow decreased relative to the unadjusted gage data. This results in the critical RMSE' increasing from 1.62 to 2.72]

1.2.3 Calibration Results

Results of the initial model calibration (water year 1984) and model validation (water years 1978-1987) are summarized in Table 2. Additional detail is provided in RS73A (PolyMet, 2008). Calibration of the model to observed data from water year 1984-1985 resulted in D_v, *E*, and *RMSE'* values of 16.1, 0.23, and 3.08, respectively. While the *RMSE'* is outside the desired range in the calibration year, the average RMSE' over the validation period is 1.15, below the maximum acceptable value of 1.62.

The XP-SWMM model was modified as part of the CDF process in 2012 to correct previously unidentified errors and update watershed divides based on new topographic data. In addition, the USGS data to which the XP-SWMM model was calibrated was modified in 2011 to remove the effects of Peter Mitchell Pit dewatering as part of the IAP process. Due to changes in both the model and the baseline data used in the calibration, the model calibration/validation parameters described herein were reevaluated (see Table 2). The Surface Water IAP group determined XP-SWMM model recalibration unnecessary based on the approximate equivalence or improvement of model calibration/validation parameters.

Table 2 XP-SWMM model calibration statistics with and without adjustment for dewatering

Water Year	Deviation in Volume (D_v)		Coefficient of Efficiency (E)		RMSE' (30-day low flow)	
	Unadjusted Gage Data	Adjusted Gage Data	Unadjusted Gage Data	Adjusted Gage Data	Unadjusted Gage Data	Adjusted Gage Data
Acceptance Criteria	± 40 %		> 0		1.62	2.72
Model Calibration						
1984	16.1	9.1	0.23	0.24	3.08	3.08
Model Validation						
1978-1987	33.1	28.1	0.24	0.25	1.15	2.01
1978	76.6	74.4	0.09	0.12	0.68	1.28
1979	23.6	10.1	-0.19	-0.30	3.05	--*
1980	24.4	14.6	0.17	0.17	6.65	8.95
1981	31.0	24.7	0.47	0.49	0.32	--*
1982	28.2	22.8	0.42	0.42	0.45	0.67
1983	25.2	20.3	0.37	0.38	0.75	13.08
1985	38.6	35.4	-0.03	-0.01	0.04	0.88
1986	41.0	41.0	0.39	0.39	0.27	0.27
1987	1.8	1.8	0.15	0.15	5.98	5.98

* RMSE cannot be calculated when observed value is zero (divide by zero)

1.3 Mine Site Natural Watershed Runoff

The water quality of runoff from natural watershed areas within the Partridge River watershed was determined through calibration. The water quality from natural watershed areas is modeled as a unique probabilistic distribution for each constituent. This calibration is documented in the Calibration of the Mine Site Existing Conditions Water Quality Model document (PolyMet, 2012a). Calibration was conducted using the Mine Site No Action model, which represents existing conditions at the Mine Site.

1.3.1 Calibration Targets

Each probabilistic distribution was calibrated using the following calibration targets:

- 90th percentile of the observed data set
- 50th percentile of the observed data set
- 10th percentile of the observed data set

The observed data set varies by constituent, but includes water quality samples collected within the Partridge River between SW-002/PM-2 and SW-005/PM-4 from 2004 through 2011. Water quality samples were collected at flows ranging from less than 1 cfs to 286 cfs.

1.3.2 Calibration Objectives

The objective of the model calibration was to minimize the difference between the observed and simulated values for each of the calibration targets. The probabilistic water quality model does not attempt to model actual water quality on a specific date or during a specific event. Instead, it attempts to capture the typical or mean water quality and the range in potentially observable values. Therefore, comparisons between observed data and model estimates were made at low, high and intermediate values to meet the objectives. The difference between observed and modeled values is quantified as the root mean squared error (RMSE) at the 10th, 50th, and 90th percentiles. The RMSE was calculated as:

$$RMSE = \sqrt{\frac{\sum\left(C_{obs,i} - C_{mod,i}\right)^2}{n}}$$

…where $C_{obs,i}$ = observed concentration at the 10th, 50th, or 90th percentile

$C_{mod,i}$ = modeled concentration at the 10th, 50th, or 90th percentile

n = number of percentiles included in calculation (3)

A normalized RMSE was calculated by dividing the RMSE by the mean of the observed data set for each constituent. The normalized RMSE is presented as a percentage of the mean (e.g., +/- 10%). Calibration was performed until the RMSE was minimized for each constituent. The overall acceptability of each constituent calibration was not quantitative, but considered the model fit to the entire distribution of observed data (figures included in the Calibration of the Existing Natural Watershed at the Mine Site document).

1.3.3 Calibration Results

The modeled mean concentrations and mean concentrations in the observed data set (i.e., Partridge River water quality) are presented in Table 3, along with the RMSE and normalized RMSE. The normalized RMSE is less than 1 percent of the observed mean for 22 of the 27 modeled constituents (note: no RMSE or normalized RMSE was calculated for vanadium due to lack of observed data). The normalized RMSE is less than 10 percent of the observed mean for all constituents except of sulfate. The normalized error for the sulfate calibration is 17 percent of the observed mean. The calibrated sulfate distribution provides a reasonable fit over the entire distribution of observed values (see the Calibration of the Existing Natural Watershed at the Mine Site document) and was considered acceptable.

Table 3 Mine Site natural watershed runoff calibration statistics – comparison between observed and modeled Partridge River concentrations. Negative values indicate model is under-predicting observed concentrations.

Constituent	Modeled Runoff Mean (ug/L)	Modeled Runoff Standard Deviation (ug/L)	RMSE	Observed Mean River Concentration (ug/L)	Normalized RMSE (% error)
Ag	0.106	0.012	0.005	0.234	< 1%
Al	95	68	4.8	81.0	< 1%
Alk	63000	60000	1178	69041	1.7%
As	0.30	0.05	1.13	1.06	< 1%
B	81	149	3.1	70.4	< 1%
Ba	4.7	1.2	1.3	9.55	< 1%
Be	0.095	0.00095	0.006	0.100	< 1%
Ca	16000	12800	599	18115	< 1%
Cd	0.057	0.055	0.021	0.074	< 1%
Cl	12700	9000	687	8278	8.3%
Co	0.30	0.13	0.07	0.480	< 1%
Cr	0.95	0.85	0.11	0.742	< 1%
Cu	0.83	1.8	0.13	1.39	< 1%

Constituent	Modeled Runoff Mean (ug/L)	Modeled Runoff Standard Deviation (ug/L)	RMSE	Observed Mean River Concentration (ug/L)	Normalized RMSE (% error)
F	99	87	3.8	154.8	2.5%
Fe	1970	410	106	1584	< 1%
K	1760	1860	62	1855	< 1%
Mg	8000	4700	387	8303	< 1%
Mn	84	142	0.22	141.0	< 1%
Na	8200	21000	823	5469	< 1%
Ni	1.42	1.58	0.11	1.64	< 1%
Pb	0.14	0.05	0.02	0.528	< 1%
Sb	1.67	0.0167	0.24	1.50	< 1%
Se	0.28	0.36	0.02	1.014	< 1%
SO4	6000	13700	1966	10409	18.9%
Tl	0.01	0.006	0.09	0.012	< 1%
V	5.4	0.054	--	--	--
Zn	13.7	13.5	1.84	12.6	< 1%

1.4 Plant Site MODFLOW Model

The calibration of the Plant Site MODFLOW Model is documented Attachment A to the Water Modeling Data Package Volume 2 – Plant Site (PolyMet, 2012e). All of the information presented below is provided in that document.

1.4.1 Calibration Targets

The calibration target dataset includes a total of 601 observations among the following groups:

- Steady state heads (31 observations);
- Transient drawdowns (471 observations);
- Transient heads (96 observations);
- Estimated seepage from the ponds in Cells 1E and 2E in the steady-state stress period (2 observations); and
- Discharge from the south seep at the end of model simulation (1 observation).

Locations of observed data are presented in Attachment A of the Water Modeling Data Package Volume 2 – Plant Site. Calibration observations were assigned weights such that the contribution of each observation group to the initial objective function in PEST was roughly equal. Some observations were assigned slightly higher weights in order to produce a calibrated model that better simulated those observations. Weights were varied between individual observations within some observation groups to reflect differing levels of data quality. Of the original 601 observations, a total of 51 were assigned zero weight, which removes them from consideration during the calibration. Fifty of the zero-weight observations were in the transient drawdown group and one was in the transient head group. The drawdown observations that were assigned zero weight generally represent observations that are inconsistent with other observations at that location.

The transient drawdown observations that were eliminated were from the following locations: DH96-30 (11 observations); P2HB-99 (23 observations - all available at this location); P3H1-99 (15 observations - all available at this location); GW-005 (1 observation). The eliminated data points are indicated on Figures 6a, 6c, and 6f of Attachment A of the Plant Site Water Modeling Package. The specific rationale for eliminating the selected data points is described below:

- DH96-30: Water levels at this location rose abruptly (by approximately 10 feet) between May and December 2004, which is inconsistent with the declining water levels observed before May 2004 at this location and at the majority of the other piezometers in the Tailings Basin area since operations ceased. The boring log for this piezometer indicates that it is screened in fine tailings and slimes between approximately 115 and 120 feet below grade. A review of boring logs from nearby piezometers indicates that the material encountered at DH96-30 is similar to that observed at other locations. The reason for the abrupt rise in water levels is unknown, but could be related to factors such as surface water infiltration due to surface seal failure, problems with the piezometer instrumentation, or a shift in vertical datum. Because it was not possible to determine exactly what caused the shift in water levels, the anomalous data were removed from the calibration.

- P2HB-99 and P3H1-99: Water levels at these two locations were essentially unchanged from 2002 to 2010, which is inconsistent with the water level trends observed at surrounding piezometers. The construction records for these two piezometers indicate that they are completed at depths of approximately 51 feet and 67 feet below grade, respectively. Water level data collected from these locations prior to the calibration simulation start date (February 2002) indicates that both of these piezometers were occasionally dry. Therefore, it is believed that although they were not indicated as being dry, the water levels recorded at these locations from 2002 to 2010 may reflect a small amount of water stored at the base of the piezometer, rather than the water table elevation, which had likely dropped below these relatively shallow piezometers by February 2002.

- GW-005: A single data point from 2008 was removed because it appeared to be an outlier compared with the other data points for this location. It was not possible to isolate the specific factor(s) that may have resulted in the anomalous data point.

1.4.2 Calibration Objectives

The objective of the model calibration was to minimize the difference between the observed and simulated values for each of the calibration targets. Calibration was conducted using the inverse modeling code PEST (Watermark Numerical Computing, 2005, 2009). When using PEST, the difference between observed and modeled values is quantified as the sum of squared weighted residuals and is termed the “objective function”. Therefore, the goal of the calibration was to minimize the objective function. The techniques used to evaluate the MODFLOW calibrations are consistent with the guidance presented in ASTM D5490-93(2002) - Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information and ASTM D5981-96(2002) - Standard Guide for Calibrating a Ground-Water Flow Model Application. Specific numeric measures for evaluating calibrations are not provided in the guidance documents referenced above.

The acceptability of the model calibration was assessed by comparing the absolute residual mean of the head and drawdown targets to the range in observed heads and drawdowns. The model calibration was considered acceptable if the absolute residual mean was less than 15% of the observed range. In addition, simulated flows should be within 5% of the flow targets in order for calibration to be considered acceptable. This criterion considers the intended uses of the model. The model is a simplification of the actual system and was not intended to represent the complex small-scale, heterogeneity present within the

Tailings Basin. Therefore, some degree of mismatch between the model results and observations is expected and acceptable.

1.4.3 Calibration Results

Calibration statistics summarized in Table 4 indicate that the model fit is slightly better for transient heads than for steady-state heads. For this calibration, the fit to head observations was deemed acceptable if the absolute residual mean (ARM) was less than 15% of the observed range in heads across the model domain. As shown in Table 4, the ARM is less than 3% of the observed range in steady-state heads and less than 1% of the observed range in transient heads. A scatter plot of simulated and observed head values (transient and steady state) is presented on Figure 2. As shown in Table 4, the ARM is 2% of the observed range of drawdowns. The model closely matched the estimates of seepage from the ponds in Cells 1E and 2E and the discharge from the south seep. Each residual is three percent or less of the corresponding observation.

Table 4 Plant Site MODFLOW model calibration statistics

Statistic	Observation Group		
	Steady State Head	Transient Head	Drawdown
Range in Observed Values (ft)	302.2	368.7	27.3
Residual Mean (ft)	0.2	-0.5	0.7
Absolute Residual Mean (ft)	7.4	1.8	0.5
Maximum Absolute Residual (ft)	27.2	11.9	3.2
Absolute Residual Mean / Range[1]	0.024	0.0048	0.020

[1] Maximum acceptable value for calibration is 0.15

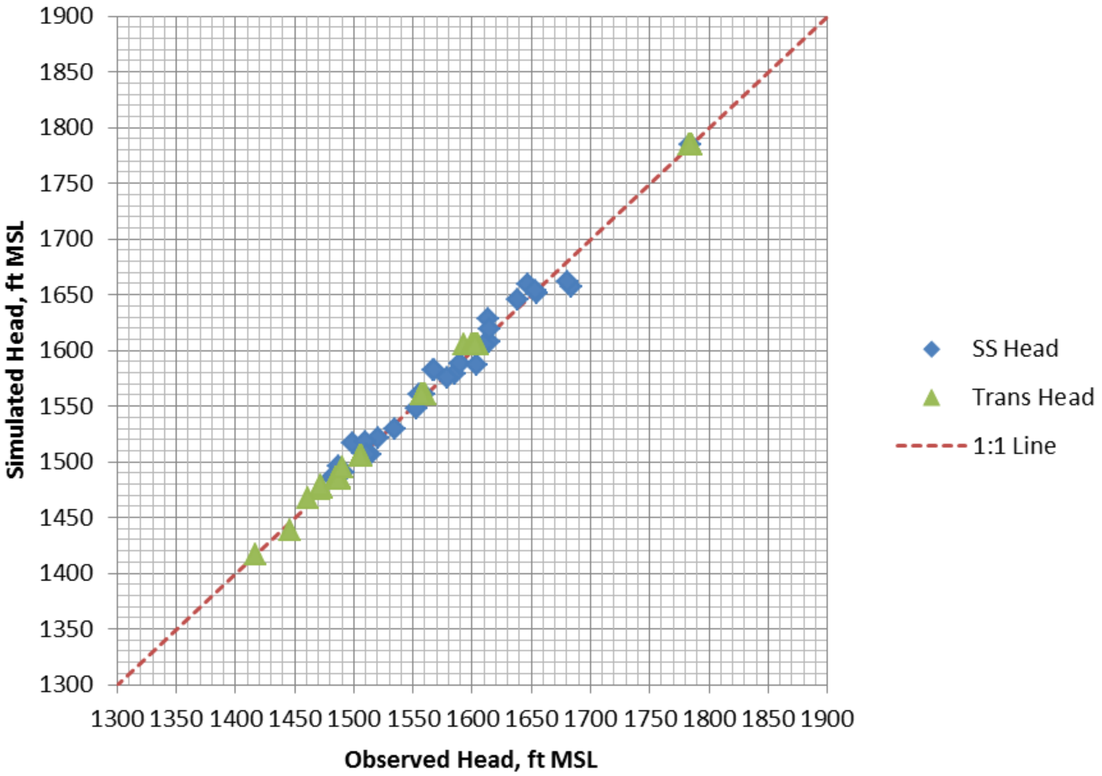

Figure 2 **Simulated versus observed heads - Plant Site model**

1.5 Plant Site Natural Watershed Runoff

The water quality of runoff from the natural, undisturbed areas at the Plant Site was determined through calibration of the probabilistic Plant Site water quality model at PM-12. The evaluation location PM-12 was chosen to represent natural existing conditions because it is upstream of any current and proposed mining impacts. The water quality from natural watershed areas is modeled as a unique probabilistic distribution for each constituent (that is resampled at each time step). This calibration is documented in the Calibration of the Existing Natural Watershed at the Plant Site document (PolyMet, 2012b) and CDF053, which presents updated calibrations for As, Ba, Co, Fe and Pb. Calibration was conducted within Microsoft Excel by replicating the water quality modeling of the GoldSim probabilistic model at PM-12.

1.5.1 Calibration Targets

The probabilistic distributions representing surface runoff water quality were calibrated using the following calibration targets:

- The mean of the observed data (used to calibrate the mean of each distribution)
- The 10th , 50th, and 90th percentiles of the observed data (used to calibrate the standard deviation of each distribution)

The number of samples in the observed data set varies by constituent. Water quality samples were collected at flows ranging from less than 1 cfs to 42 cfs.

1.5.2 Calibration Objectives

The objective of the calibration was to minimize the difference between the observed data (water quality samples at PM-12) and the simulated water quality values at PM-12. The probabilistic water quality model does not attempt to model actual water quality on a specific date or during a specific event. Instead, it attempts to capture the typical or mean water quality and the range in potentially observable values. Therefore, comparisons between observed data and model estimates were made at low, high and intermediate values to meet the objectives.

First, the mean of the distribution for each constituent was set equal to the mean of the observed values for that constituent, resulting in zero error at the mean. Second, the calibration objective was achieved by adjusting the standard deviation of the surface runoff water quality to minimize the root-mean-squared error calculated at the 10th, 50th, and 90th percentiles. By minimizing the difference between the observed data and the model estimates at the calibration targets, the model estimates most accurately represents distributions of observed values. The root-mean-squared error (RMSE) of the 10th, 50th, and 90th percentiles was calculated as:

$$RMSE = \sqrt{\frac{\sum\left(C_{obs,i} - C_{mod,i}\right)^2}{n}}$$

…where $C_{obs,i}$ = observed concentration at the 10th, 50th, or 90th percentile
$C_{mod,i}$ = modeled concentration at the 10th, 50th, or 90th percentile
n = number of percentiles included in calculation (3)

A normalized RMSE was calculated by dividing the RMSE by the mean of the observed data set for each constituent. The normalized RMSE is presented as a percentage of the mean (e.g., +/- 10%). Calibration was performed until the RMSE was minimized for each constituent (while maintaining a minimum standard deviation of at least 1 percent of the mean). The overall acceptability of each constituent calibration was not quantitative, but considered the model fit to the entire distribution of observed data (figures included Calibration of the Existing Natural Watershed at the Plant Site document).

1.5.3 Calibration Results

The calibrated standard deviation, RMSE, sample mean and normalized RMSE are presented below in Table 5. The normalized RMSE is below 10% for 11 of the 26 calibrated constituents and below 20% for 19 of the 26 calibrated constituents. For the following constituents, the standard deviation of surface runoff water quality was set to 1% of the mean surface runoff water quality estimate because the RMSE was not minimized: Ag, As, B, Be, Co, Ni, Sb, and V. Vanadium (V) was not measured in the field and as such does not have a best fit value.

Table 5 Plant Site natural watershed runoff calibration statistics – comparison between observed and modeled Embarrass River concentrations. Negative values indicate model is under-predicting observed concentrations.

