TECHNICAL MEMORANDUM

DATE May 15, 2020 **Project No.** 20143789

TO Josip Deronja, Senior Project Manager
Colliers Project Leaders

CC Project File

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SUPPLEMENTARY LAKE GERALDINE WATER BALANCE MODELLING

1.0 INTRODUCTION

This technical memorandum has been prepared by Golder Associates Limited (Golder) for Colliers Project Leaders (Colliers) on behalf of the City of Iqaluit (the City) to provide additional water supply forecasting estimates to an earlier water balance report prepared by Golder in 2013, and updated estimates provided during the 2018 and 2019 ice-free seasons. In order to minimise the risk of misinterpretation, the information presented in this technical memorandum should be read and interpreted in conjunction with Golder (2013), Golder (2018a/b/c) and Golder (2019).

1.1 Background

The City of Iqaluit depends on the Lake Geraldine reservoir for its year-round municipal water supply. Given that the reservoir is frozen over for approximately eight months of the year, raw water supplies at the end of summer need to be sufficient to service the City over the following winter until snowmelt runoff replenishes the reservoir during the next spring melt period.

The City has commissioned a number of studies in recent years which suggest that the existing reservoir will not be able to supply sufficient water over the long term to meet growing demands. A number of supplementary water supply alternatives were investigated by Trow in 2004 leading to recommendations to (i) increase the storage capacity of the reservoir and (ii) identify a suitable supplementation source that may be used to augment water supplies during the ice-free period on a needs-must basis.

The height of the Lake Geraldine reservoir was subsequently increased by two meters in 2006, however, it is understood that regulatory limits for water takings from the nearby Apex River have prevented the implementation of a suitable water supply supplementation system at this time. Based on recent communications with Colliers (2020), it is Golder’s understanding that the City of Iqaluit requires completion of an updated water balance for the 2020 period to support the conditional permit for the Nunavut Water Board in order to initiate supplementation activities during the 2020 ice free period.

1.2 Objectives

The purpose of this technical memorandum is to provide additional water supply forecasting estimates that may be used by the City of Iqaluit to identify a suitable water supply solution during the 2020 ice-free period and fulfil the requirements associated with Part D, Item 11 of License No. 3AM-IQA1626 Amendment 4. To this end, the City has specifically requested that Golder address the study objectives by determining:

1) The accuracy of the existing model via completion of a validation exercise focused on comparing modelled water levels at Lake Geraldine against a subset of measured water levels collected over a fifteen-month period, noting that missing meteorological records exist at various times throughout this period;

2) The amount of precipitation and meteorological surplus that can be expected during the remaining ice-cover period of 2019/2020 and ice-free period of 2020 and to what elevation this would fill the reservoir at various consumption rates identified later in this document;

3) The predicted Lake Geraldine water storage deficit at the end of 2020 ice-free season, at various consumption rates identified later in this document;

4) The amount of precipitation and meteorological surplus that would be required to replenish the reservoir from 110.56 masl (recorded on January 6, 2020) to as close as possible to its design level of 111.3 masl at the end of 2020 ice-free season, at various consumption rates identified later in this document; and,

5) Minimum, average and maximum daily evaporative losses from Lake Geraldine by month as a function of reservoir level.

In addressing these uncertainties, it is noted that the limiting effects of evapotranspiration and soil and depression storage mean that only a portion of precipitation within the Lake Geraldine catchment (referred to as meteorological surplus) will translate into recharge of the reservoir. For ease of interpretation, this technical memorandum thus presents corresponding estimates for both precipitation and surplus.

2.0 METHODOLOGY

The methods employed for this investigation are generally consistent with, and limited by previous assumptions incorporated into, the approach documented in Golder (2013), Golder (2018a/b/c) and Golder (2019). A brief summary of the 2020 approach, and a detailed inventory of any modifications to this approach, is provided below for context.

2.1 Consistencies with the 2018 and 2019 Modelling Approach

As noted previously, the methods employed for this investigation are largely premised on, and consistent with, the model setup developed in 2013 and the approach and results reported in 2018 and 2019. Specifically, consistencies with the previous approach include:

2.1.1 Catchment and Basin Physiography

The physiographic representation of the contributing catchment and reservoir basin within the model have remained unchanged since 2013. Specifically, this maintains consistency with the approach used to characterise the surficial geology, topography and size of the drainage catchment as well as Lake Geraldine's bathymetry and stage-storage relationship.

It should be noted that communications with Nunami Stantec (June 2, 2019) suggest that relative to the digital elevation model representation derived using survey data received from Natural Resources Canada (2008), Lake's Geraldine's active stage-storage capacity may have been reduced by up to 195,000 m^3 (from 1,875,000 m^3 estimated by Golder to 1,680,000 m^3 estimated by Nunami Stantec). Formal validation of this change in physiography has not been presented at the time of reporting.