Constituent	Modeled Mean Runoff Concentration (ug/L)	Modeled Runoff Standard Deviation (ug/L)	RMSE (ug/L)	Observed In-Stream Mean Concentration (ug/L)	Normalized RMSE (% error)
Ag	1.30E-01	1.3E-03	8.71E-03	1.11E-01	7.81%
Al	1.11E+02	4.1E+01	6.49E+00	1.01E+02	6.42%
Alk	3.24E+04	3.5E+04	1.96E+03	4.88E+04	4.02%
As	1.04E+00	1.0E-02	4.02E-02	9.06E-01	4.44%
B	1.56E+01	1.6E-01	1.09E+00	1.96E+01	5.55%
Ba	1.77E+00	7.9E-01	5.40E+00	1.53E+01	35.30%
Be	5.12E-02	5.1E-04	4.52E-02	1.00E-01	45.22%
Ca	6.22E+03	2.2E+03	3.47E+02	1.27E+04	2.73%
Cd	6.82E-02	1.6E-02	1.14E-02	8.64E-02	13.15%
Cl	5.15E+03	3.3E+03	2.08E+02	4.42E+03	4.71%
Co	6.19E-01	2.0E-01	1.50E-01	5.15E-01	29.13%

Constituent	Modeled Mean Runoff Concentration (ug/L)	Modeled Runoff Standard Deviation (ug/L)	RMSE (ug/L)	Observed In-Stream Mean Concentration (ug/L)	Normalized RMSE (% error)
Cr	9.81E-01	9.8E-01	8.28E-02	9.90E-01	8.36%
Cu	5.65E-01	7.5E-01	1.55E-01	1.26E+00	12.33%
F	7.66E+01	7.4E+01	9.78E+00	1.01E+02	9.69%
Fe	2.32E+03	9.6E+02	2.62E+02	1.74E+03	15.04%
K	2.86E+02	1.9E+02	1.86E+02	7.62E+02	24.36%
Mg	3.34E+03	7.7E+02	8.22E+02	5.81E+03	14.15%
Mn	4.22E+01	2.7E+02	2.87E+01	1.58E+02	18.25%
Na	2.34E+03	9.5E+01	4.02E+02	3.09E+03	13.01%
Ni	2.53E-01	2.5E-03	5.68E-01	1.61E+00	35.29%
Pb	2.74E-01	3.8E-01	2.06E-02	2.69E-01	7.66%
Sb	2.42E-01	2.4E-03	2.07E-02	2.50E-01	8.27%
Se	6.09E-01	4.5E-01	1.97E-01	7.17E-01	27.49%
SO4	3.08E+03	1.6E+04	1.11E+03	4.34E+03	25.49%
Tl	1.78E-01	5.0E-02	2.95E-02	1.71E-01	17.22%
V	5.41E+00	5.4E-02	-	-	-
Zn	8.92E+00	5.9E+00	1.84E+00	1.16E+01	15.84%

1.6 Existing LTVSMC Tailings Basin Loading

The calibration of the loading from the existing LTVSMC Tailings Basin is discussed in Section 10.2.1 of the NorthMet Project - Waste Characterization Data Package (PolyMet, 2012c). The release rates of constituents from the LTVSMC tailings in the existing Tailings Basin were calibrated such that modeled concentrations leaving the toes of the Tailings Basin matched as closely as possible to observed concentrations at the toes of the Tailings Basin. For sulfate (SO_4), the release from laboratory experiments is defined as release per mass of load-generating tailings per time. The release rate for sulfate was modified by multiplying the lab determined rate by calibration factors (one factor for coarse tailings and one factor for fine tailings) to generate a field scale rate. For some constituents (Ag, As, Cd, Co, Cu, Fe, Ni, Pb, Sb, Se, Tl, and Zn), the release rate was assumed to be a ratio to the release of sulfide. For these constituents, a calibration factor was applied to the release ratio. For other constituents (Al, B, Be, Ca, Cl, Cr, K, Mg, Mn, and Na), the release rate was assumed to be concentration capped with an uncertain cap. For these constituents, the cap was calibrated so that modeled seepage matched closely to observed seepage. Finally, for a few constituents (Alkalinity, Ba, and F), release was modeled as a mineral formula. For these few constituents, no calibration was performed.

1.6.1 Calibration Targets

The calibration targets for the calibration of the loading from the existing Tailings Basin were the mean observed seepage concentrations in wells or surface seeps assumed to be most representative of actual Tailings Basin seepage (i.e., least affected by potential dilution water). For the North Toe, which is the north face of Cell 2E, GW001 and GW012 were used. For the North-West Toe, which is the north face of Cell 2W, GW006 was used. For the West Toe, which is the west face of Cell 2W, GW007 and SD004 were used. For the South Toe, which is the entire southern length of the Tailings Basin, SD026 was used. Samples through July of 2011 were used to determine a mean concentration at each toe for each constituent. These mean concentrations were the targets for calibration.

1.6.2 Calibration Objectives

The model estimates seepage flow and concentrations at each of the four toes mentioned in the previous section. The objective of the calibration was to minimize the absolute difference between the modeled and observed total load leaving the Tailings Basin under average conditions (mean release rates, average infiltration and seepage, etc.).

$$f = \sum_{i=1}^{n} \left(\dot{M}_{obs,i} - \dot{M}_{mod,i} \right)$$

…where f = objective function to minimize for calibration

$M\text{-}dot_{obs,i}$ = observed loading rate at the i^{th} toe under average conditions

$M\text{-}dot_{mod,i}$ = modeled loading rate at the i^{th} toe using average model inputs

n = number of Tailings Basin toes with available seepage data (3 or 4)

This objective method allows for some of the toes to potentially over-predict seepage concentrations while other toes could potentially under-predict, for each constituent. There was no quantitative calibration acceptance criterion.

1.6.3 Calibration Results

The normalized error, presented as a percent of the observed mean concentration, is shown for each modeled constituent at each evaluation location in Table 6. The actual error is shown rather than the absolute error to show additionally whether the model is under (negative error) or over-predicting (positive error).

Table 6 LTVSMC load calibration statistics. Negative values indicate model is under-predicting observed concentrations.

	Toe Location				*Average by Constituent*
Constituent	**North**	**North-West**	**West**	**South**	
Ag	10%	-12%	-13%	--	-5%
Al	-4%	24%	28%	--	16%
Alkalinity	--	--	--	--	
As	277%	-37%	-9%	--	77%
B	5%	-4%	0%	19%	5%
Ba	--	--	--	--	
Be	-24%	-21%	-22%	--	-22%
Ca	-55%	-13%	50%	-53%	-18%
Cd	13%	-21%	18%	--	3%
Cl	-3%	33%	-22%	63%	18%
Co	-37%	3%	76%	-27%	4%
Cr	-3%	4%	-3%	--	-1%
Cu	-14%	-15%	138%	--	36%
F	--	--	--	--	
Fe	-54%	98%	51%	--	32%
K	184%	-16%	3%	-11%	40%
Mg	28%	-24%	42%	-33%	3%
Mn	-79%	7%	33%	-54%	-23%

	Toe Location				***Average by Constituent***
Constituent	**North**	**North-West**	**West**	**South**	
Na	-13%	0%	-2%	46%	8%
Ni	-50%	14%	217%	--	60%
Pb	-23%	138%	60%	--	59%
Sb	13%	-7%	-8%	--	0%
Se	12%	-10%	-11%	--	-3%
SO4	25%	-31%	29%	-1%	6%
Tl	9%	-5%	-7%	--	-1%
V	0%	0%	0%	0%	0%
Zn	6%	-16%	2%	--	-3%
Average by Location	9%	4%	27%	-5%	

Additionally, Table 6 shows the un-weighted average error for each location and for each constituent. The large differences in errors between the different toes for a given constituent suggest that there is more variability in the natural system than can be captured in the model. The fact that one toe is not consistently under or over-predicting relative to the other toes suggests that there is not something systematically wrong with the underlying assumptions that the model is built on.

The North and South toes are heavily controlled by the concentration which is seeping from the existing ponds in Cells 2E and 1E respectively. Average observed concentrations in those ponds are used in the model to represent the existing seepage concentrations from those ponds. The North-West and West toes are largely controlled by the release rates from the tailings themselves.

Figure 3 through Figure 15 show the model results compared to observed seepage concentrations at each of the four toes for the constituents where the release rate or ratio was modified with a calibration factor. In the figures, the blue bars represent model results. They show a range of results from the 10th percentile to the 90th percentile with breaks in the colors at the 25th, 50th (median), and 75th percentiles. The observed data is also shown by gray X's and the mean of the observed data (calibration target) is shown as an orange circle. As documented in the Plant Site Water Modeling Work Plan (Table 1-21), the order of magnitude of the calibration factors ranges from about 0.01 to about 0.0001.

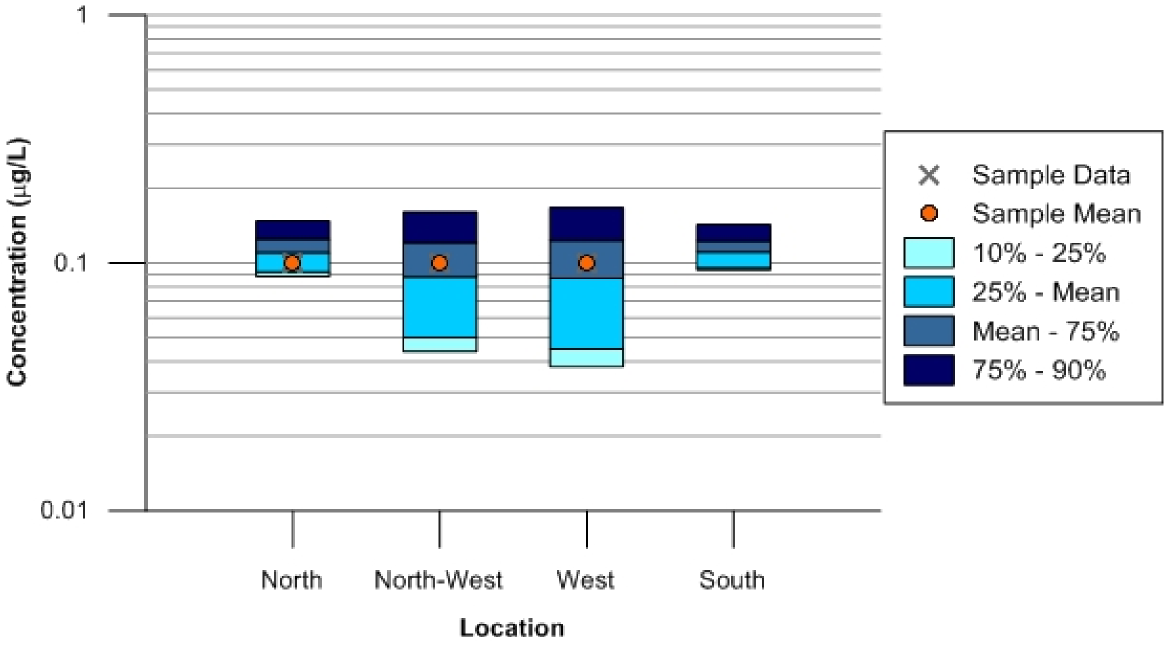

Figure 3 Existing conditions model calibration at the Tailings Basin toes for Silver

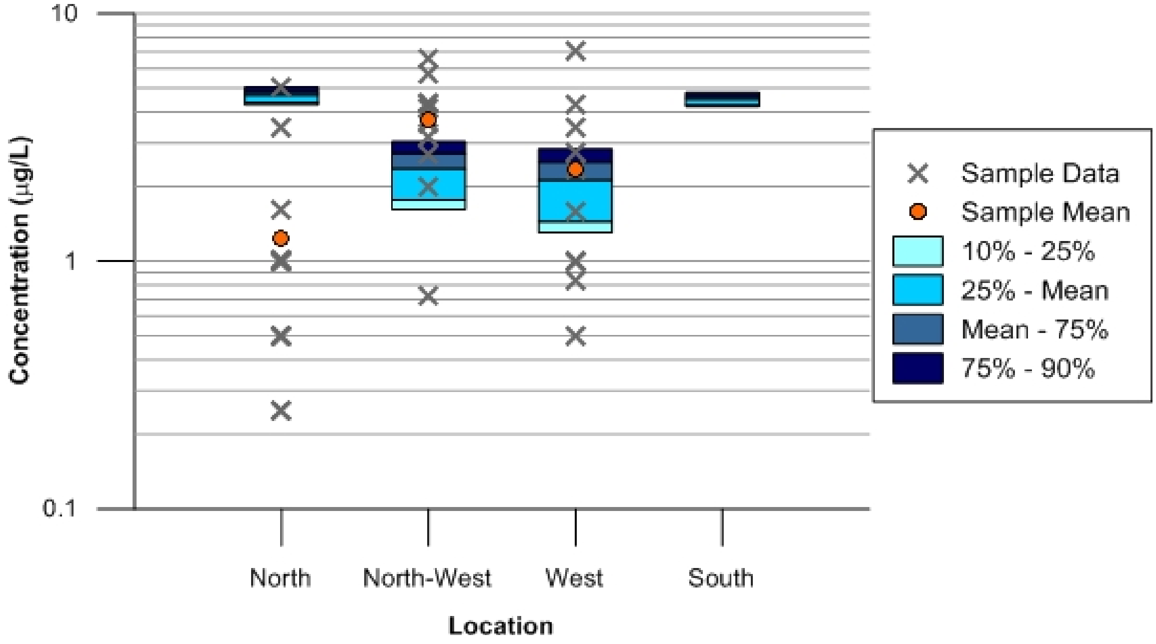

Figure 4 Existing conditions model calibration at the Tailings Basin toes for Arsenic

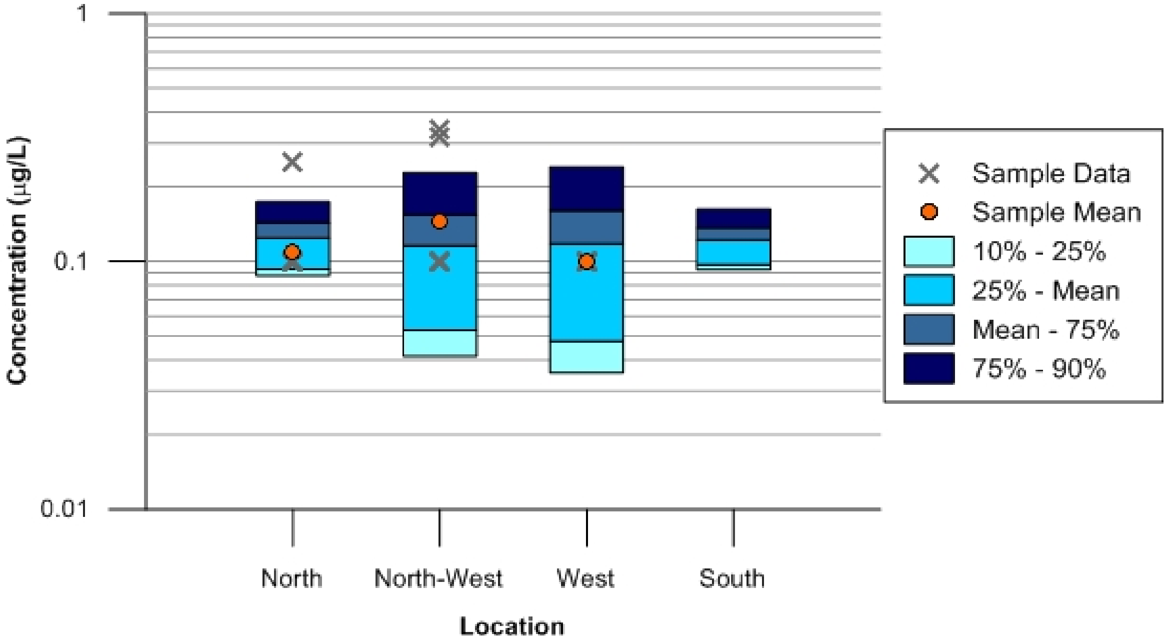

Figure 5 Existing conditions model calibration at the Tailings Basin toes for Cadmium

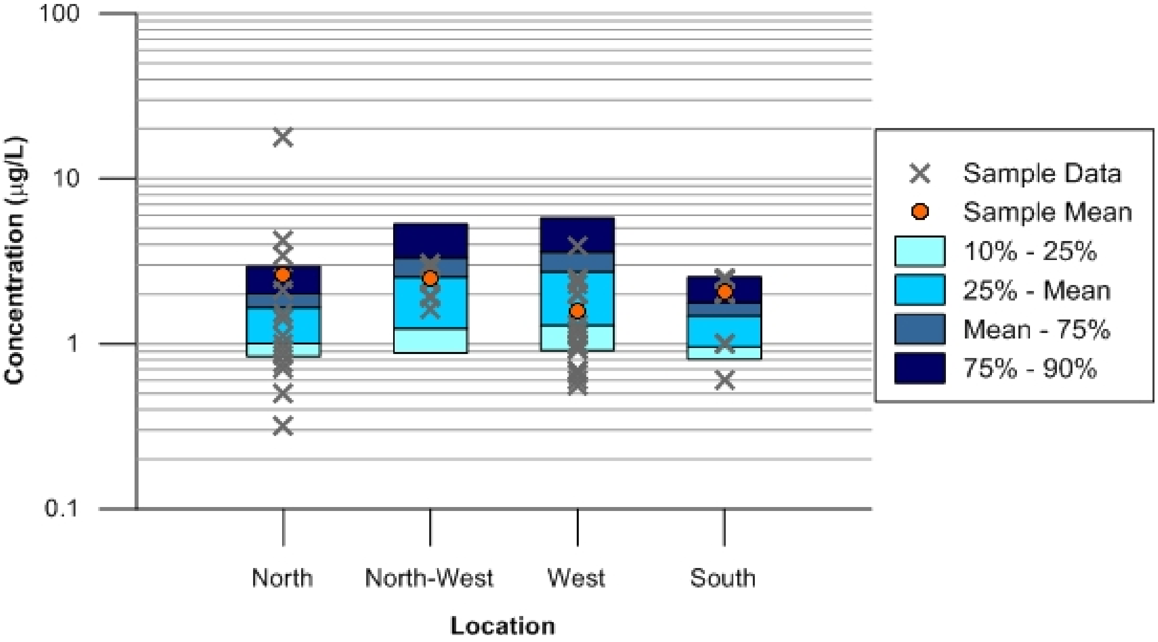

Figure 6 Existing conditions model calibration at the Tailings Basin toes for Cobalt

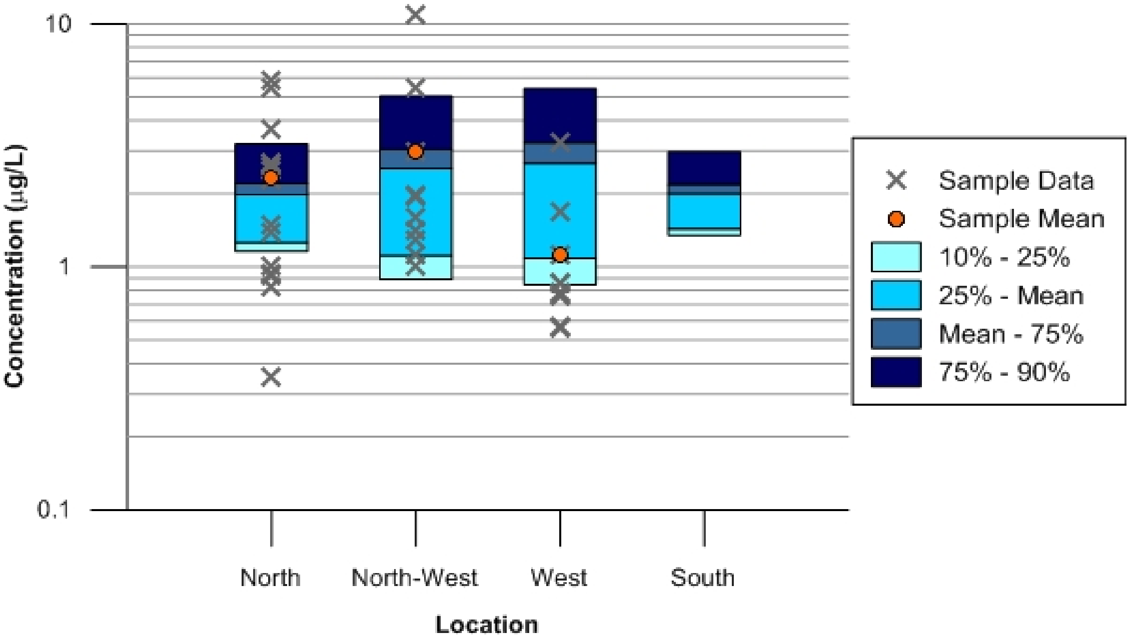

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Figure 7 Existing conditions model calibration at the Tailings Basin toes for Copper

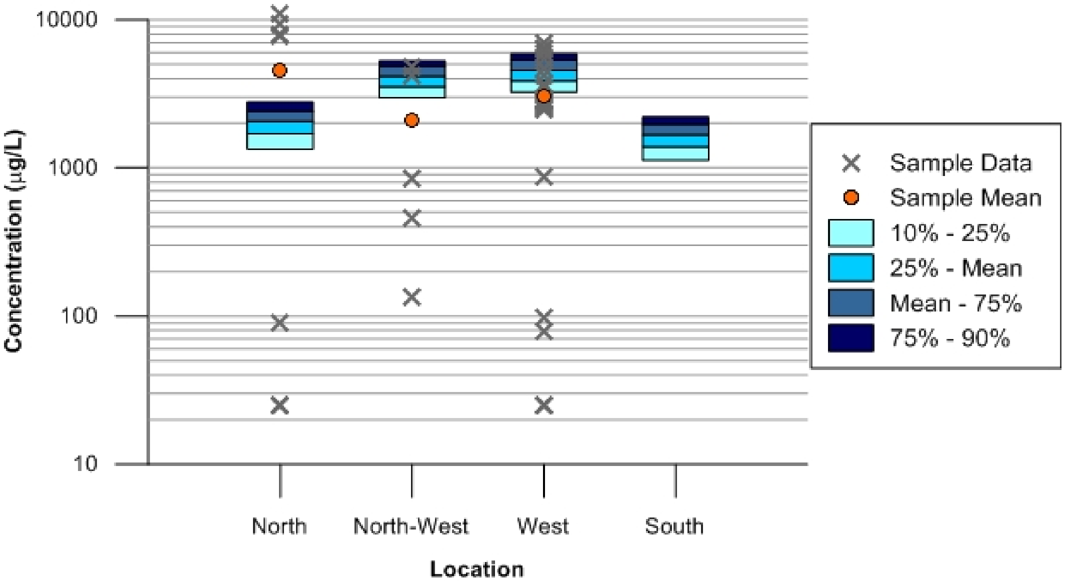

Figure 8 Existing conditions model calibration at the Tailings Basin toes for Iron

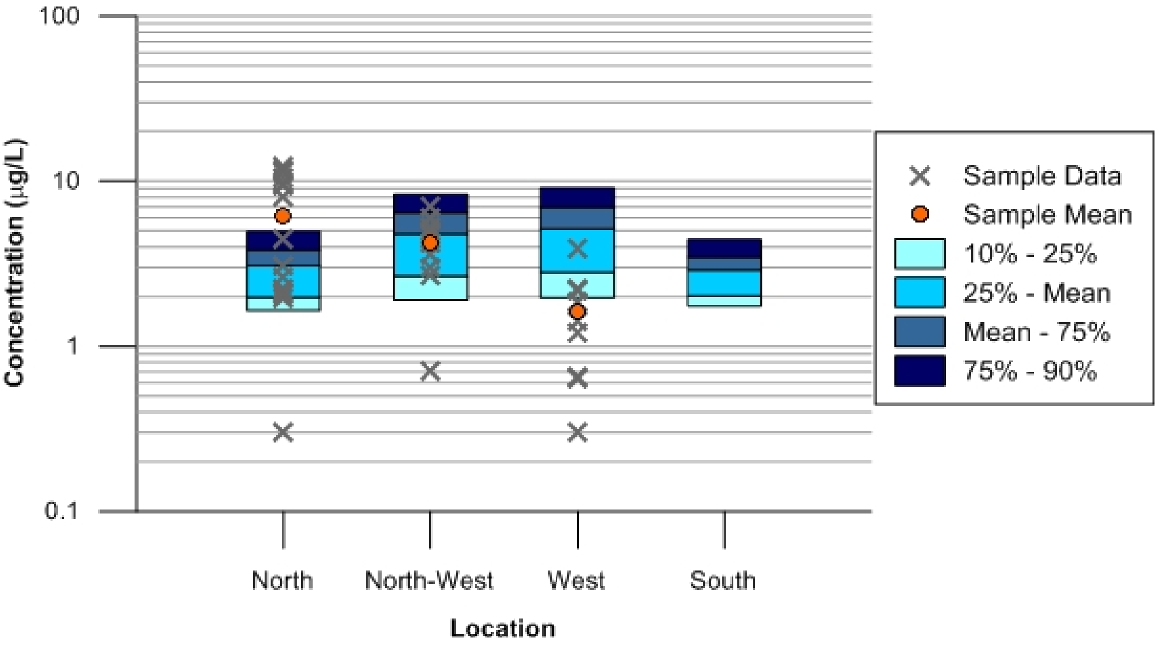

Figure 9 Existing conditions model calibration at the Tailings Basin toes for Nickel

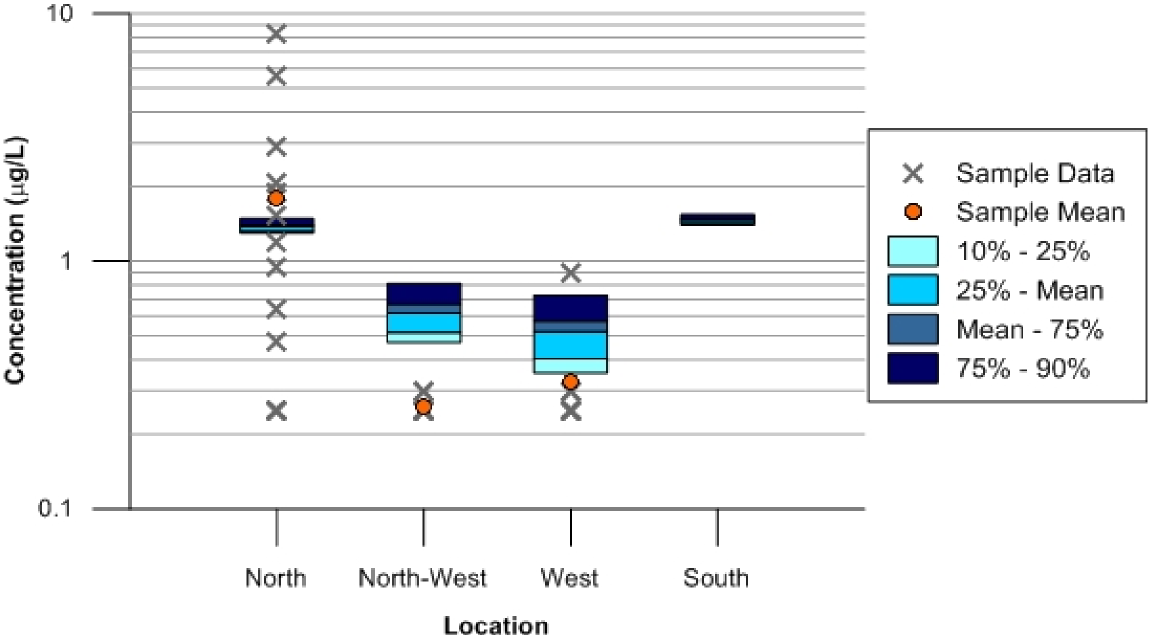

Figure 10 Existing conditions model calibration at the Tailings Basin toes for Lead

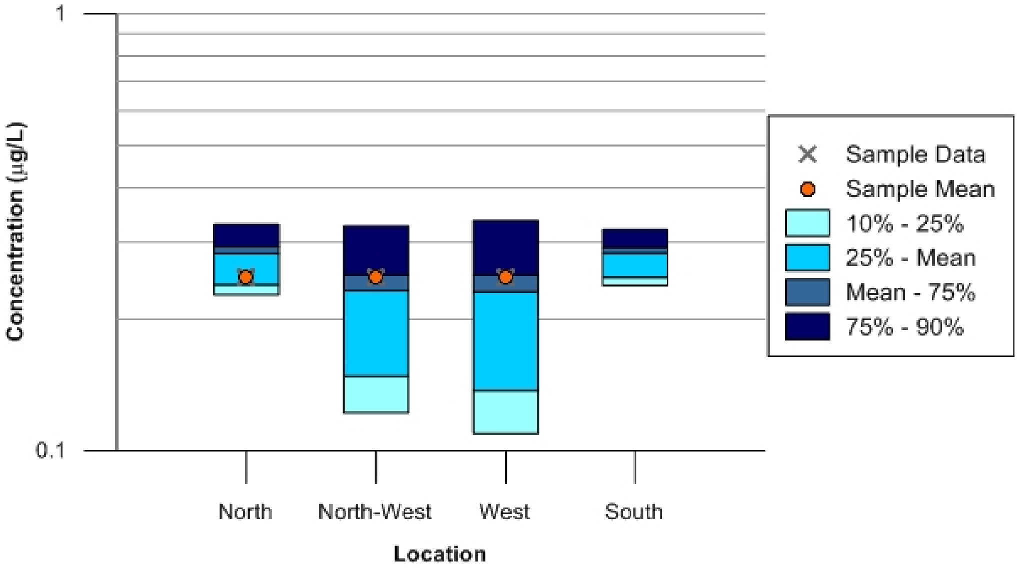

Figure 11 Existing conditions model calibration at the Tailings Basin toes for Antimony

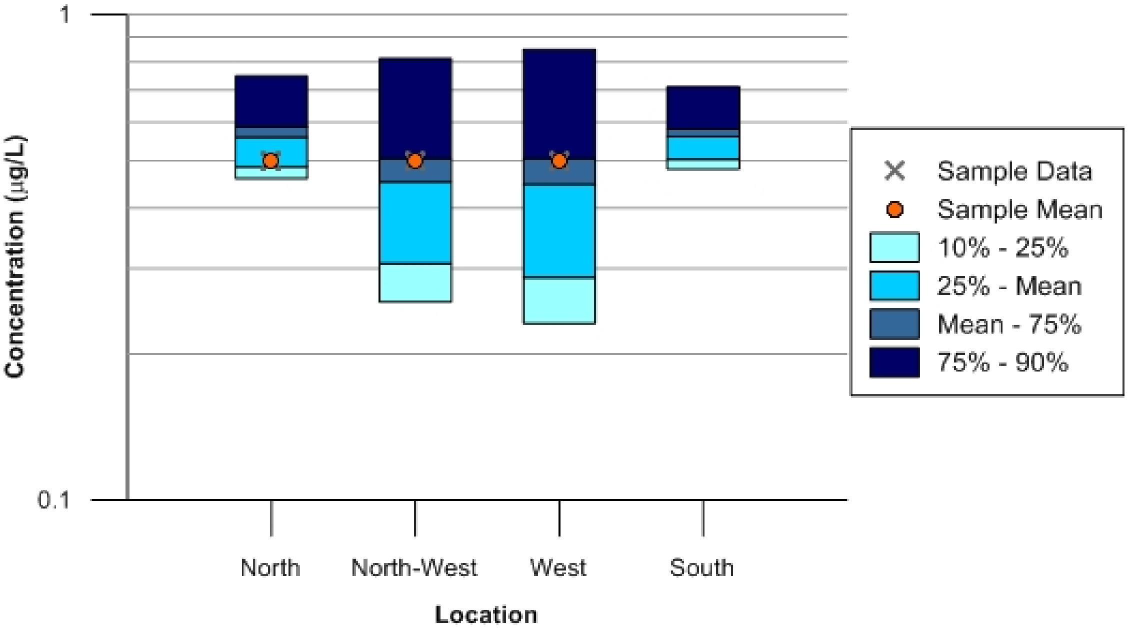

Figure 12 **Existing conditions model calibration at the Tailings Basin toes for Selenium**

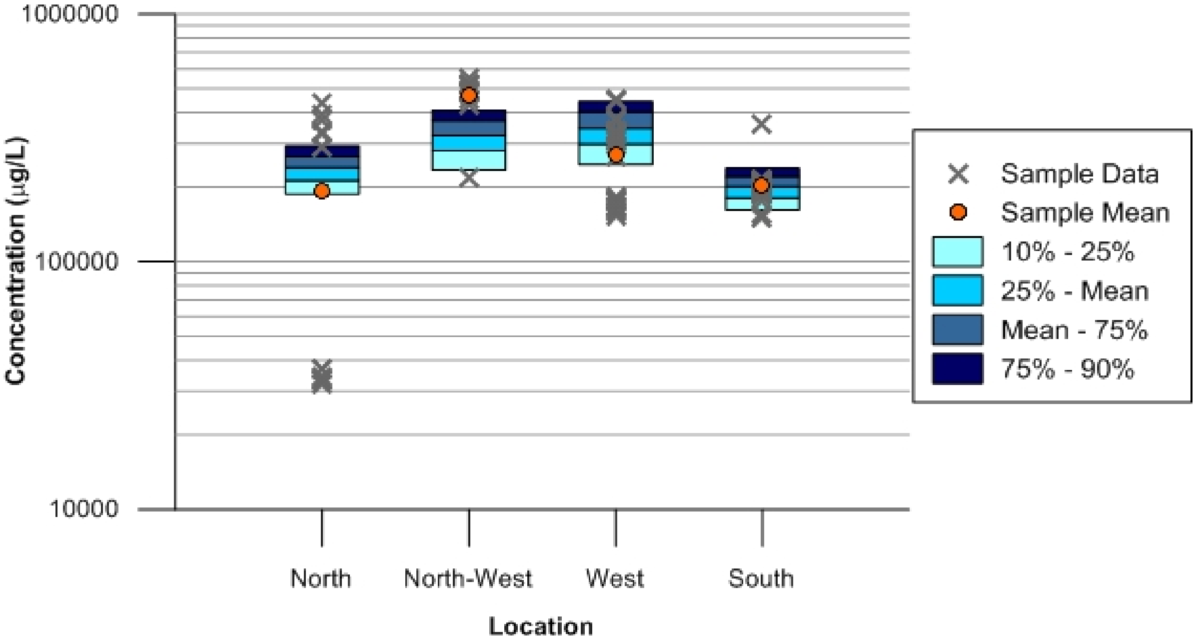

Figure 13 **Existing conditions model calibration at the Tailings Basin toes for Sulfate**

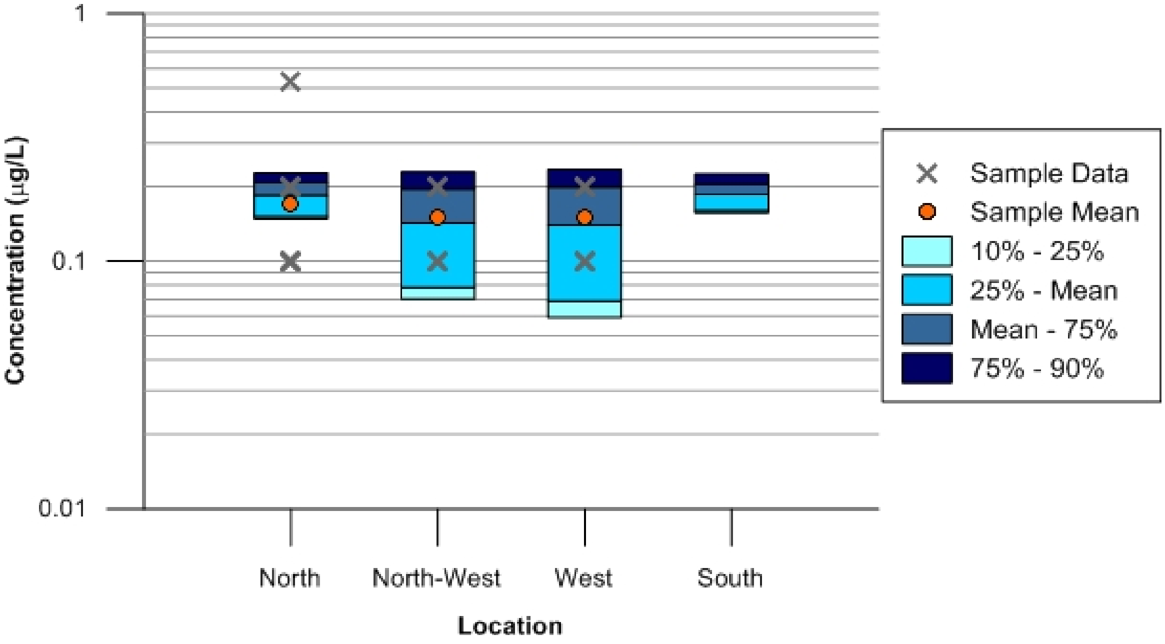

Figure 14 Existing conditions model calibration at the Tailings Basin toes for Thallium

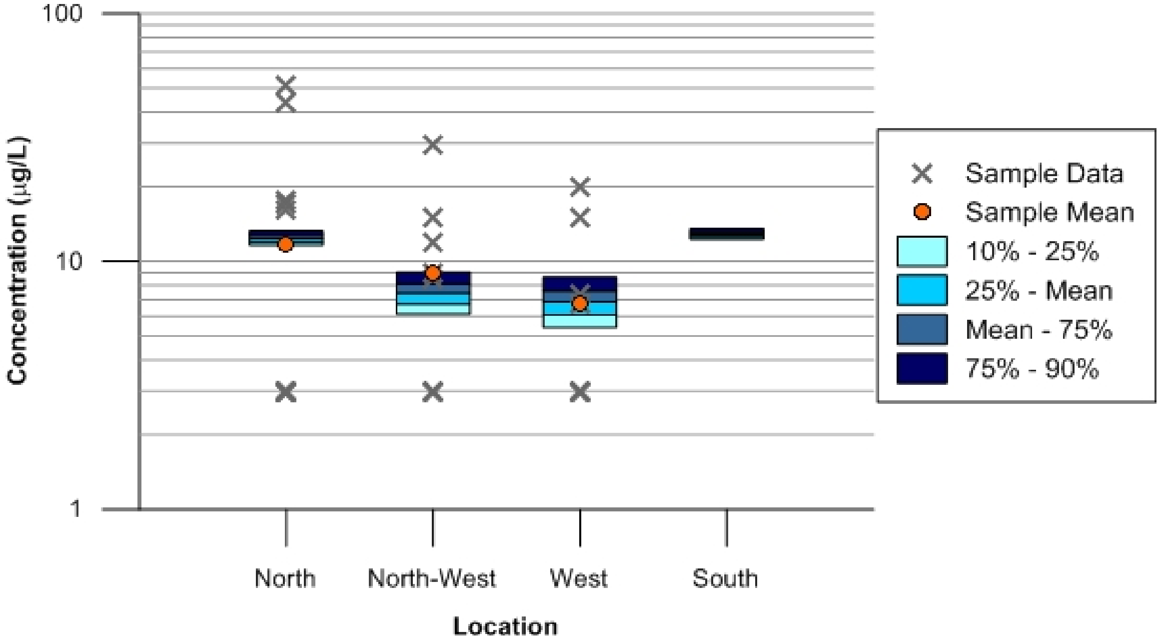

Figure 15 Existing conditions model calibration at the Tailings Basin toes for Zinc

Figure 16 through Figure 25 show the model results compared to observed seepage concentrations at each of the four toes for the constituents which were assumed to be concentration capped.

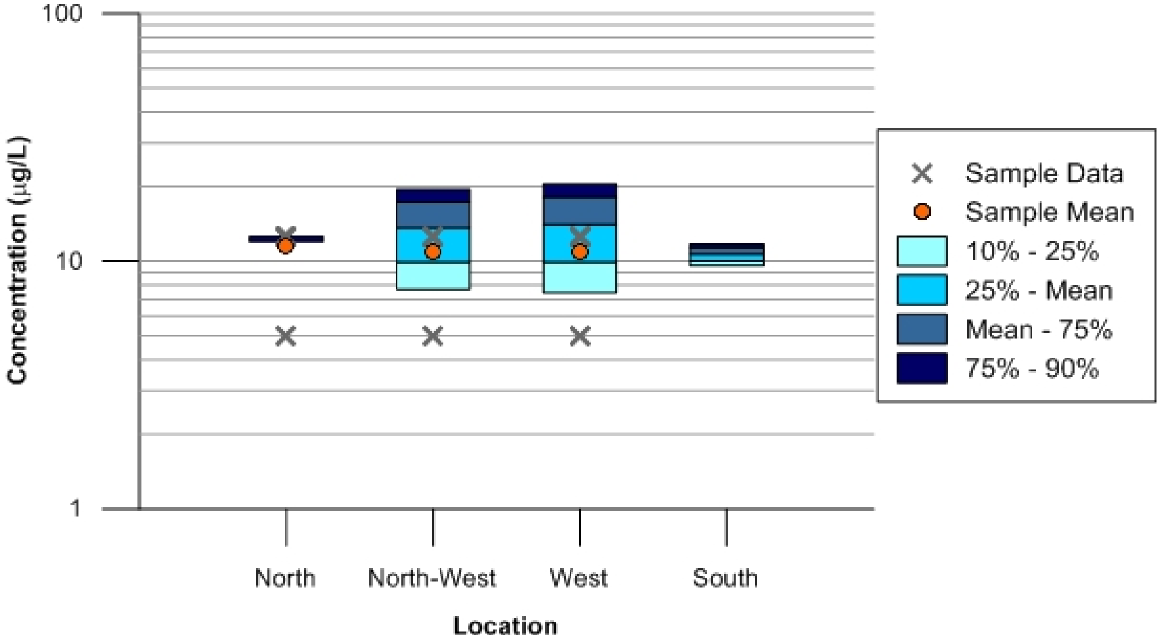

Figure 16 Existing conditions model calibration at the Tailings Basin toes for Aluminum