If the revised stage-storage curve (Nunami Stantec 2019) is indeed validated, the implications of the potentially reduced storage capacity on reservoir supplies and supplementation requirements are numerous and complex, but can be conceptually summarised as follows:

- A higher proportion of catchment snowmelt and rainfall runoff generated early in the open-water season may be lost to reservoir overflows during the early summer than simulated within the existing Lake Geraldine model;
- The supplementation volumes required to fill the reservoir prior to freeze-up could be lower for some meteorological conditions than presented in this technical memorandum;
- The volumetric consequences of over-winter ice storage may be a greater risk to over-winter water supplies than presented in this technical memorandum; and,
- The risk of exhausting water supplies prior to freshet is likely to be greater than considered in this technical memorandum.

Notwithstanding these differences, it is recommended that the City of Iqaluit use the higher end of water supply deficit values provided throughout this document as guidance for supplementation planning rather than risk an underestimate of supplementation volumes that could result in insufficient overwinter supplies.

2.1.2 Water Level Control and Intake Infrastructure

All basin inputs generated by measured meteorological inputs and water supplies accumulated within the reservoir are constrained by the same spillway and intake configuration developed in the 2013 model.

As such, any inputs beyond the reservoir's active 1,875,526 m^3 storage capacity are assumed to be lost from the system. Similarly, any water below the assumed intake invert of 101.6 masl is assumed to be inaccessible for municipal use. It should be noted, that according to communications from Nunami Stantec *(June 2, 2019)*, the reservoir morphology defined from data collected by Natural Resources Canada (2008) may be outdated, although this is subject to formal validation.

2.1.3 Ice Storage

All ice formed within the reservoir is assumed to be inaccessible, and commensurately diminishes available water supplies, until the following spring freshet when it becomes available at a rate determined by meteorology and simplified model assumptions.

2.1.4 Water Balance Formulation

The calculation of basin yields and reservoir supplies is identical to that detailed in Golder (2018a/b/c) and Golder (2013).

Catchment yield, or surplus, is calculated as follows:

(Rainfall + Snowmelt) - (Evapotranspiration + Sublimation) – Change in Available Soil Storage = Surplus (Runoff)

2.1.5 Water Consumption and Intake Withdrawal Rates

The water balance investigation presented herein instead considers three different consumption rates as used in Golder (2018a/b/c) for specific examination, including:

- No Water Consumption Scenario - 0 m^3/day;
- 100,000 m^3/month Water Consumption Scenario - 3,335 m^3/day; and,
- 115,000 m^3/month Water Consumption Scenario - 3,850 m^3/day.

2.1.6 Historical Meteorology

The same historical meteorological dataset used in Golder (2018a/b/c and 2019), featuring precipitation, air temperature, wind speed and relative humidity records for the 2008 through 2017 period, was applied to this study. As a reminder of the 2018a/b/c and 2019 approach, historical meteorological records were predominantly obtained for Iqaluit Climate (Station ID: 2402592) and supplemented with data from the four overlapping years (2008 through 2011) of data recorded at Iqaluit A (Station ID: 2402590). A few minor remaining data gaps of a few days or less were identified for wind speed and relative humidity (both used in the determination of potential evapotranspiration estimates) as well as precipitation and air temperature. To develop a complete meteorological record for the water balance model, these data gaps were filled using linear interpolation.

2.2 Updates to the 2020 Modelling Approach

The following subsection documents changes made to the 2018 and 2019 water balance model in order to accommodate the particulars of the 2020 scope of work.

2.2.1 Reintegration of Snowmelt Model

Given that the 2020 Lake Geraldine model had to consider the beneficial effects of snowmelt replenishment, the snowmelt function was reintegrated into the model used for the 2018 and 2019 studies.

2.2.2 Incorporation of 2019/2020 Overwinter Meteorology

Meteorological data for the 2019/2020 winter period between November 1, 2019 and January 6, 2020 were obtained from the Environment Canada climate station at Iqaluit Climate (Station ID: 2402592) for the purposes of air temperature, pressure, snowfall, wind speed and several other parameters. Meanwhile, the sky clearness co-efficient (required as one of the inputs to determine PET) was estimated from weather observation data collected for the Environment Climate station at Iqaluit A (Station ID: 2402590).

2.2.3 Validation Period

For the purposes of model validation, meteorological and water level data for the period October 6, 2018 through January 6, 2020 was sourced from the Iqaluit Climate station (Station ID: 2402592) – and linearly interpolated to fill data gaps – and water level data from the Real-Time Hydrometric Portal, Station 10UH013 (ECCC 2020).