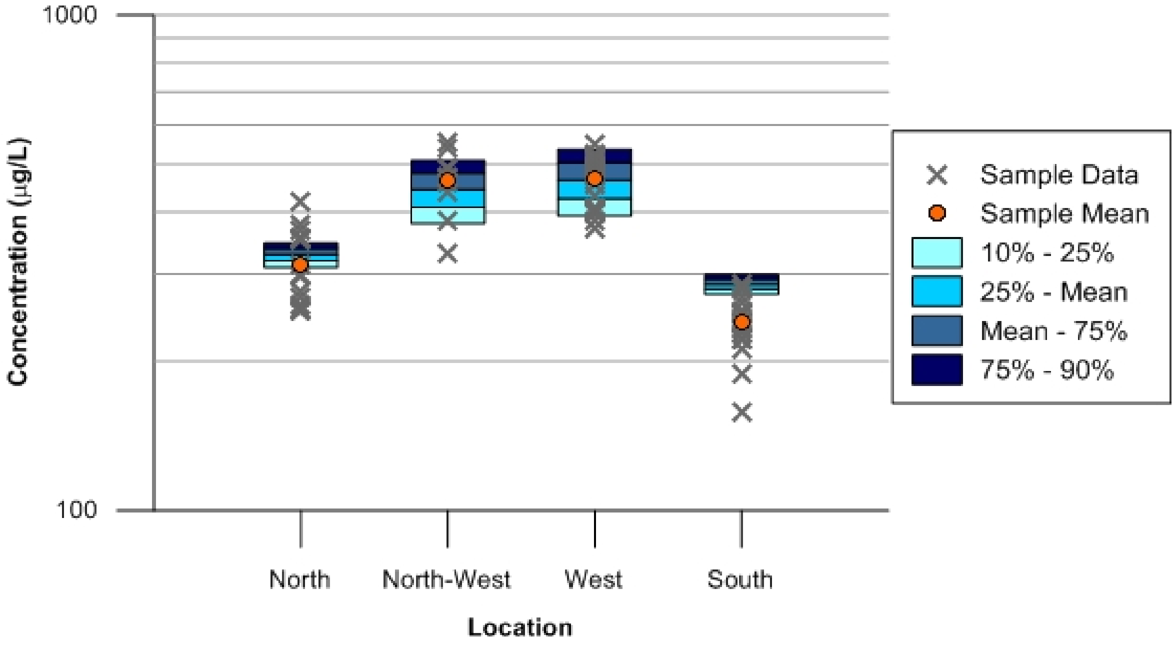

Figure 17 Existing conditions model calibration at the Tailings Basin toes for Boron

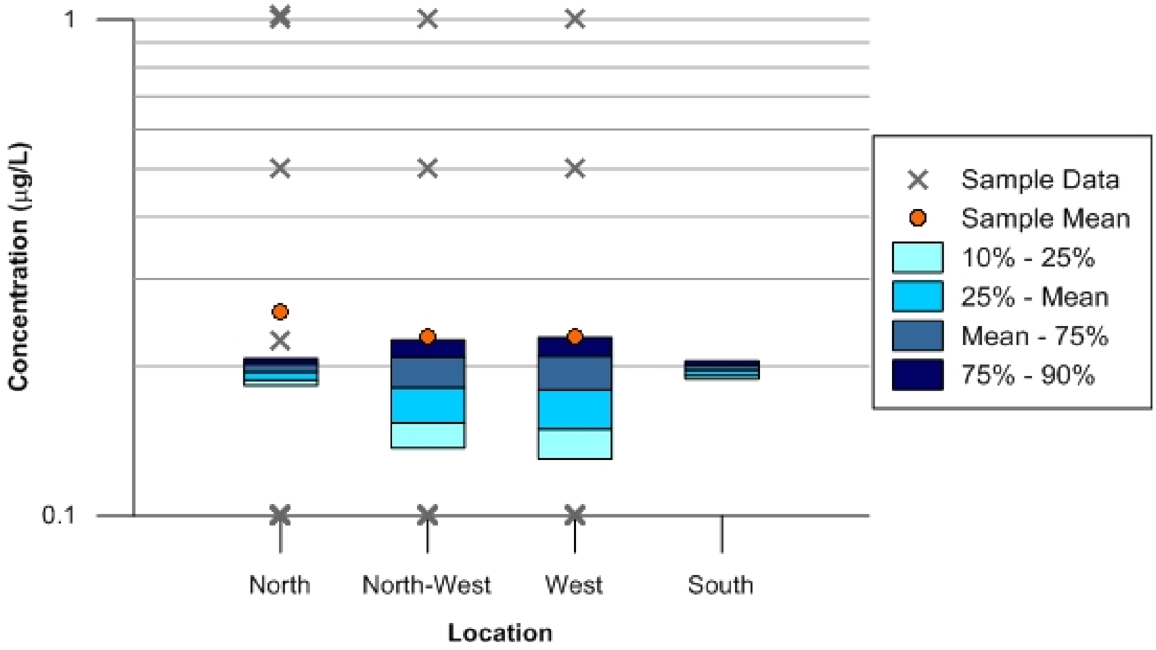

Figure 18 Existing conditions model calibration at the Tailings Basin toes for Beryllium

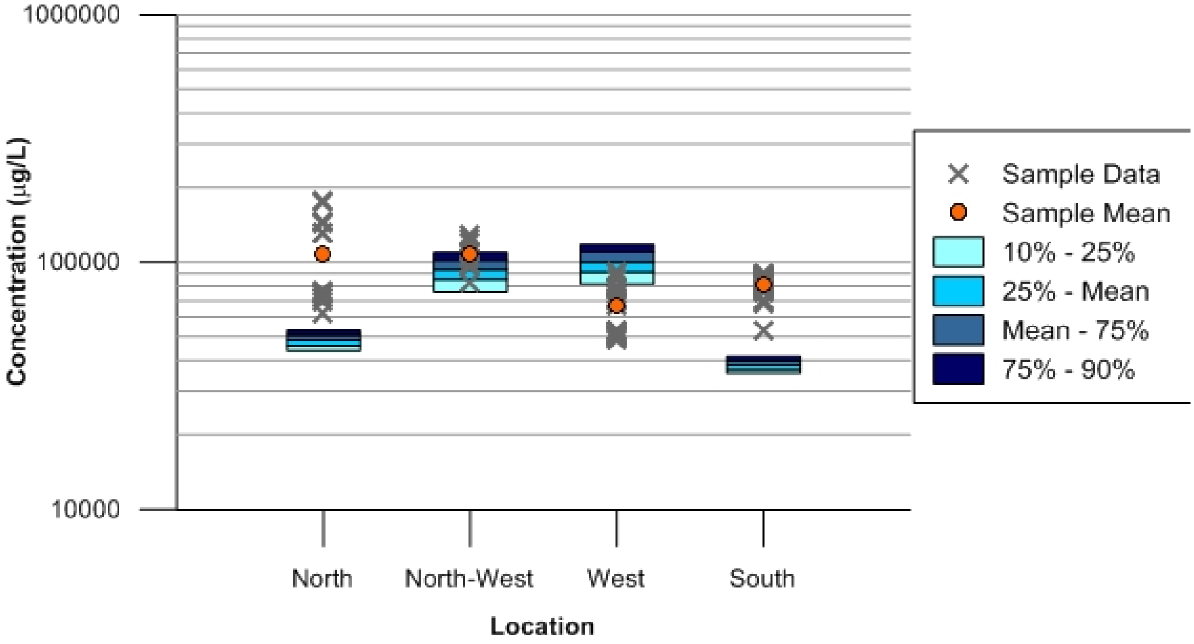

Figure 19 Existing conditions model calibration at the Tailings Basin toes for Calcium

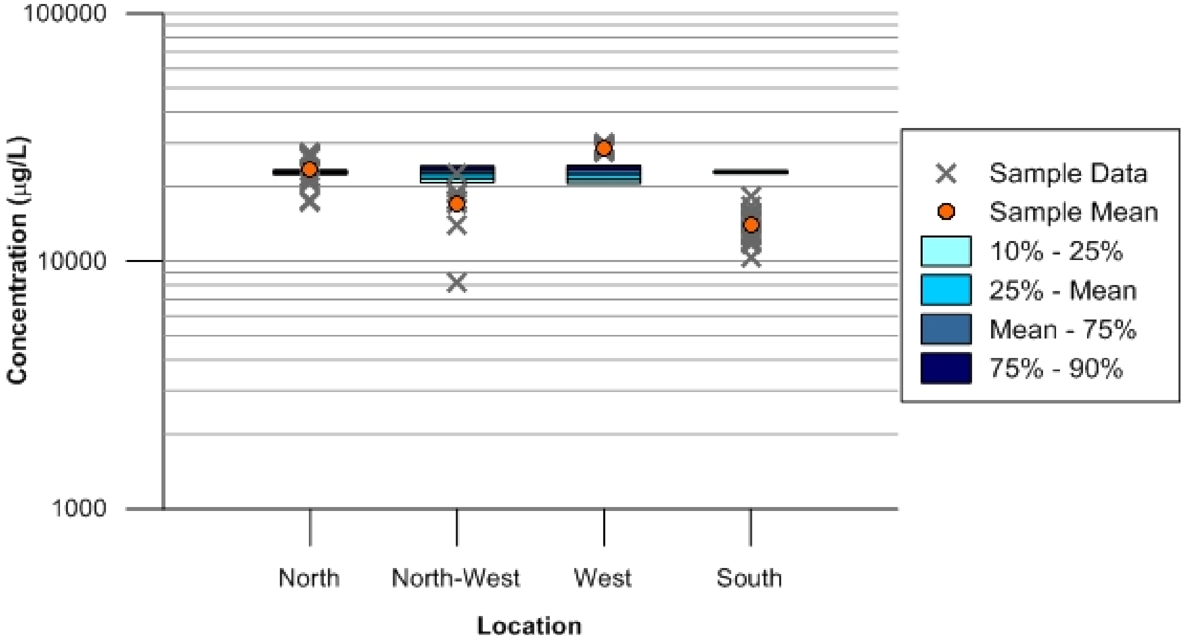

Figure 20 Existing conditions model calibration at the Tailings Basin toes for Chloride

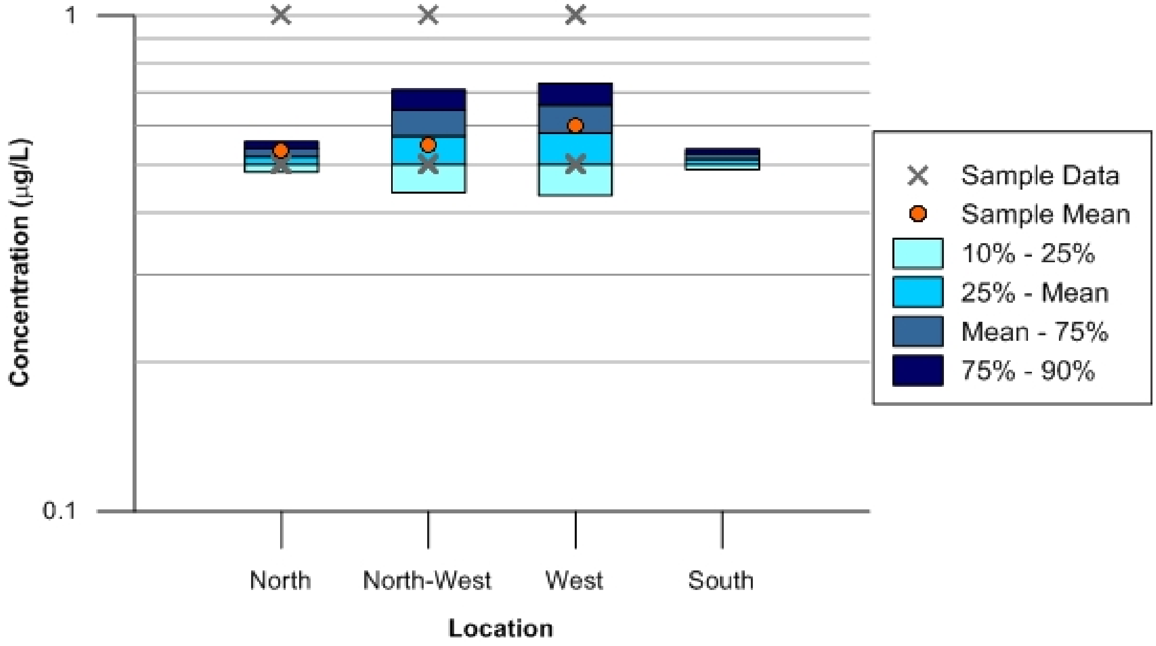

Figure 21 Existing conditions model calibration at the Tailings Basin toes for Chromium

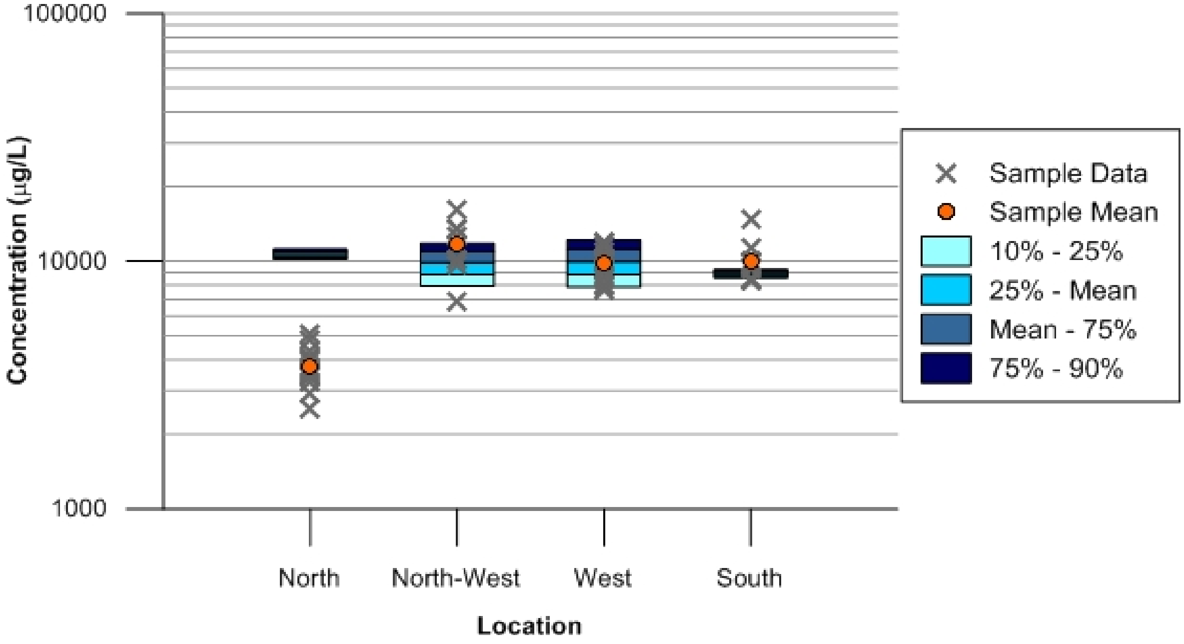

Figure 22 Existing conditions model calibration at the Tailings Basin toes for Potassium

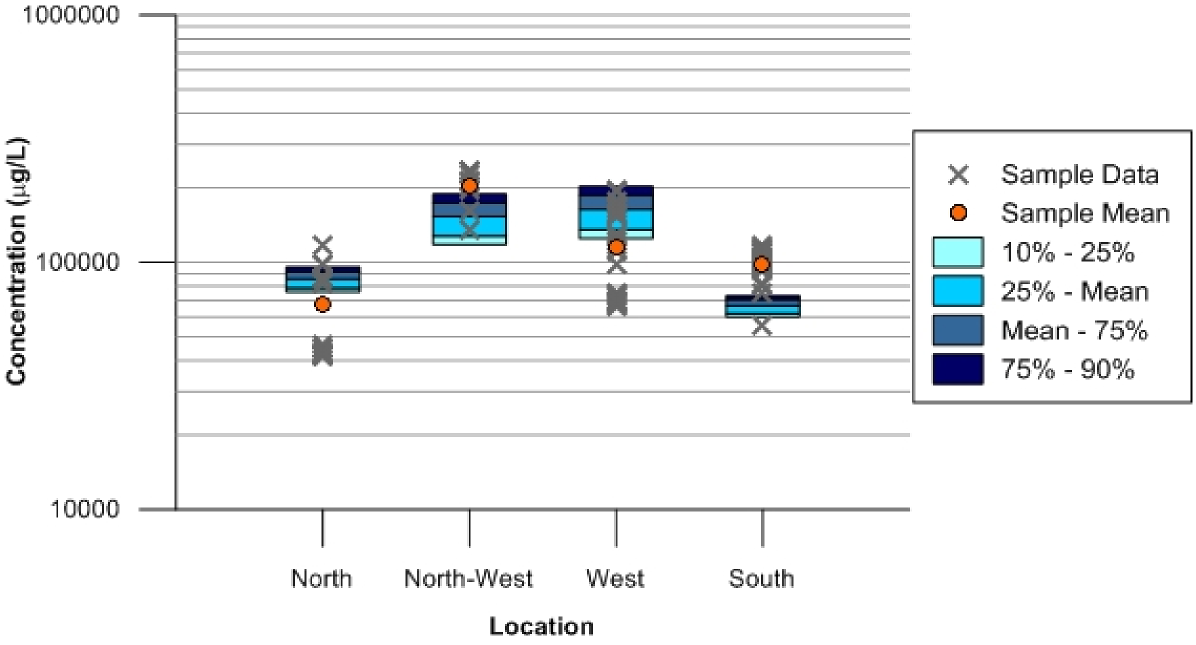

Figure 23 Existing conditions model calibration at the Tailings Basin toes for Magnesium

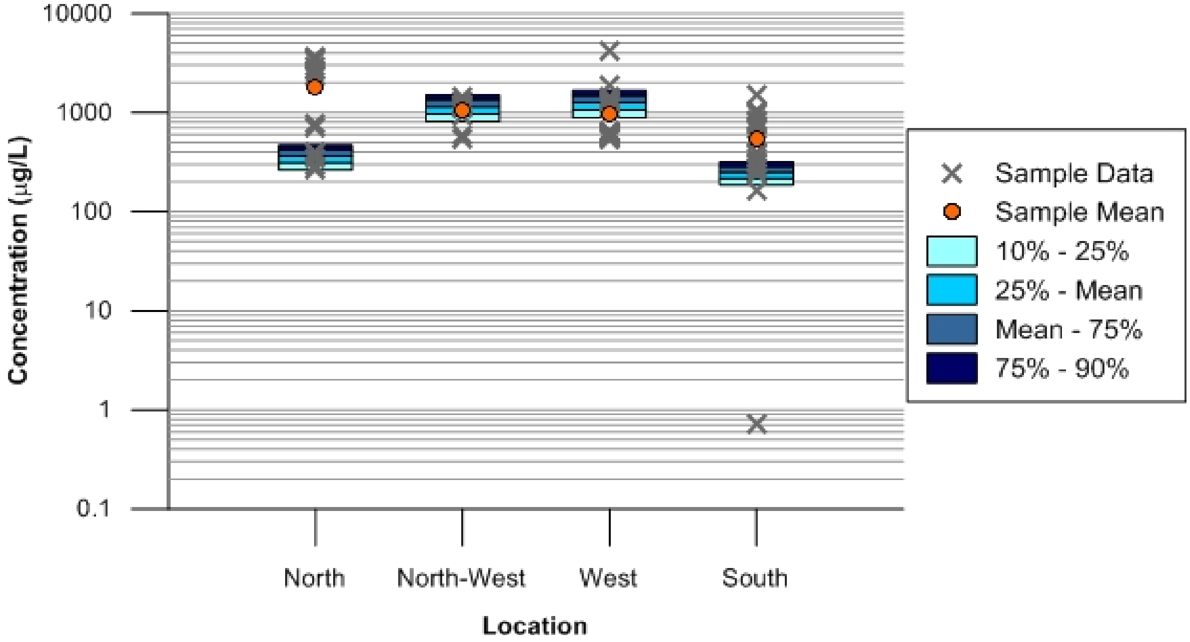

Figure 24 Existing conditions model calibration at the Tailings Basin toes for Manganese

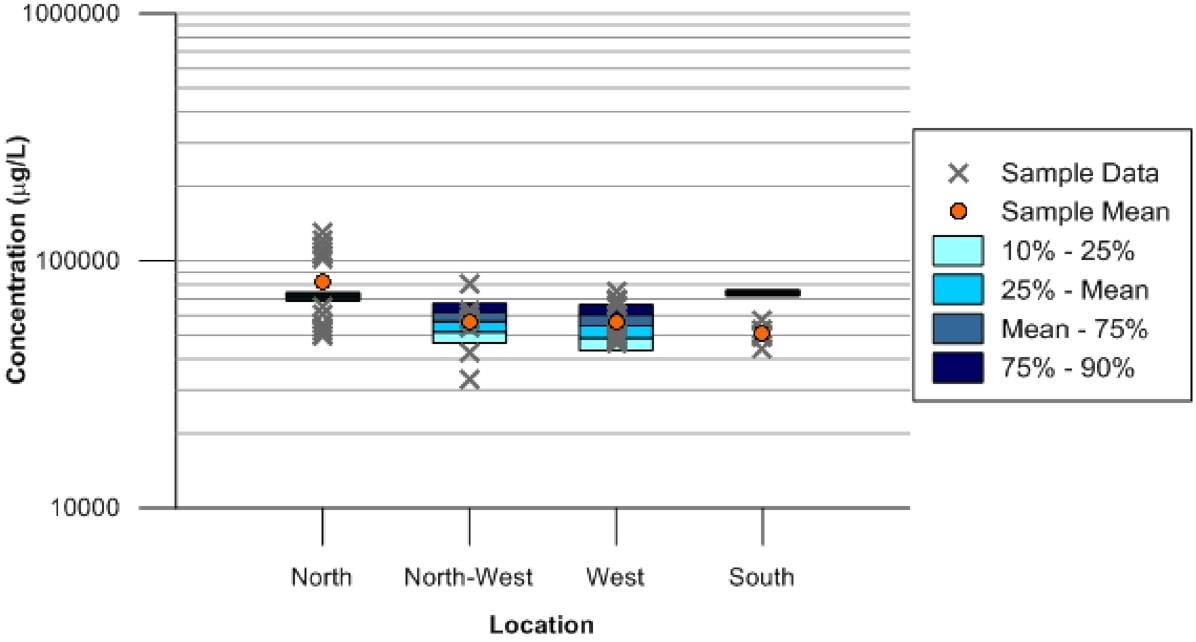

Figure 25 Existing conditions model calibration at the Tailings Basin toes for Sodium

Finally, Figure 26 through Figure 28 show the model results compared to observed seepage concentrations at each of the four toes for the constituents which were not calibrated.

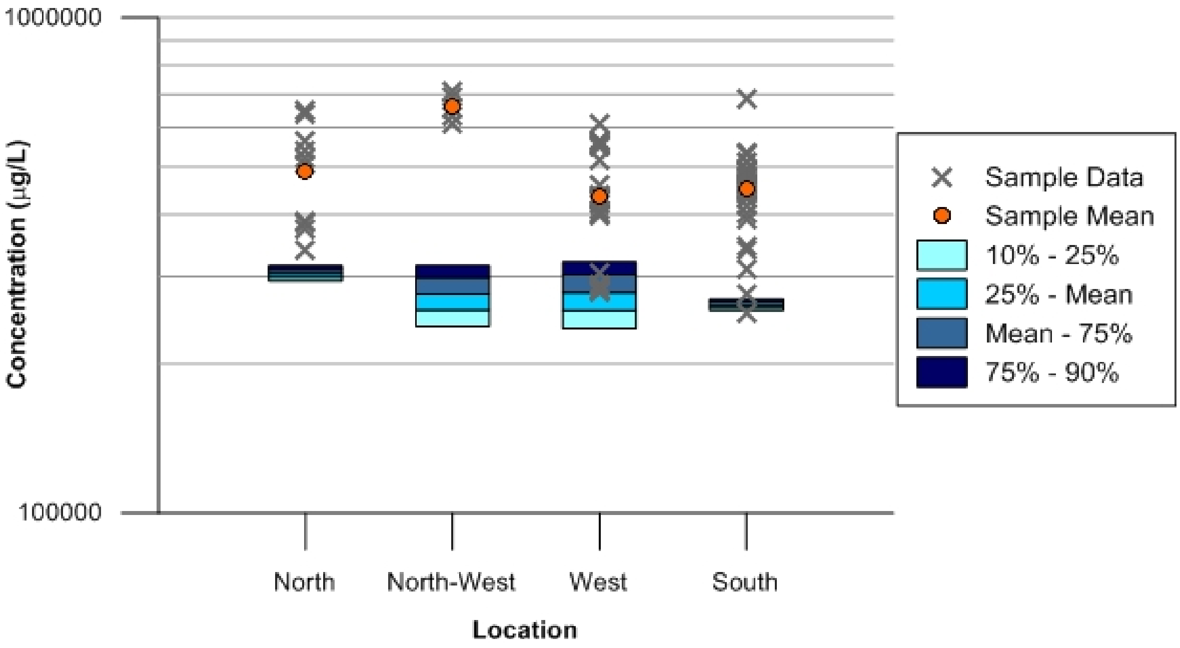

Figure 26 Existing conditions model calibration at the Tailings Basin toes for Alkalinity

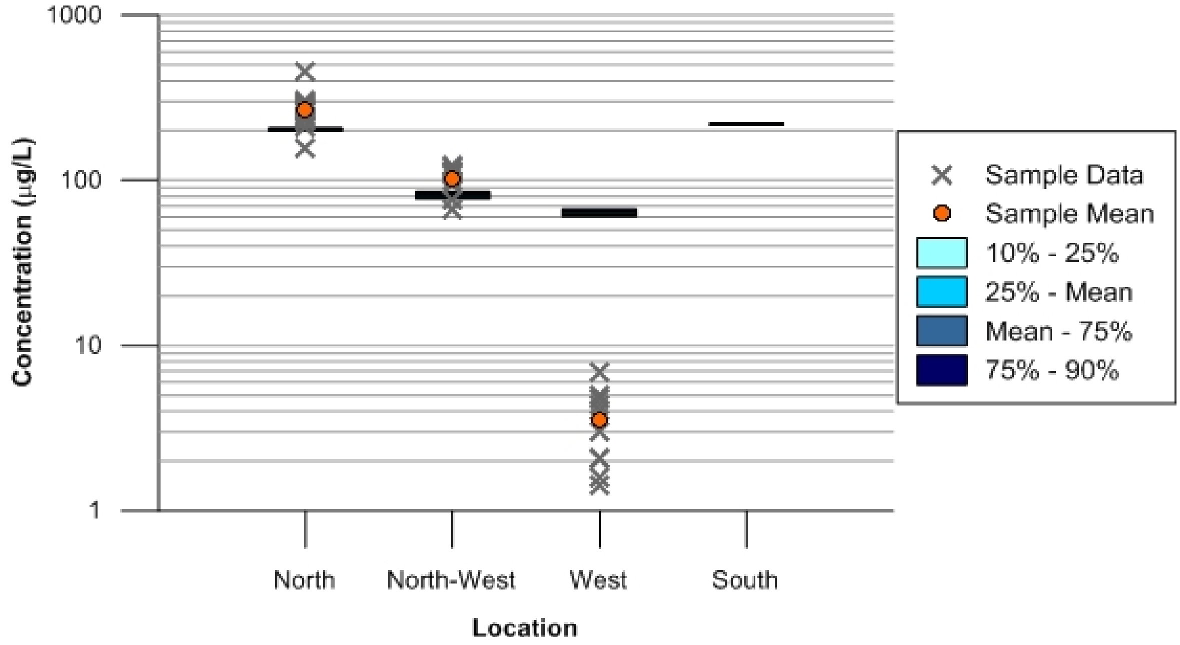

Figure 27 Existing conditions model calibration at the Tailings Basin toes for Barium

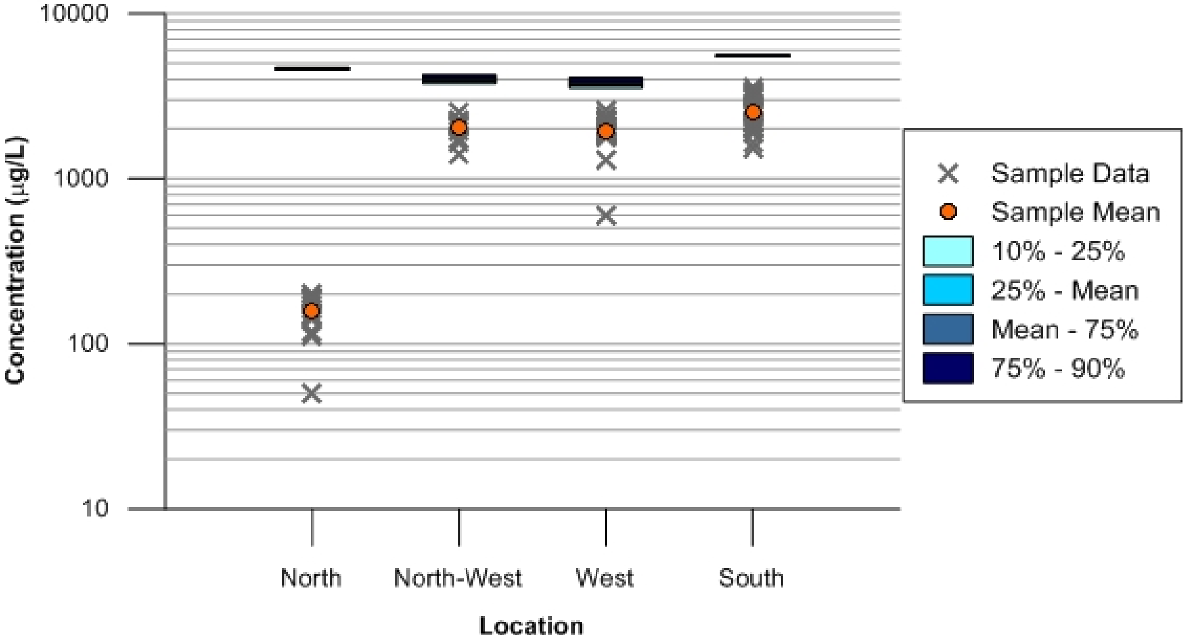

Figure 28 **Existing conditions model calibration at the Tailings Basin toes for Fluoride**

2.0 Plant Site Model Corroboration

The modeling methodologies and assumptions for the generation of load from the LTVSMC Tailings Basin and the transportation of this load to the receiving streams are corroborated by simulating existing conditions within the GoldSim model. This model performance evaluation is part of the Plant Site Water Quality Model Quality Assurance Project Plan (Plant Site QAPP, version 2). A qualitative comparison between the estimated and measured concentrations at evaluation locations PM-11 (Unnamed Creek), PM-19 (Trimble Creek), MLC-2 (Mud Lake Creek), and PM-13 (Embarrass River) has been performed and is presented here.

2.1 Corroboration Data

Model performance is evaluated by comparing the mean from sample data to the predicted mean at each location. The average model performance for each constituent and location was also computed to identify general trends and potential model issues. Available surface water data through July 2011 at the four evaluation locations mentioned above (PM-11, PM-19, MLC-2, and PM-13) were used for model corroboration. Monitoring data used for corroboration is provided in Large Table 3 of the Water Modeling Data Package Volume 2 – Plant Site (PolyMet, 2012e).

2.2 Corroboration Results

The normalized error, presented as a percent of the observed mean concentration, is shown for each modeled constituent at each evaluation location in Table 7. The actual error is shown rather than the absolute error to show additionally whether the model is under or over-predicting.

Normalized error is calculated as follows:

$$Error = \frac{\left(\bar{C}_{mod,i} - \bar{C}_{obs,i}\right)}{\bar{C}_{obs,i}}$$

…where $Error$ = normalized model error

$C_{mod,i}$ = mean modeled concentration at the ith evaluation location

$C_{obs,i}$ = mean observed concentration at the ith evaluation location

Table 7 Plant Site corroboration summary – normalized error, as a percent of observed mean concentration, for each constituent at each evaluation location. Negative values indicate model is under-predicting observed concentrations.

	Location				***Average by Constituent***
Constituent	**PM-11**	**PM-19**	**MLC-2**	**PM-13**	
Ag	-3%	7%	12%	-4%	***2%***
Al	69%	192%	94%	-61%	***59%***
Alkalinity	-34%	-35%	27%	5%	***-7%***
As	73%	77%	67%	34%	***50%***
B	17%	91%	440%	103%	***130%***
Ba	30%	32%	183%	13%	***51%***
Be	23%	50%	34%	7%	***23%***
Ca	67%	11%	38%	34%	***30%***
Cd	38%	88%	263%	-2%	***77%***
Cl	-1%	45%	194%	-5%	***47%***
Co	512%	555%	225%	69%	***273%***
Cr	14%	38%	63%	-36%	***16%***

	Location				
Constituent	**PM-11**	**PM-19**	**MLC-2**	**PM-13**	***Average by Constituent***
Cu	54%	274%	216%	-8%	***107%***
F	43%	208%	444%	113%	***162%***
Fe	760%	80%	-46%	58%	***171%***
K	8%	161%	468%	97%	***146%***
Mg	90%	105%	141%	138%	***95%***
Mn	524%	-9%	3%	166%	***137%***
Na	-25%	-3%	117%	32%	***24%***
Ni	142%	295%	610%	7%	***210%***
Pb	74%	430%	711%	12%	***246%***
Sb	-5%	2%	5%	-83%	***-16%***
Se	-28%	15%	294%	-25%	***51%***
SO4	72%	1438%	10043%	107%	***2332%***
Tl	29%	205%	2173%	-17%	***478%***
V	--	--	--	--	
Zn	19%	236%	165%	2%	***84%***
Average by Location	***99%***	***176%***	***653%***	***29%***	

For comparing the calibration at the toes of the Tailings Basin and the corroboration of the surface water evaluation locations, the surface seepage from the North Toe contributes to both MLC-2 (25%) and PM-19 (75%), surface seepage from the North-West Toe contributes to PM-19, and surface seepage from the West Toe contributes to PM-11.

Evaluation location PM-13 is the most downstream evaluation location on the Embarrass River and captures all of the assumptions and calibrations that went into the existing conditions Plant Site model. In general, the model seems to be over-predicting concentrations at the evaluation locations. At this location, there are five constituents where the model is over-predicting the mean concentration by at least 100% (model mean is at least twice the observed mean). There are 10 constituents where the modeled mean concentration is within 15% of the observed mean concentration.

Figure 29 through Figure 54 compare the model results at five evaluation locations (four surface water corroborated locations and the one calibrated surface water location). In these figures, the color bars represent the range of model results from the 10th to 90th percentiles, with breaks at the 25th, 50th (median), and 75th percentiles. The observed concentrations are shown with gray X's and the mean observed concentration at each location is shown with a black circle. The figures do not differentiate between detected samples and non-detects. Some locations appear to have only few samples. This may be true in the case of MLC-2 which has much fewer samples than the other locations. However, this is more often caused by all or most of the samples being non-detects at the same detection limit (see beryllium in Figure 46 for example). It should be noted that sampling at MLC-2 began in 2011 and for many constituents, there are only two samples. Given the amount of available data at this location, care needs to be taken when evaluating model performance.

Model corroboration results for each solute are discussed below either individually for key solutes or solutes with unexpected results, or grouped for solutes with similar results.

2.2.1 Chloride

Chloride is a good tracer for Tailings Basin seepage as it is currently elevated in seepage from the basin relative to background and is generally considered conservative in that it doesn't readily react in natural environments. The model is providing a good match to observed concentrations at PM-13 and PM-11 and is over-predicting concentrations at PM-19 (45%) and MLC-2 (194%) (Figure 29 and Table 7). One possible explanation for these results is that the model may be assuming more Tailings Basin seepage reaches the tributaries upstream of evaluation locations PM-19 and MLC-2 that is actually occurring.

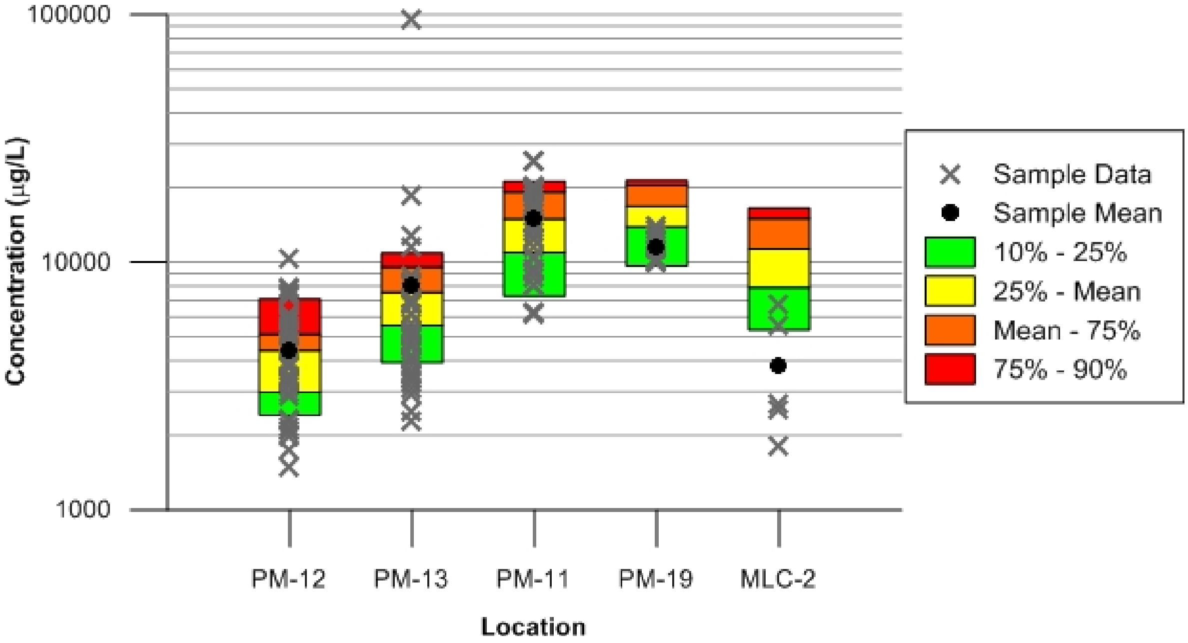

Figure 29 **Surface water model corroboration for Chloride**

2.2.2 Sulfate

The model is over-predicting sulfate concentrations downgradient of the Tailings Basin, particularly within the tributaries north of the basin (Figure 30). Data collected at several locations along Spring Mine Creek and the Embarrass River in 2010 and 2011 demonstrates significant sulfate reduction in these waters (see Section 4.4.4 of the Water Modeling Data Package – Volume 2 Plant Site, version 7). The average load increase calculated between PM-12.2 and PM-13 was less than 10 percent of the load leaving the Tailings Basin towards the Embarrass River under existing conditions. In comparison, the calculated load of chloride (a parameter which is a tracer for Tailings Basin seepage and is generally considered conservative) clearly increases in the downstream direction indicating that the Tailings Basin seepage is reaching the Embarrass River. The probabilistic model does not account for this reduction, which explains the model's over-prediction. This is most evident for the tributaries with significant wetland areas between the toe of the Tailings Basin and the headwaters (PM-19 and MLC-2).

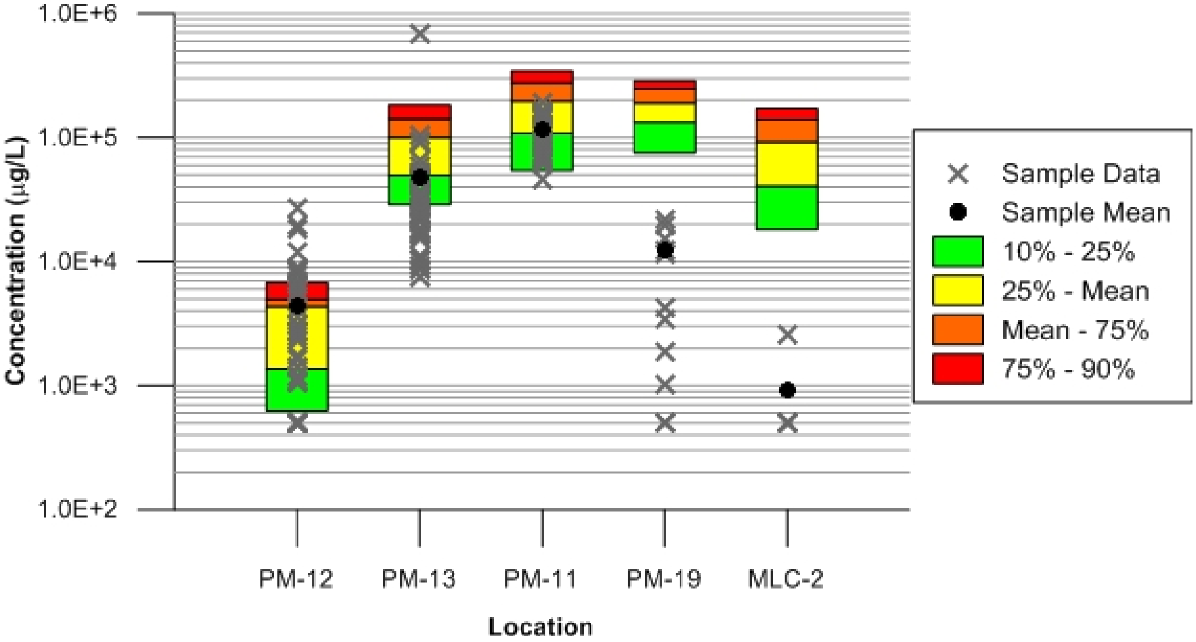

Figure 30 **Surface water model corroboration for Sulfate**

2.2.3 Aluminum, Iron and Manganese

Aluminum, iron and manganese are all redox sensitive. The model is matching observed aluminum concentrations at PM-12, but is under-predicting aluminum at PM-13and over-predicting in the tributaries (Figure 31). Aluminum concentrations measured at the toe of the Tailings Basin are lower than concentrations measured at PM-12. Thus, the increase in measured aluminum concentration between PM-12 and PM-13 is not caused by seepage from the Tailings Basin.