2.2.4 Water Level, Snowpack and Ice Cover Initial Condition

In keeping with the Golder (2018a/b/c and 2019) approach, a water level condition (110.56 masl) recorded at Lake Geraldine Near Iqaluit (10UH013) on January 6, 2020 was used to initialise the model. It is noted that model catchment snow cover and reservoir ice cover up to January 6, 2020 were calculated from available meteorological data and assumed to be assimilated into the reservoir following the melt date along with the accumulated snowfall from January 6 for each of the historic years (2008 through 2017). Such snowfall accumulations and ice thickness were implemented in the predictive model as initial conditions.

3.0 ASSUMPTIONS AND LIMITATIONS

The analyses, results and discussion included in this technical memorandum are presented in good faith and limited by a number of assumptions, including:

- Assumptions and Limitations presented in Golder 2013, Golder 2018a/b/c, Golder 2019 and the covering proposal entitled Proposal for Lake Geraldine Water Balance Assessment submitted to the Colliers Project Leaders by Golder Associates Ltd. on April 17, 2020 at 5:46 pm;
- Recent communications from Nunami Stantec (June 2, 2019) suggest that Lake's Geraldine's active storage capacity may have been reduced relative to the digital elevation model representation derived from Natural Resources Canada (2008), however, formal validation of this change in physiography could not be confirmed at the time of reporting. If the Nunami Stantec storage estimate is confirmed as valid, available water supplies as well as storage deficits could be lower than reported in this document;
- Accumulated snow and ice cover up to and including January 6, 2020 are simulated from historic precipitation data between October 6, 2018 and January 6, 2020. Supplemental snow and ice accumulation up to the thaw date for each historic (2008 through 2017) meteorological year are subsequently simulated independently for each historic year based on the snowfall and air temperature data for each of these years to derive ten individual snow- and ice-melt accumulations within the Lake Geraldine reservoir. Rainfall surplus volumes accumulated within the Lake Geraldine Reservoir are subsequently simulated for each of these historic (2008 through 2017) precipitation records up to the freeze-up date for each year;
- The timing of water levels during, and immediately following, snowmelt and ice melt may be temporarily inaccurate because the model configuration only allows for simplified determinations of snowmelt and ice melt relative to observed conditions;
- For the purposes of simulating evapotranspiration losses from Lake Geraldine's water surface, the model assumes a surface area equivalent to the maximum design elevation of the reservoir. This is conservative because evapotranspiration losses will typically be lower given the reduced surface area of the reservoir at lower elevations;
- The predicted water supply deficit is estimated as the difference between the maximum capacity of Lake Geraldine at the spillway elevation and the available volume of water at the predicted freeze-up date of each simulation year;
- The available reservoir volume is independent of the effects of consumption losses prior to January 6, 2020 and is initialised based on the water level measured on January 6, 2020;

- Estimates of necessary precipitation and meteorological surpluses to fill the reservoir are represented as percentage increases of rainfall during historically recorded rainfall days; accordingly, no increase in the number of rainfall days has been allowed for in the modelling. Owing to the distribution of historic rainfall over the ice-free period, this artefact could lead to unrealistically high additional precipitation requirements to fill the reservoir;
- The probability distributions of historic meteorological conditions are calculated as independent variables as later explained in Section 6; and,
- Freeze up is identified as the earliest day, following the summer season, when the preceding 14-day average is lower than -1°C, in order to prevent false identification of the freeze-up day, a secondary condition is imposed, requiring that the maximum temperature in the period corresponding with 14 to 28 days prior to the freeze-up date, to be larger than 2°C.

4.0 MODEL VALIDATION

The GoldSim model was validated against measured water levels in Lake Geraldine from October 6, 2018 (the approximate beginning of the 2018 freeze-up period) to January 6, 2020 (the model initialisation date for this year's water balance study).

Model performance was evaluated by visually comparing model predicted water levels against observed water levels (when available) for qualitative evaluation of modelled water level responsiveness and using Root Mean Squared Error (i.e. the magnitude of standardised error over the period examined). The validation process is beneficial as it provides a reasonable indication of confidence in predictions as well as identifying periods when model accuracy demonstrates increased or decreased performance.