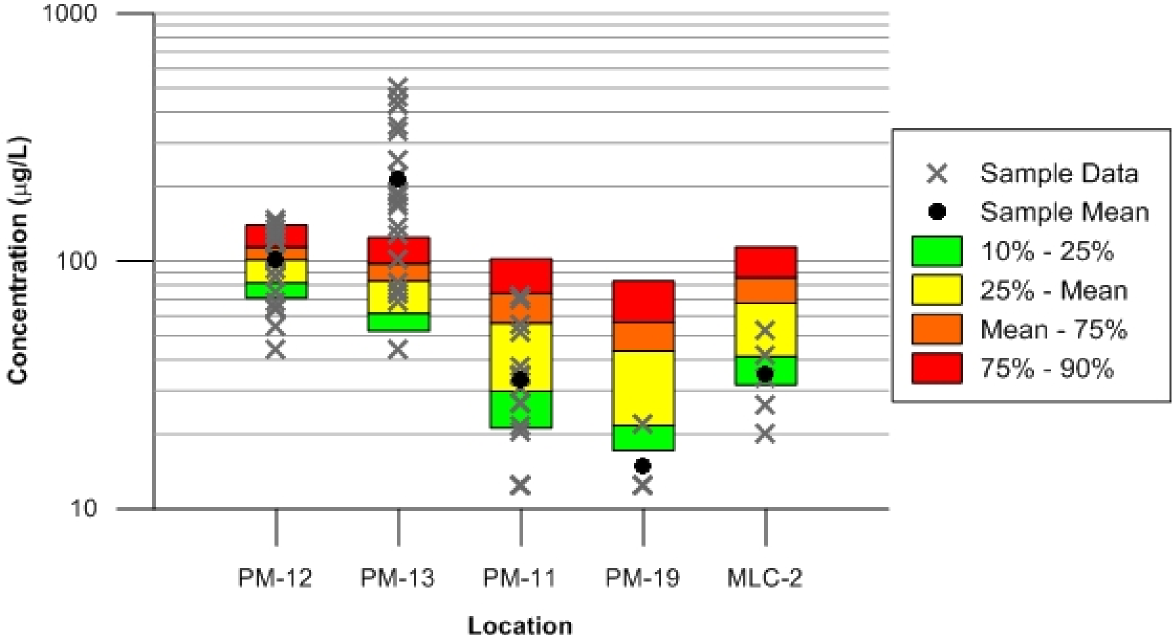

Figure 31 Surface water model corroboration for Aluminum

The model is over-predicting concentrations of iron and manganese in the tributaries and at PM-13, with the exception of iron at MLC-2 and a slight under-prediction (9%) of manganese at PM-19.

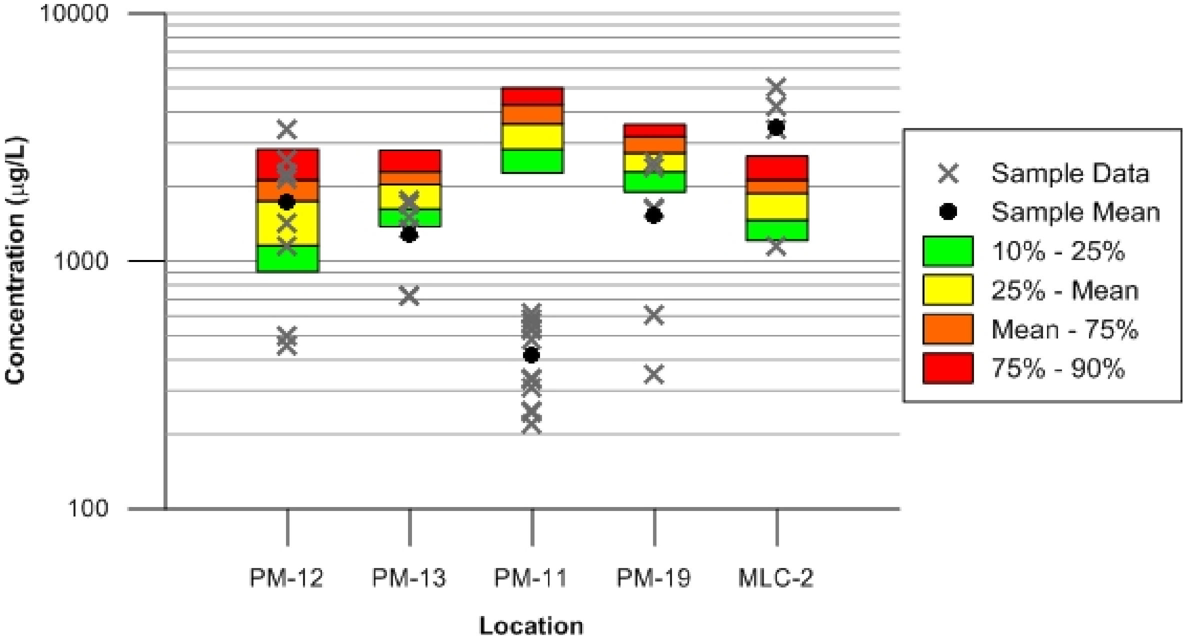

Figure 32 Surface water model corroboration for Iron

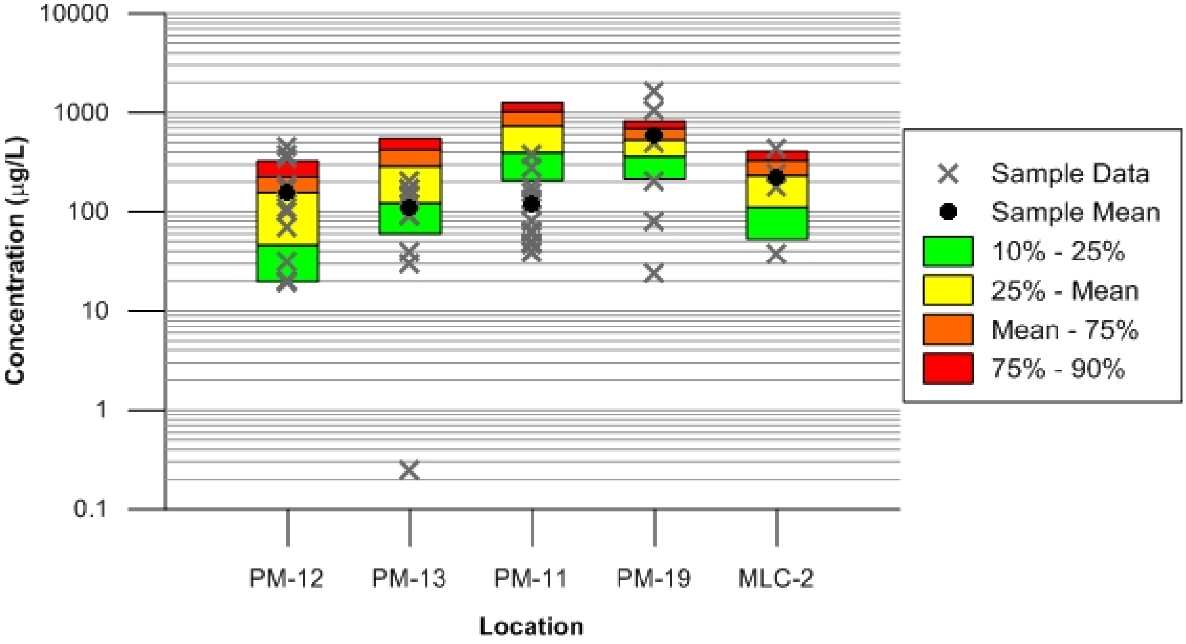

Figure 33 Surface water model corroboration for Manganese

2.2.4 Cobalt, Copper, Nickel and Lead

Cobalt (Figure 34), copper (Figure 35), nickel (Figure 36) and lead (Figure 37) are all being significantly over-predicted in the tributaries, and slightly over-predicted at PM-13. For each of these solutes, concentrations at the toe of the tailings basin were well calibrated (average of less than 60%, see Table 6). It appears that there may be a reduction of concentrations for these constituents in the existing system which is not captured in the model (sorption or co-precipitation with iron oxides). For these solutes, the concentrations measured in the tributaries at PM-11, PM-19 and MLC-2 are less than upgradient concentrations in the Embarrass River (PM-12), despite the elevated (relative to PM-12) concentrations observed at the toe of the Tailings Basin (Figure 6).

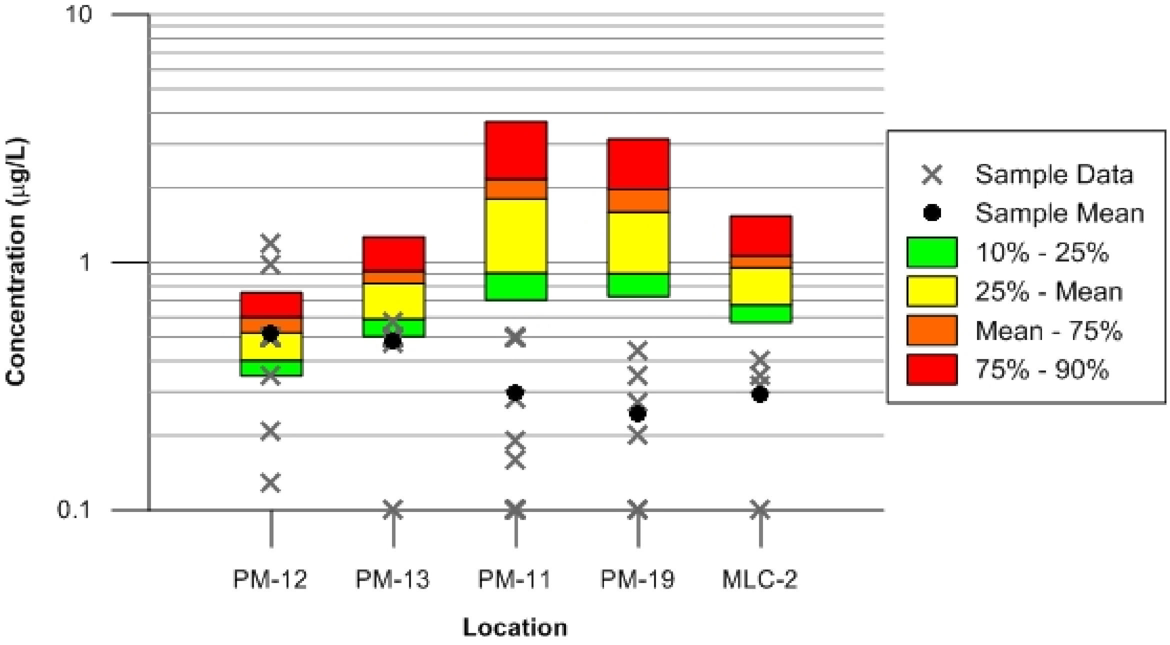

Figure 34 Surface water model corroboration for Cobalt

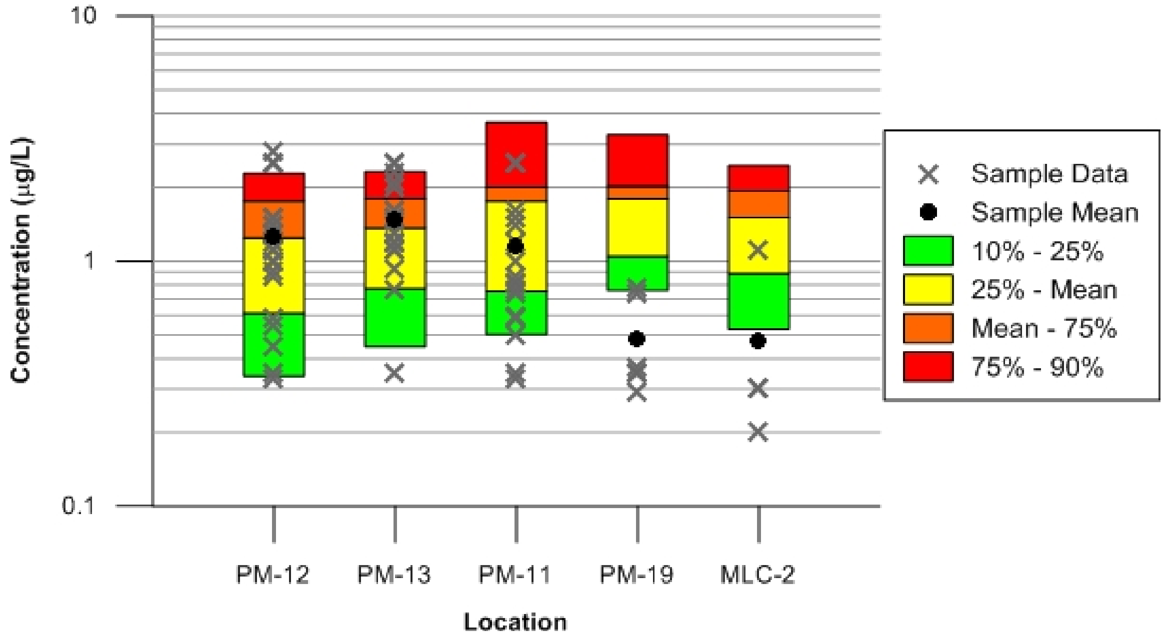

Figure 35 Surface water model corroboration for Copper

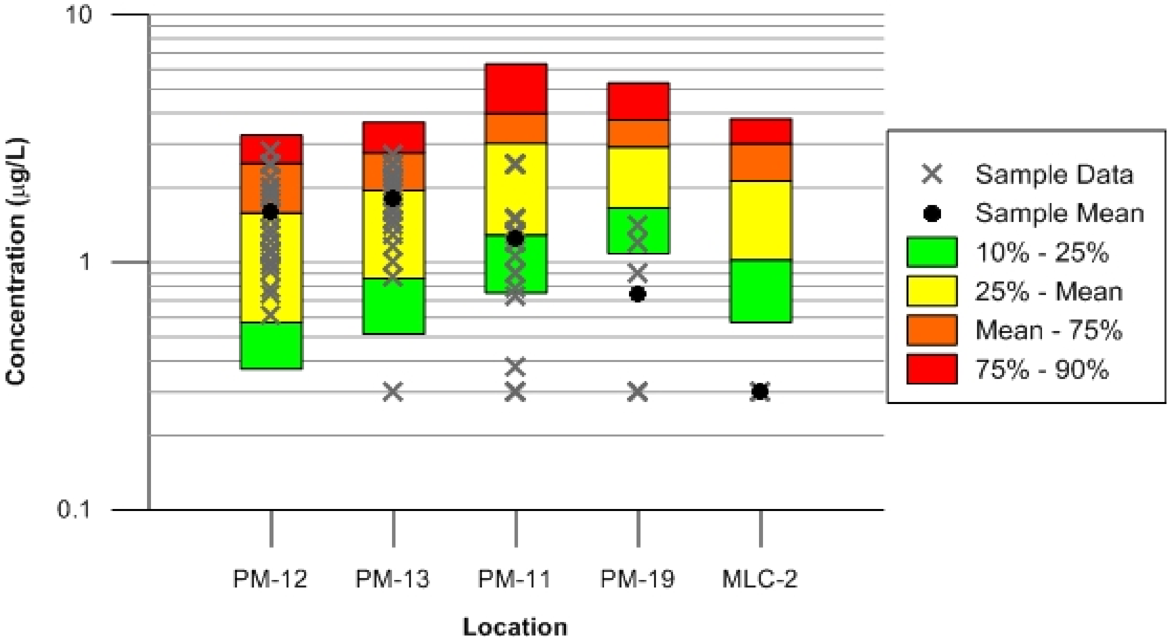

Figure 36 Surface water model corroboration for Nickel

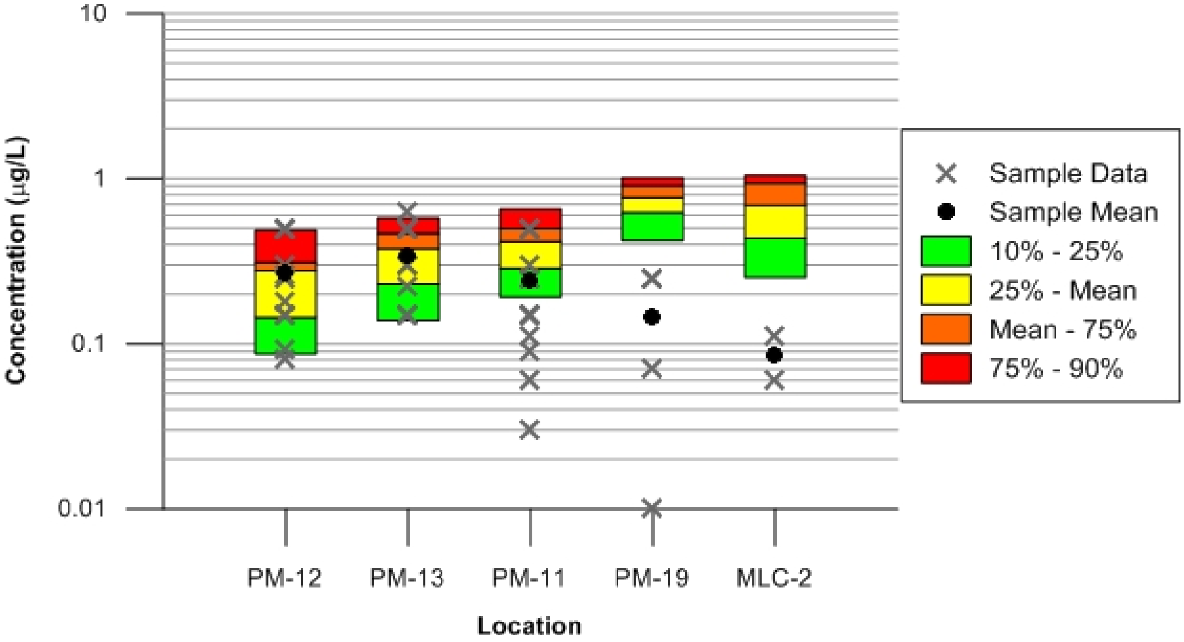

Figure 37 **Surface water model corroboration for Lead**

2.2.5 Constituents with Loading from LTVSMC Tailings not Calibrated

Loading of alkalinity, barium and fluoride from the existing LTVSMC tailings were not calibrated (see discussion in Section 1.6.3). Alkalinity is the only solute that is under-predicted on average (Table 7; see Section 2.2.7 for a discussion of antimony). This under-prediction is most likely caused by an under-prediction of loading from the existing Tailings Basin, as is shown in Figure 26; alkalinity within the tailings basin seepage is a function of pCO_2 which is not explicitly model. Barium and fluoride are being over-predicted by the model (Figure 39 and Figure 40 respectively).