Visual comparison of modelled and measured water levels suggests the model provides reasonable replication of responsiveness to the underlying mechanics of consumption, rainfall and evapotranspiration. Model RMSE over the period of comparison, October 6, 2018 to January 6, 2020, is 18 cm, which corresponds to a volume of between 9,900 m^3 at the intake invert (101.6 masl) and 55,500 m^3 at full board (111.33 masl). The difference between modelled and measured water level on the last day of simulation, January 6, 2020, is 10 cm, which corresponds to a 30,800 m^3 underestimate in water supply during the approximate middle of winter. Comparison of modelled and measured water levels on the day of first thaw (May 18, 2019) shows a 10 cm discrepancy which represents a 27,300 m^3 overestimate of water supplies. The predicted water level at freeze-up (November 1, 2019) is 8 cm lower than the measured water level which corresponds to a water supply of 27,700 m^3

It should be noted that the validation exercise was complicated through substantial amounts of missing precipitation data as shown on Figure 1 which were supplemented through linear interpolation leading to uncertainty and the possibility of underestimated or overestimated rainfall and snowfall. Commentary regarding period performance (between each vertical line enumerated below) as well as likely reasons for discrepancies between modelled and measured water levels are provided below.

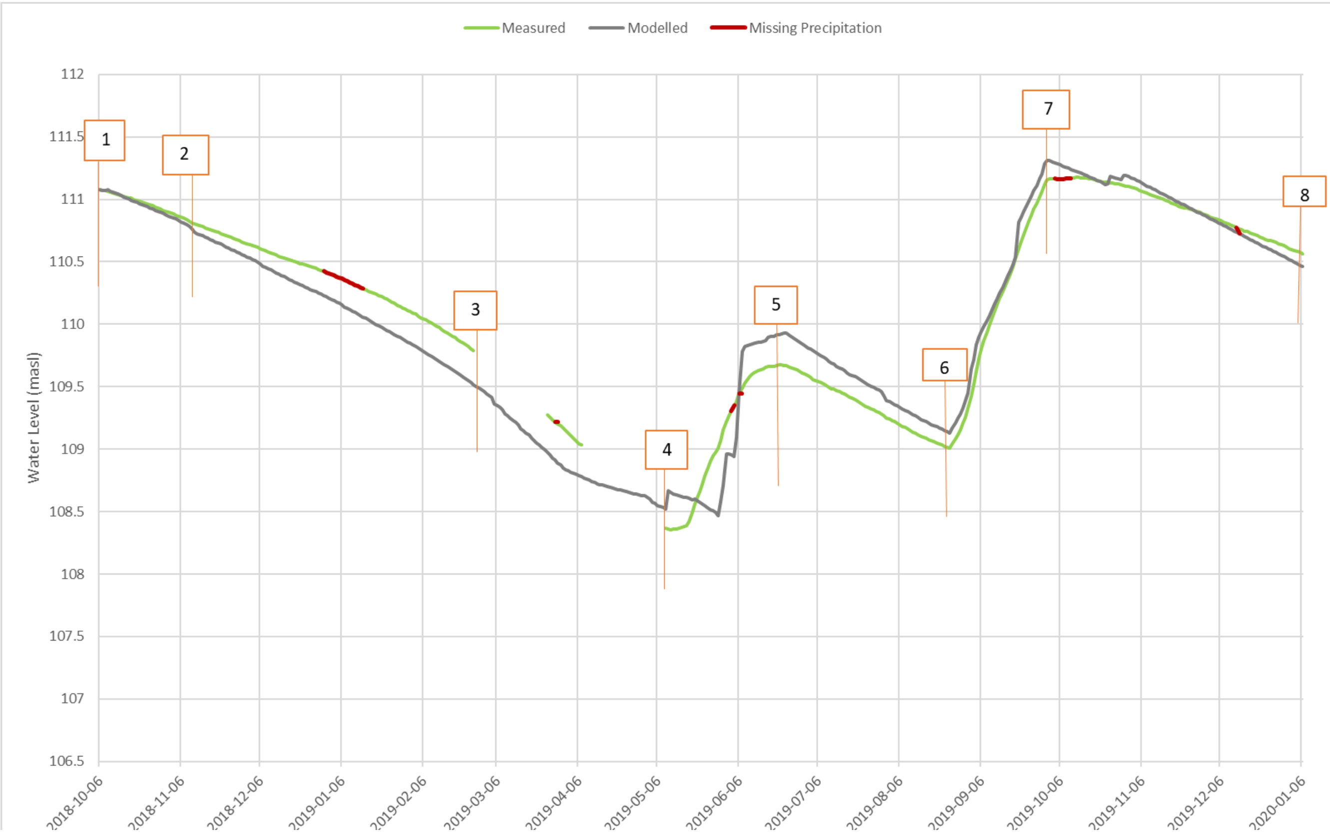

Figure 1: Visual Comparison of Modelled and Measured Water Levels, Including Periods of Missing Precipitation Data