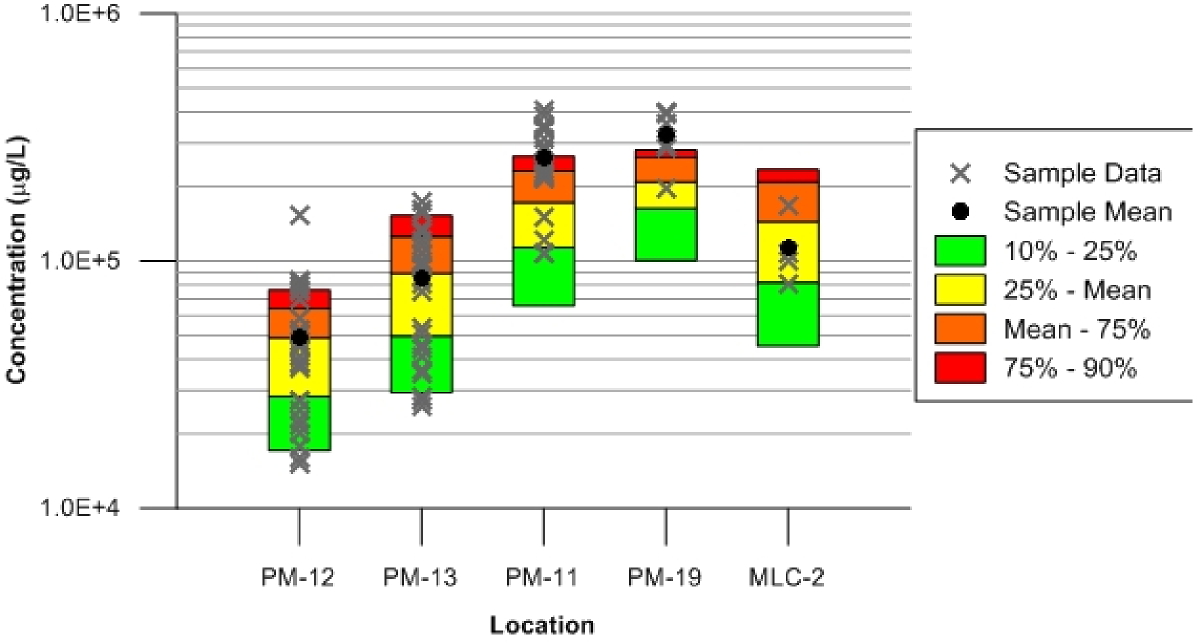

Figure 38 Surface water model corroboration for Alkalinity

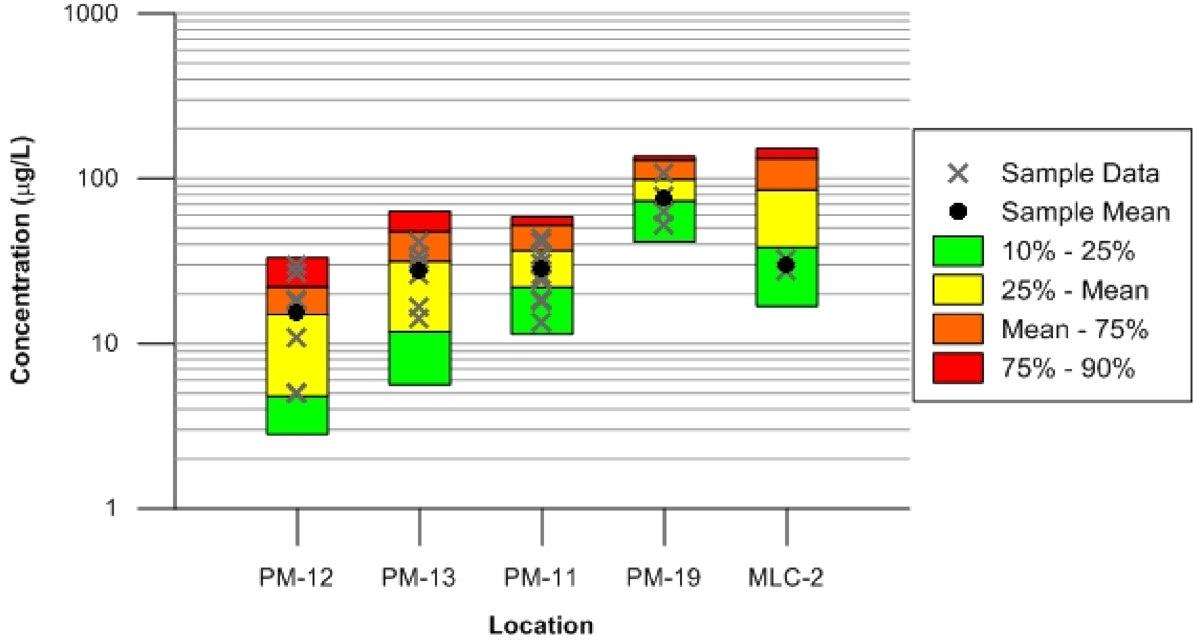

Figure 39 Surface water model corroboration for Barium

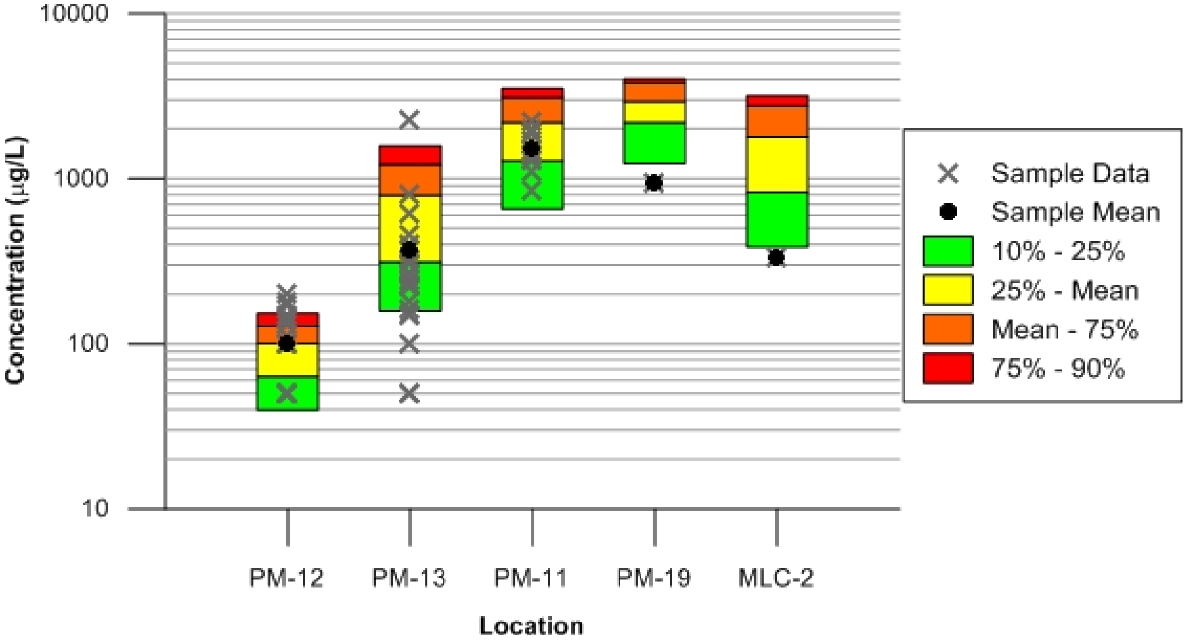

Figure 40 Surface water model corroboration for Fluoride

2.2.6 Major Cations

In general, the model is matching the observed mean concentrations for the major cations including calcium (Figure 41), potassium (Figure 42), magnesium (Figure 43) and sodium (Figure 44). The model is matching the general trend of the data (concentrations higher in PM-11 than PM-13 for example) and is over-predicting measured concentrations, with the exception of sodium which the model is under-predicting at PM-11.

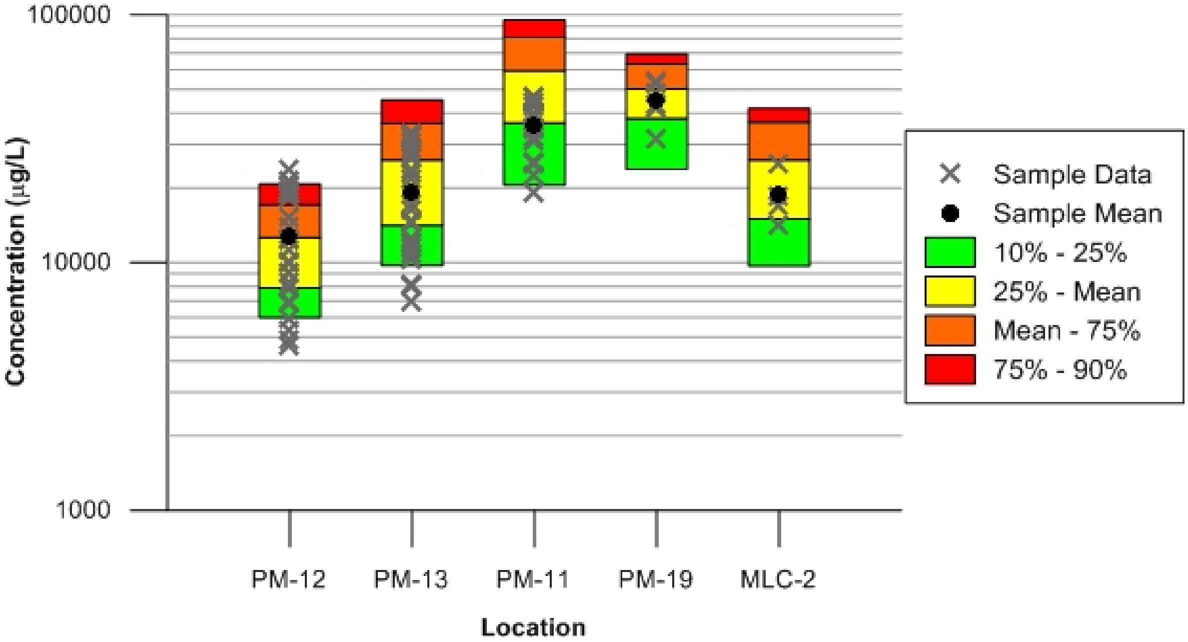

Figure 41 Surface water model corroboration for Calcium

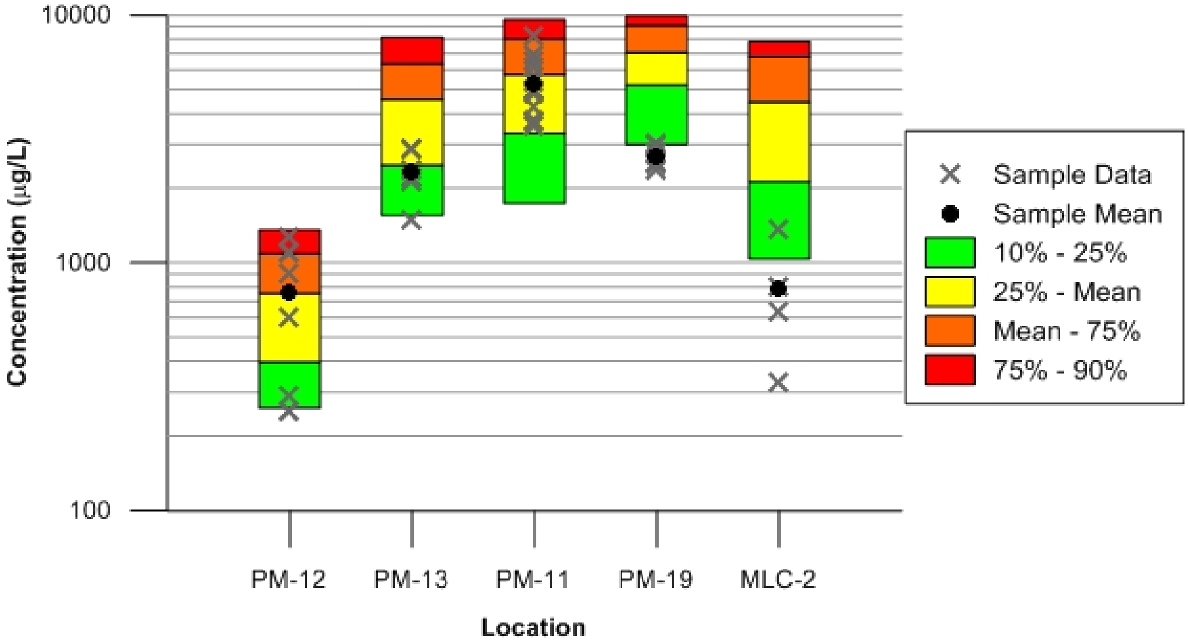

Figure 42 Surface water model corroboration for Potassium

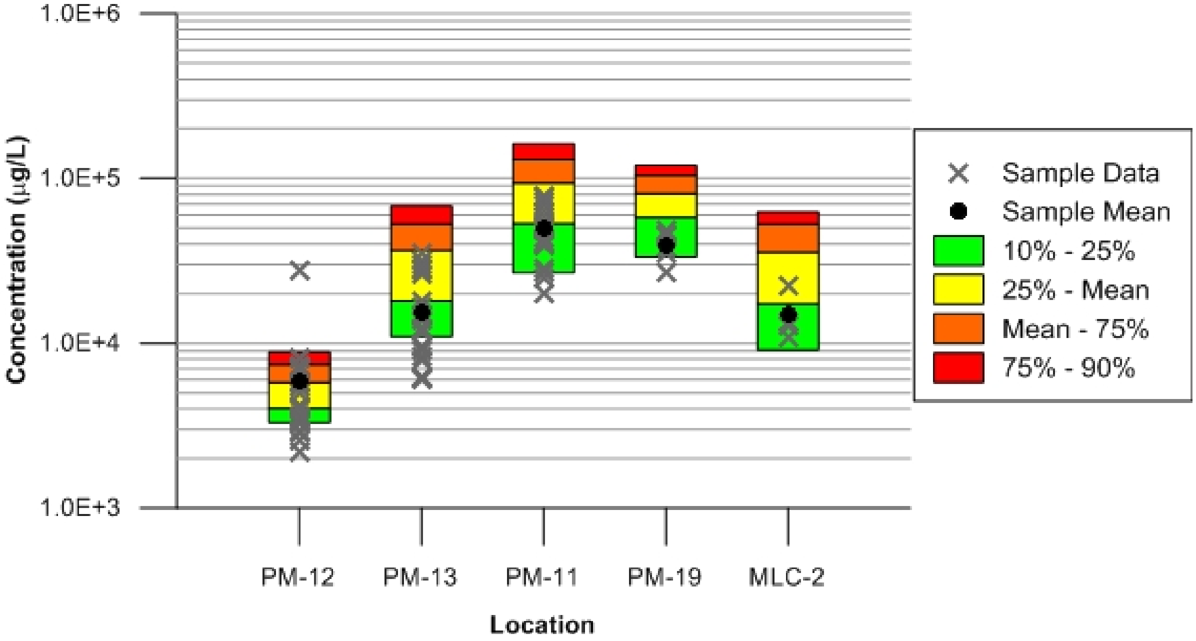

Figure 43 Surface water model corroboration for Magnesium

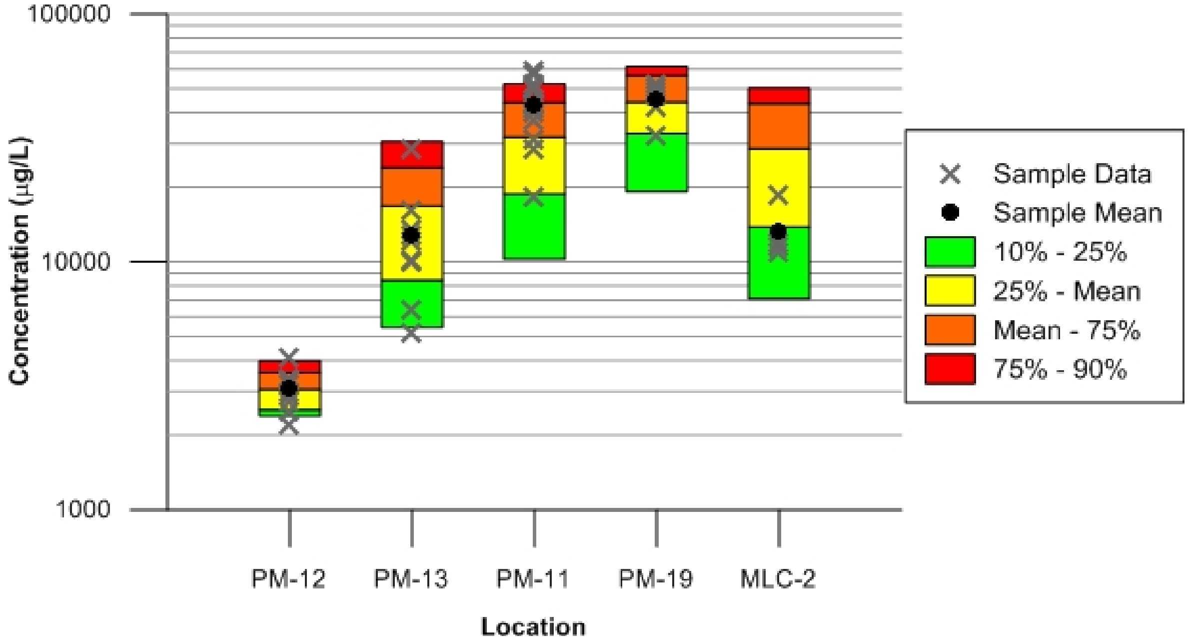

Figure 44 Surface water model corroboration for Sodium

2.2.7 Solutes Dominated by Non-detects

For several solutes, the monitoring data is dominated by non-detects, which makes model corroboration difficult. This includes silver (Figure 45), beryllium (Figure 46), antimony (Figure 47), and thallium (Figure 48). In general, the model is matching the mean observed concentrations for these solutes (Table 7), although thallium concentrations are slightly over-predicted, particularly at MLC-2. It appears that antimony is under-predicted at PM-13. However, all monitoring data at this location were non-detects with a much higher detection limit that at other locations (3ug/L as opposed to 0.5 ug/L).