- Period 1-2 (October 6, 2018 through November 9, 2018
  - Reasonable replication of measured water level reductions occurs during this period, likely following the earlier period of maximum ice development.
  - Only two days of missing precipitation data are evidenced and likely do not compromise predictions as these may have been low magnitude or occurred in the form of snowfall.
  - Unexpectedly, no observable water level response is identified as a result to reported fire fighting activities at the end of this period.
- Period 2-3 (November 10, 2018 through February 25, 2019)
  - A likely overestimate in ice formation leads to an overestimate of water level reductions in the reservoir. Although initially similar, the predicted rate of ice development outpaces that observed from water level records.
  - As expected, missing precipitation data (16 days) starting from 30 December 2018 to 14 January 2019, falling as snow, do not compromise water level predictions during the ice cover period.
- Period 3-4 (February 26, 2019 through May 9, 2019)

  - Substantial periods of missing water level data mean a detailed comparison of transition between underprediction and overprediction cannot be made.
- Period 4-5 (May 10, 2019 through June 20, 2019)
  - The model fails to replicate the precise timing and magnitude of the water level rebound throughout the snowmelt and ice melt period, an artifact most likely attributed to simplified model assumptions.
  - The model predicts that the timing of the peak water level rebound at the end of snowmelt three days after the peak water level observation which is reasonable.
- Period 5-6 (June 21, 2019 through August 25, 2019)
  - The model captures the trend of decreasing water levels reasonably well, overestimating evaporative losses slightly.
  - The overestimate in water levels at the end of this period is primarily attributed to model error that originates during snowmelt (period 4-5).
- Period 6-7 (August 26, 2019 through October 3, 2019)
  - Water level recovery due to precipitation and active pumping is well replicated by the model for this period before the onset of freeze up.
- Period 7-8 (October 4, 2019 through January 6, 2020)
  - As during the 2018/2019 winter, decreases in modelled water levels accelerate below those measured. These accelerated declines are likely the result of overestimates in the rate of ice formation within the reservoir.
  - Water levels at the end of this period are underestimated by 10 cm, corresponding to a water supply of approximately 30,800 m^3.

5.0 PREDICTED MONTHLY EVAPORATIVE LOSSES

This section of the report is presented in order to offer the City some insight into the extent to which evaporative losses during the ice-free period can differ between different climatic years and, in particular, to what degree evaporative losses from the reservoir increase with stage. This information may be helpful for City planners when scheduling supplementation of water from alternate sources.

As shown in Table 1 and on Figure 2 below, evaporative losses from the reservoir are approximately 7 times greater at full stage than when water levels are at the elevation of the assumed intake invert (101.6 masl).
As expected, evaporative losses tend to peak during the month of July and are lowest in September (as little as one third of July evaporative losses) during the final month before freeze-up occurs. It should be noted that variations in cloudiness and precipitation distribution from year to year may influence the tabulated results and caution is recommended.

Table 1: The Effect of Reservoir Level on Predicted Daily Evaporative Rates by Month over the 2008 through 2017 Period of Record

Level	June - Loss to Evaporation (m^3/day)			July - Loss to Evaporation m^3/day)			August - Loss to Evaporation (m^3/day)			September - Loss to Evaporation (m^3/day)		
masl	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
98.33	13	16	21	13	18	23	12	14	14	5	6	8
99.33	13	16	21	13	18	23	12	14	14	5	6	8
100.33	24	28	38	23	33	42	21	24	26	10	11	14
101.33	40	47	64	38	55	71	35	41	44	16	19	24
102.33	67	78	107	64	92	117	59	68	72	27	31	39
103.33	104	123	167	99	143	183	92	106	113	42	48	61
104.33	132	156	212	126	182	232	116	135	144	53	61	78
105.33	167	196	267	159	230	293	147	170	181	67	77	98
106.33	212	249	339	202	291	372	186	216	230	85	97	124
107.33	253	297	404	241	347	444	222	257	274	102	116	148
108.33	292	344	468	279	402	513	257	298	318	118	134	171
109.33	332	390	530	316	456	582	291	338	360	133	152	194
110.33	361	424	577	344	496	633	317	367	392	145	166	211
111.33	374	440	599	357	515	657	329	381	407	150	172	220