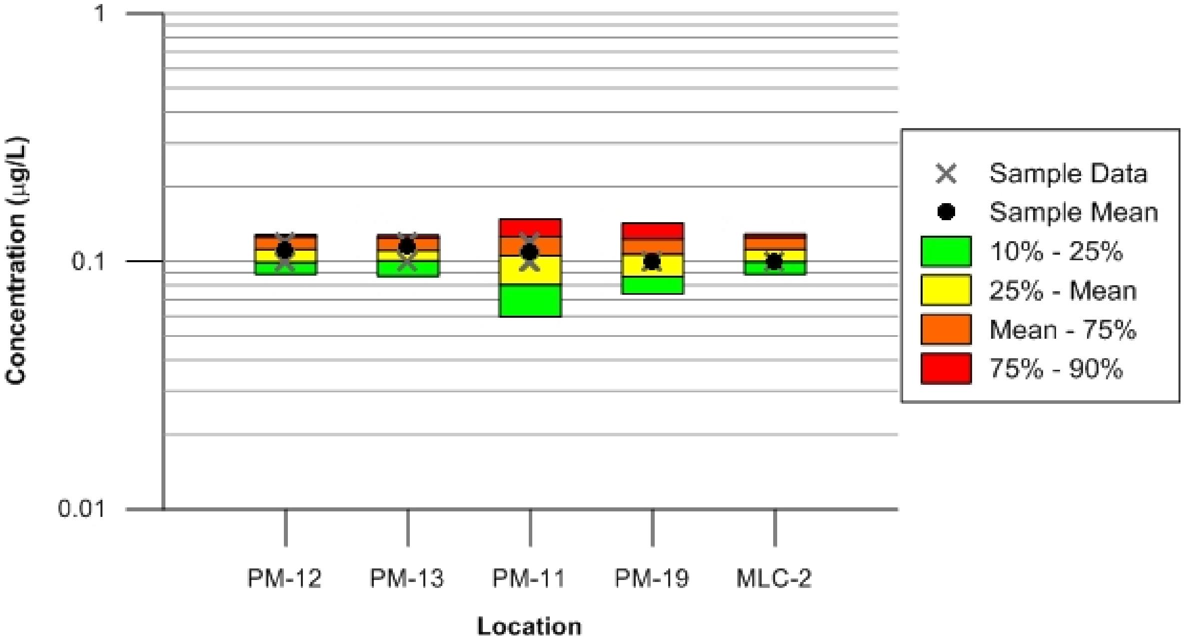

Figure 45 Surface water model corroboration for Silver

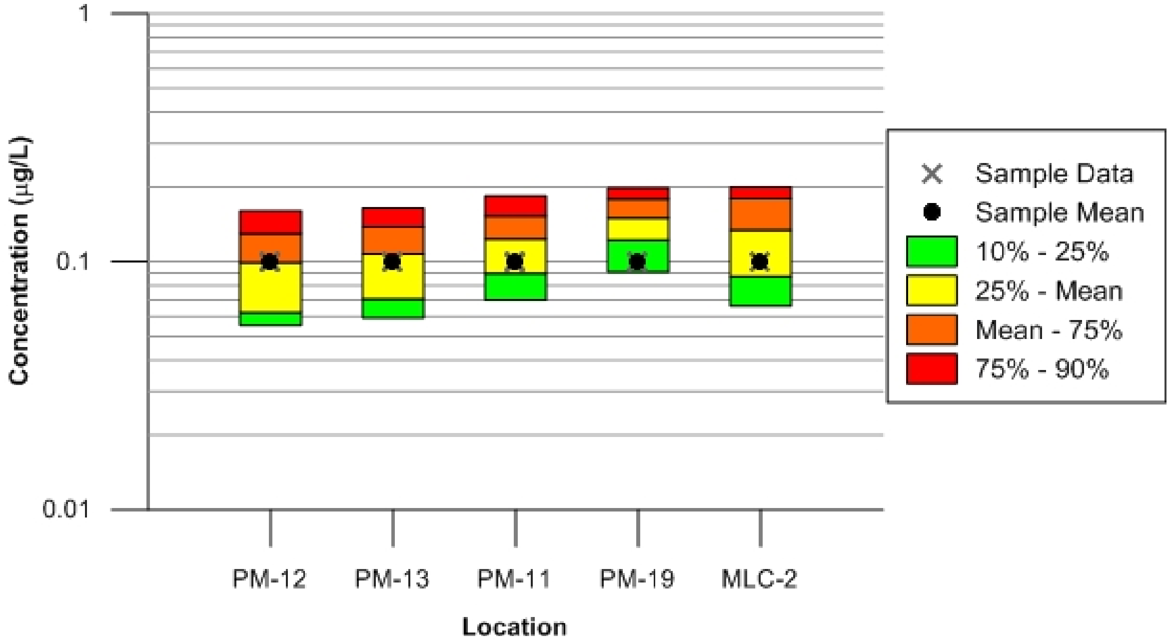

Figure 46 Surface water model corroboration for Beryllium

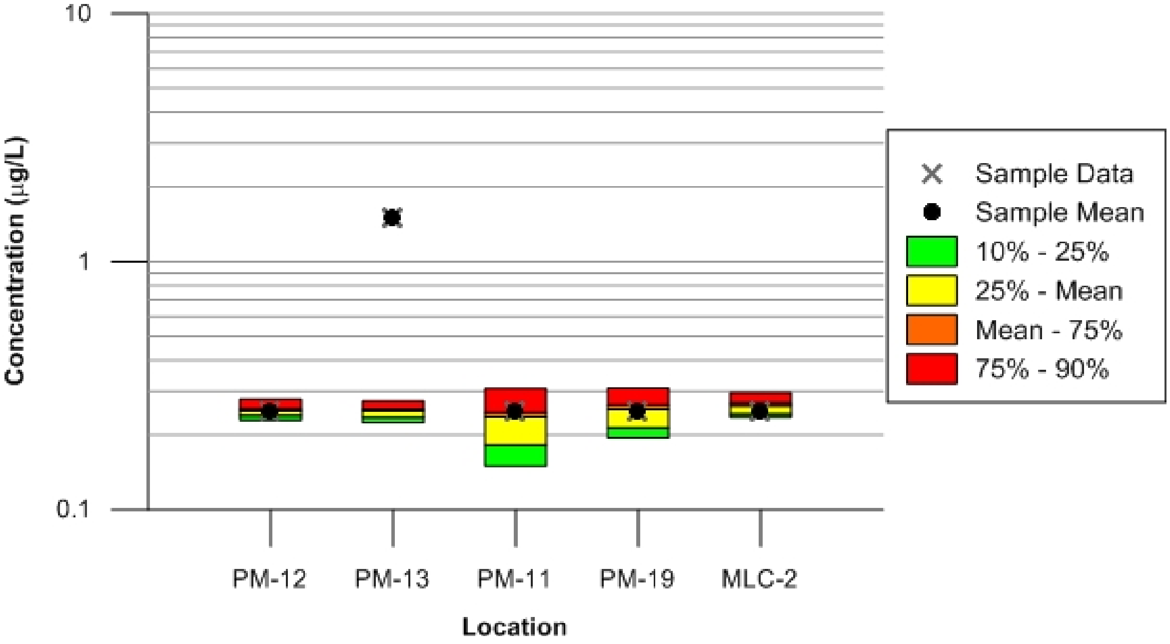

Figure 47 Surface water model corroboration for Antimony

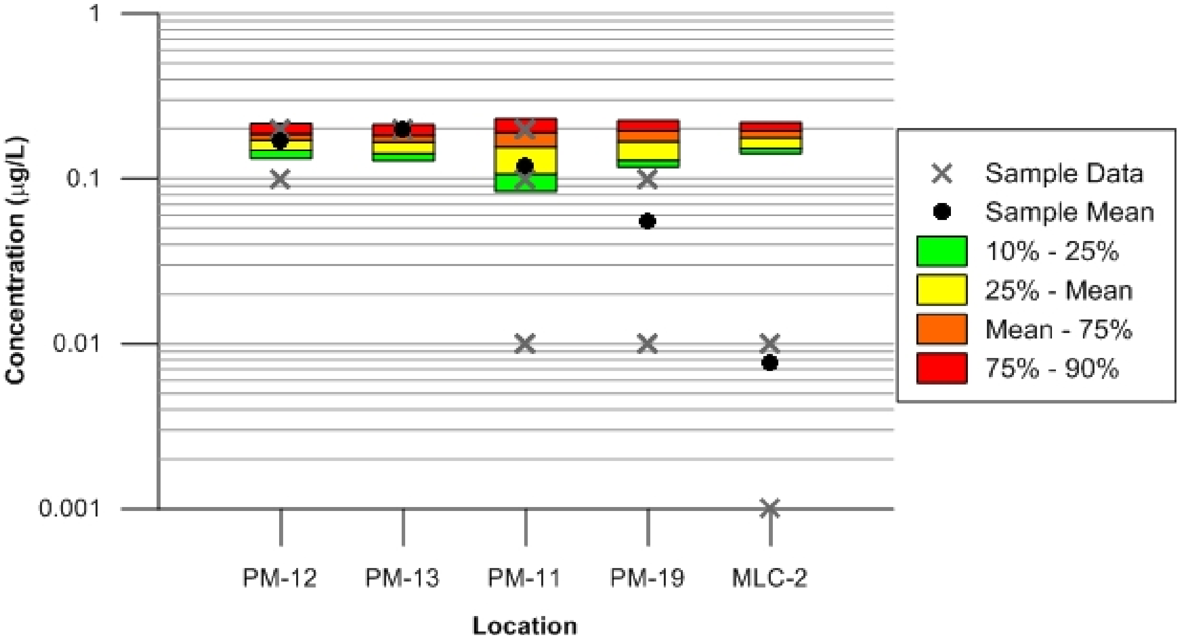

Figure 48 Surface water model corroboration for Thallium

2.2.8 Other Constituents

Model corroboration results for the remaining constituents are shown below in Figure 49 through Figure 54.

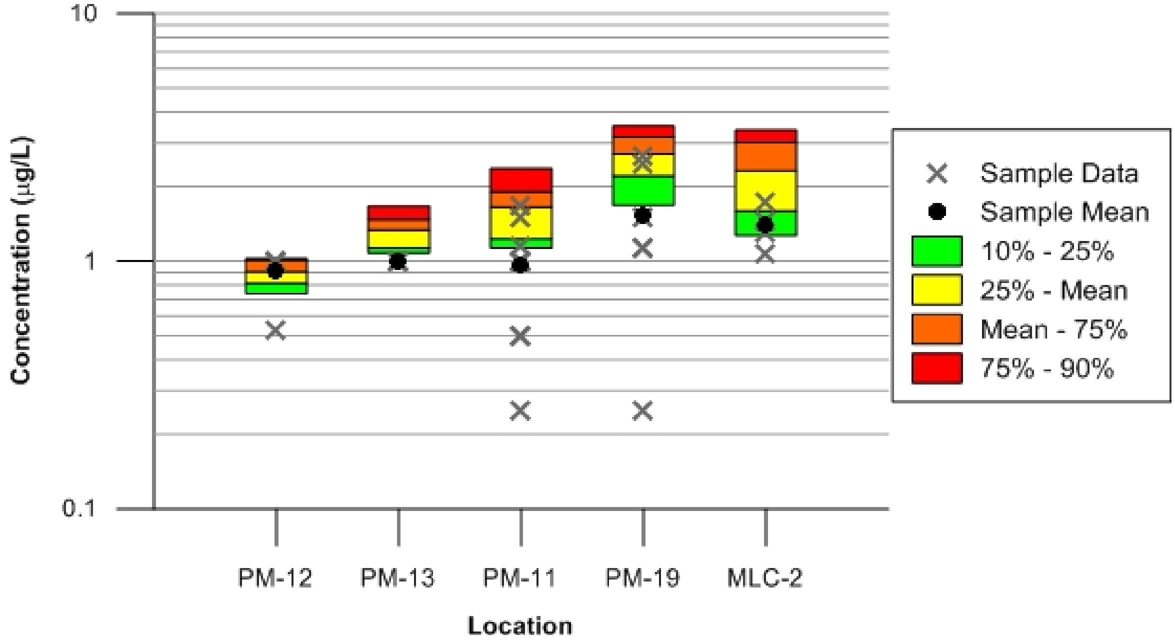

Figure 49 Surface water model corroboration for Arsenic

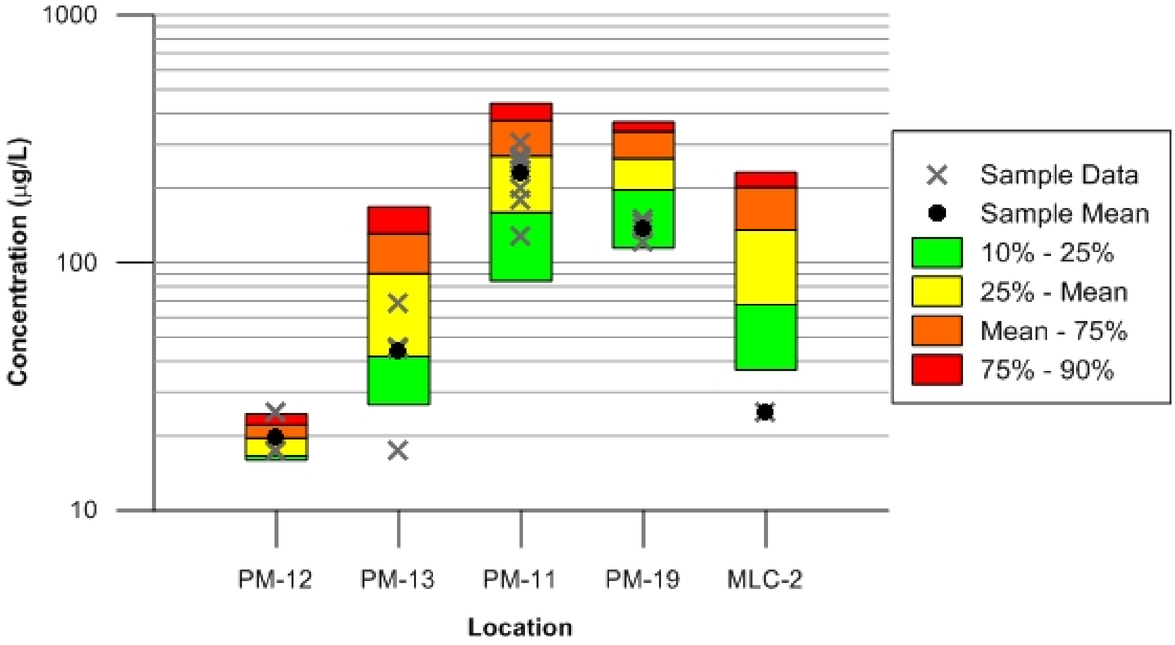

Figure 50 Surface water model corroboration for Boron

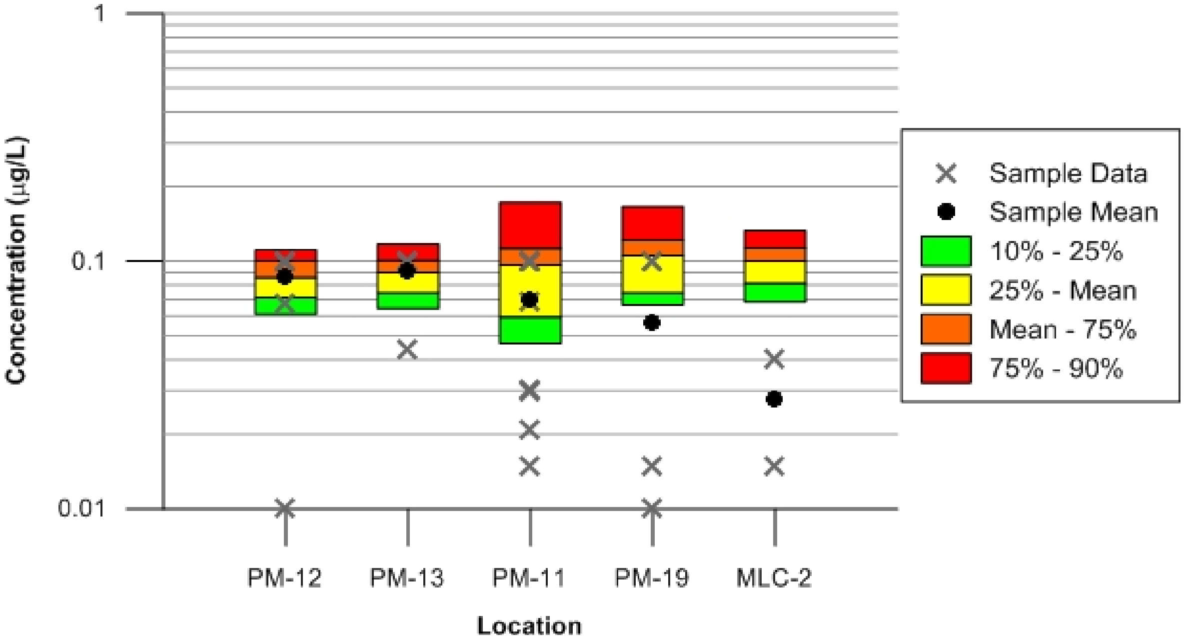

Figure 51 Surface water model corroboration for Cadmium

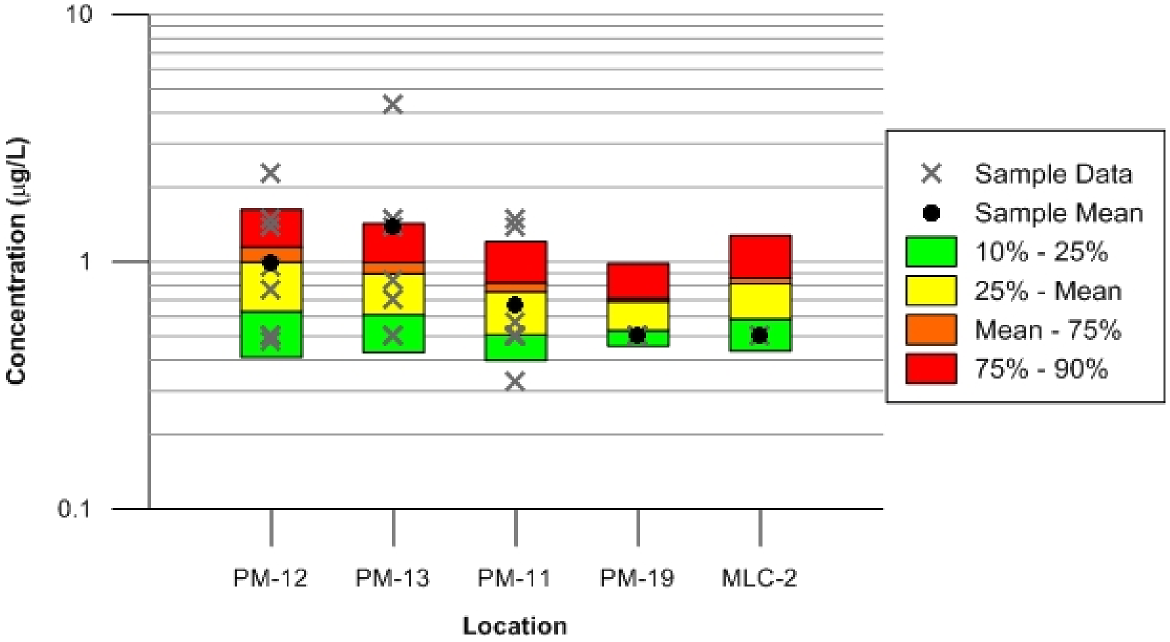

Figure 52 Surface water model corroboration for Chromium

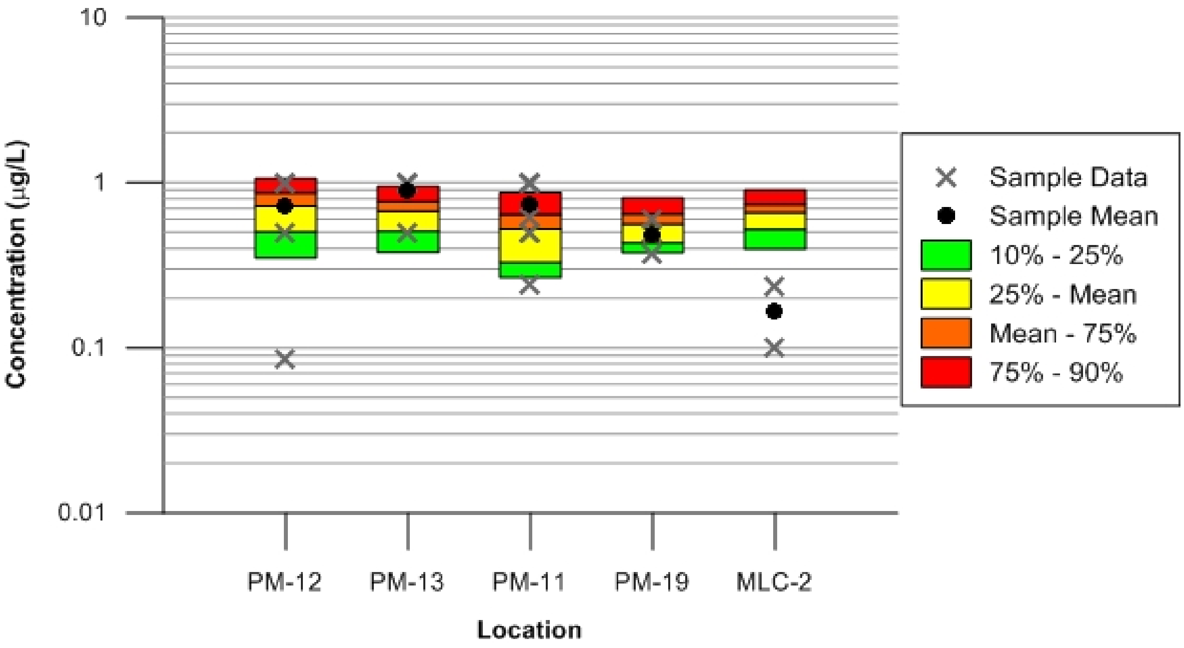

Figure 53 Surface water model corroboration for Selenium

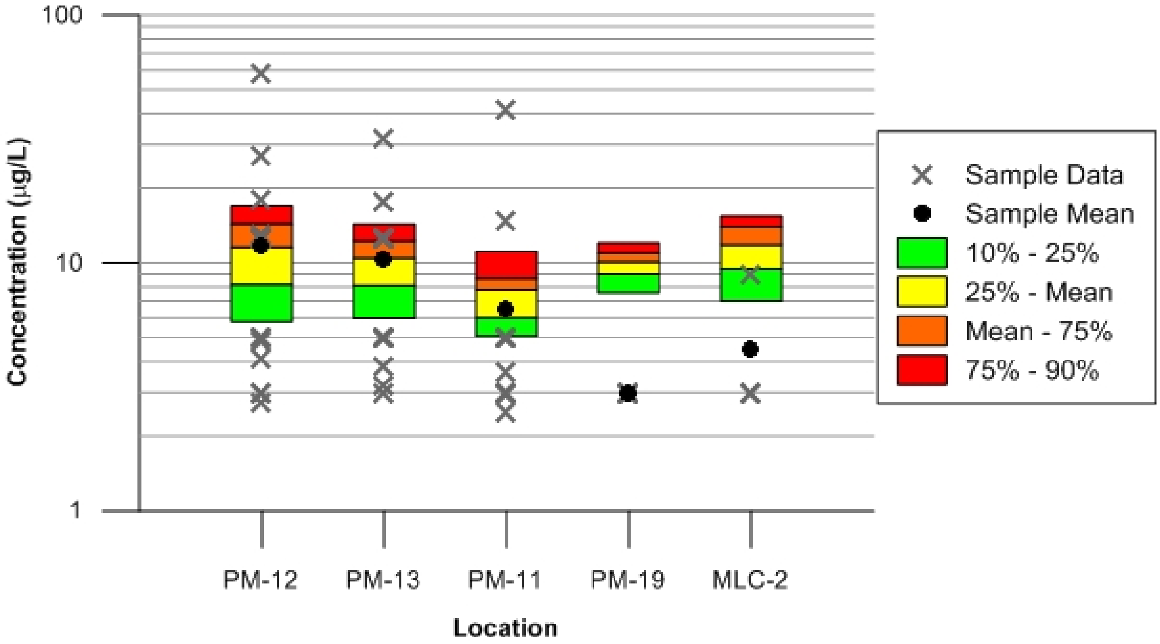

Figure 54 Surface water model corroboration for Zinc

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