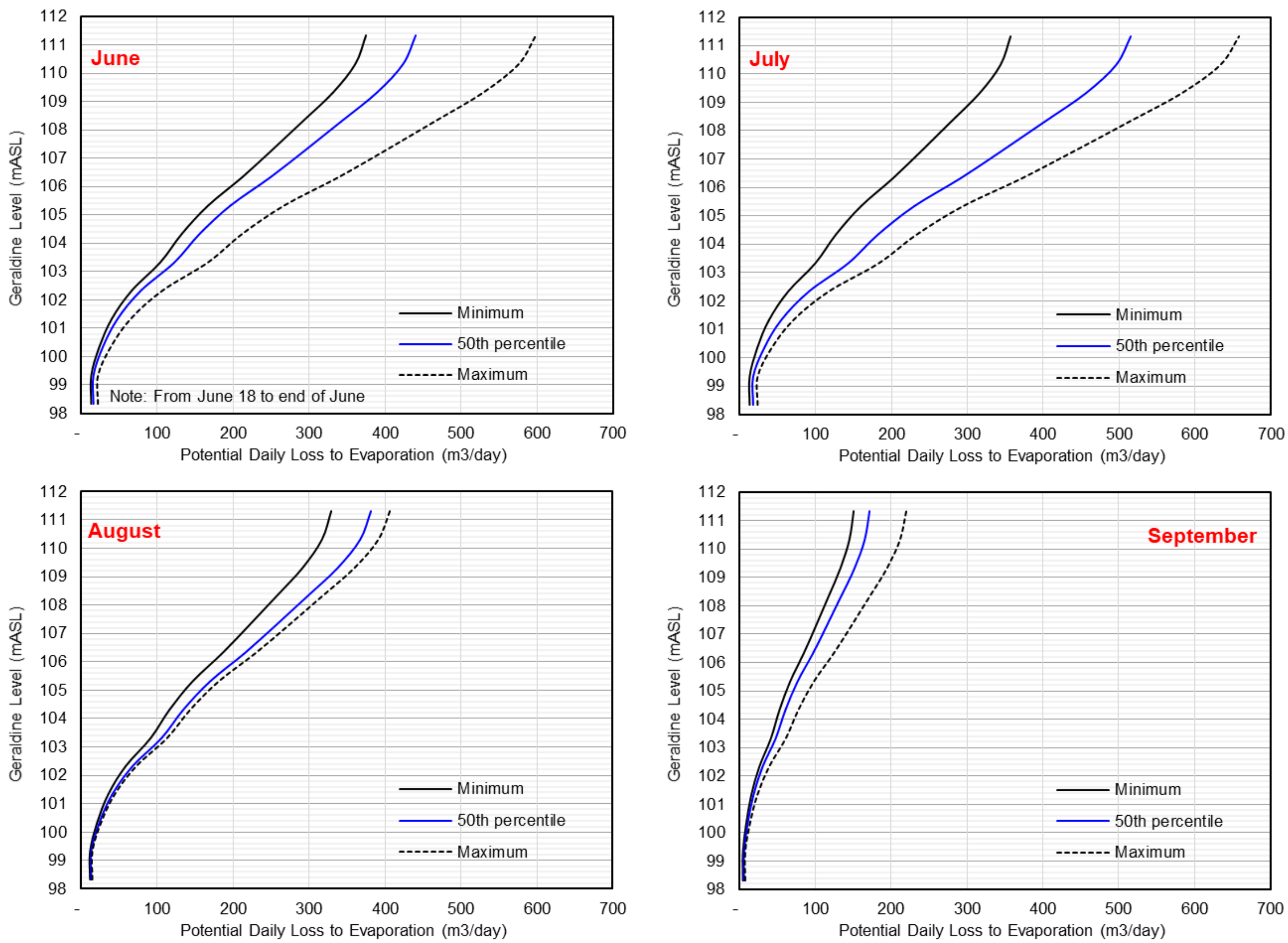

Figure 2: The Effect of Reservoir Level on Predicted Daily Evaporative Rates by Month over the 2008 through 2017 Period of Record

6.0 RESULTS

The results presented in Sections 6.1 through 6.3 often concern independently calculated probability distributions of historic (2008 through 2017) meteorological data which are intended to confer an understanding of the range of meteorological variability affecting water surplus outcomes for each of the consumption scenarios discussed in Section 2.1.5.

As such, it is important that the reader understand that the percentage probability distributions presented for precipitation and meteorological surplus in Tables 3, 4, 5, 7, 9 and 11 are considered as independent distributions and should not be considered as co-dependent to one another. For example, the 50 percent probability surplus for August presented in any of these tables does not necessarily correspond to the 50 percent probability value for the simulation period. Similarly, the 75 percent probability value for meteorological surplus does not necessarily result from the 75 percent probability value for precipitation.

6.1 Historic Precipitation, Predicted Surplus and Predicted Reservoir Level at Freeze-Up

After applying the gap-filled meteorology data (Section 2.1.6), water level and snow storage reset function (Section 2.2.2) to the model, simulations were carried out for the three water consumption scenarios identified in Section 2.1.5 to ascertain the quantity of surplus that would be delivered to the Lake Geraldine Reservoir between January 6 and predicted freeze-up of each year.

Table 2 provides a simplified representation of key periods of interest for the 2019/2020 winter and 2008 through 2017 meteorological window considered in this assessment. This information is presented with a view of providing baseline information against subsequent precipitation and meteorological surplus increases presented in Tables 6, 8 and 10.

As shown, a significant portion of total precipitation over the catchment is lost in the form of evapotranspiration either directly from ground surface or more indirectly from soil and depression storage within the catchment. With cooling air temperatures and reasonable precipitation amounts, the proportion of rainfall translated to surplus is shown to generally peak in September (it is noted that the higher surplus/precipitation ratio for the January 6 through end of June period includes snowfall accumulated from November 1, 2019). Over the ice-free period, although higher precipitation is typically observed in July and August, the amount of generated surplus is likely limited because of increased thermal exposure at ground surface (i.e., increased losses in the form of evaporation). Meanwhile, although lower average temperatures occur in October than September, it is likely that a more significant portion of lower October rainfall is intercepted within soil storage and ground depressions, thus diminishing catchment runoff to the reservoir.

Total meteorological surpluses in the final weeks (October) before freeze-up are limited relative to earlier portions of the open-water period and thus reduce the catchments capacity to fully replenish the reservoir before freeze-up occurs.

Table 2: Average (Arithmetic) Precipitation and Meteorological Surplus recorded for Iqaluit over the 2008 through 2017 Period

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
January 6 to Freeze-Up (Varies)[1]	357	186	52%
January 6 to end of June[2] (January 6 to Thaw day[2]) (Thaw day to end of June[2])	171 (134) (37)	109 (51) (58)	63%
July	67	26	38%
August	56	19	34%
September	50	27	55%
October 1 to Freeze-Up (Varies)[1]	11	5	43%
November 1 to Freeze-Up (Varies) [1,3]	1	0[3]	36%

Notes:

1. Effective length of ice-free period (i.e., the number of days since thaw day to estimated freeze up day) differs between years.
2. The 63% of precipitation converted to surplus by the end of June includes recorded snow accumulation between November 1, 2019 and January 6, 2020 and is the reason more surplus than precipitation is delivered for the period immediately after thaw.
3. Rounding errors over a short period in 2010 mean a meteorological surplus is higher than tabulated.

6.1.1 Predicted Precipitation, Surplus and Reservoir Level under No Water Consumption Scenario

Table 3 presents precipitation amounts and corresponding meteorological surplus between January 6, 2020 and freeze-up for a range of percentage probabilities accounting for snow accumulation between November 1, 2019 and January 6, 2020 and the 2019/2020 and the ten meteorological scenarios (2008 and 2017). Depending on the wind and air temperature magnitudes as well as intensity and distribution of rainfall, the meteorological surplus could represent between 14% and 76% of total precipitation over the Lake Geraldine catchment.

Based on the meteorological data considered, it is estimated that the median water supply deficit without any consumption would approximate 7,600 cubic metres. It is noted that depending on the extreme annual water balances over the same period, there is a possibility that the reservoir deficit at the predicted freeze-up date would range from approximately 6,200 cubic metres to approximately 23,800 cubic metres.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9-month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the 2020/2021 winter (Golder 2013), the total available surplus for the over-winter period would range between 1,266,800 m^3 and 1,284,300 m^3.

Table 3: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under No Water Consumption Scenario

Percentage Probability Of Exceedance	Predicted Freeze-Up Date[4]	Predicted Thaw Date[4]	Number of Open-Water Days from Jan 6 to Freeze Up	Number of Rainfall Days from Thaw to Freeze-Up	Historic Precipitation (mm)						Predicted Historic Surplus (mm)						Predicted Reservoir Deficit at Freeze-Up (m^3)	Predicted Available Water Supply At Freeze-up (m^3) [4]	Predicted Reservoir Level at Freeze-Up (masl)
					Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[11]	August[1]	September[1]			
0 (Max)	06-Nov	23-May	156	94	626	393	82	189	93	92	474	154	360	155	40	78	6,193	1,284,333	111.30
5	02-Nov	27-May	150	94	586	302	73	141	84	92	431	116	238	101	39	73	6,193	1,284,333	111.30
10	29-Oct	31-May	144	93	545	210	65	93	74	92	389	77	117	47	38	69	6,193	1,284,333	111.30
25	16-Oct	04-Jun	135	84	337	160	44	67	63	58	173	62	49	22	34	35	6,609	1,283,917	111.30
50	14-Oct	08-Jun	127	70	332	87	33	57	58	45	151	42	14	13	18	17	7,626	1,282,900	111.30
75	10-Oct	11-Jun	124	64	297	74	24	45	47	34	120	24	3	4	4	8	9,110	1,281,416	111.30
90	05-Oct	13-Jun	121	57	267	65	17	37	32	24	75	20	3	-2	-1	7	11,014	1,279,512	111.29
95	04-Oct	14-Jun	118	55	226	58	13	28	31	22	50	20	2	-2	-1	5	17,397	1,273,129	111.27
100 (Min)	03-Oct	15-Jun	116	54	185	52	9	19	30	20	25	19	2	-2	-1	3	23,779	1,266,747	111.25

Notes:
1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total.
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
3. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m3), reservoir deficit (tabulated) and dead storage (80,667 m3) from total reservoir storage capacity (1,956,193 m^3).
4. Percentage of probability exceedance calculated using independent probability for the thaw dates and freeze up dates, meaning that the combination of thaw date and freeze update may have not occurred on the same year

6.1.2 Predicted Precipitation, Surplus and Reservoir Level under 100,000 m^3/Month Water Consumption Scenario

Table 4 considers the same meteorological data discussed for Table 3, but accounts for the additional effects of a daily water consumption rate of 3,335 m^3 (or 100,000 m^3 per month).

Based on the November 1, 2019 to January 6, 2020 snow accumulation and the ten-year historical meteorological period considered, it is estimated that the median water supply deficit at a consumption rate of 100,000 m^3 would approximate 413,000 cubic metres. At the extreme ends of the annual water balances for the same period, there is a possibility that this water supply deficit could decrease, or increase, to 16,100 or 881,400 cubic metres, respectively.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9-month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the winter months (Golder 2013) and assuming an average winter length of 9 months, a 100,000 m^3/month water consumption rate (i.e., a total winter period consumption of 900,000 m^3) could potentially lead to over-winter water shortages for the 50 through 100 percent probability outcomes presented in Table 4.

Table 4: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under 100,000 m^3/month Water Consumption Scenario (3,335 m^3/day)

Percentage Probability Of Exceedance	Predicted Freeze-Up Date[4]	Predicted Thaw Date[4]	Number of Open-Water Days from Jan 6 to Freeze Up	Number of Rainfall Days from Thaw to Freeze-Up	Historic Precipitation (mm)						Predicted Historic Surplus (mm)						Predicted Reservoir Deficit at Freeze-Up (m^3)	Predicted Available Water Supply At Freeze-up (m^3) [4]	Predicted Reservoir Level at Freeze-Up (masl)
					Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]			
0 (Max)	06-Nov	23-May	156	94	626	393	82	189	93	92	474	154	360	155	40	78	16,110	1,274,416	111.27
5	02-Nov	27-May	150	94	586	302	73	141	84	92	431	116	238	101	39	73	26,133	1,264,393	111.24
10	29-Oct	31-May	144	93	545	210	65	93	74	92	389	77	117	47	38	69	36,157	1,254,369	111.21
25	16-Oct	04-Jun	135	84	337	160	44	67	63	58	173	62	49	22	34	35	347,909	942,618	110.19
50	14-Oct	08-Jun	127	70	332	87	33	57	58	45	151	42	14	13	18	17	412,954	877,572	109.97
75	10-Oct	11-Jun	124	64	297	74	24	45	47	34	120	24	3	4	4	8	517,135	773,392	109.62
90	05-Oct	13-Jun	121	57	267	65	17	37	32	24	75	20	3	-2	-1	7	648,402	642,124	109.17
95	04-Oct	14-Jun	118	55	226	58	13	28	31	22	50	20	2	-2	-1	5	764,888	525,638	108.74
100 (Min)	03-Oct	15-Jun	116	54	185	52	9	19	30	20	25	19	2	-2	-1	3	881,375	409,151	108.31

Notes:
1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total.
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
3. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m3), reservoir deficit (tabulated) and dead storage (80,667 m3) from total reservoir storage capacity (1,956,193 m^3).
4. Percentage of probability exceedance calculated using independent probability for the thaw dates and freeze up dates, meaning that the combination of thaw date and freeze update may have not occurred on the same year

6.1.3 Predicted Precipitation, Surplus and Reservoir Level under 115,000 m^3/Month Water Consumption Scenario

Table 5 considers the same meteorological data previously discussed for Table 3, but accounts for the additional effects of a daily water consumption rate of 3,850 m^3 (or 115,000 m^3 per month).

Based on the November 1, 2019 to January 6, 2020 snow accumulation and ten-year meteorological period considered, it is estimated that the median water supply deficit at a consumption rate of 115,000 m^3 would approximate 533,700 cubic metres. At the extreme ends of annual water balances for the same period, there is a possibility that this water supply deficit could decrease, or increase, to approximately 29,400 or 1,013,600 cubic metres, respectively.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9-month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the winter months (Golder 2013) and assuming an average winter length of 9 months, a 115,000 m^3/month water consumption rate (i.e. 1,035,000 m^3 water demand in total) could potentially lead to over-winter water shortages for the 25 through 100 percent probability outcomes presented in Table 5.

Table 5: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under 115,000 m^3/month Water Consumption Scenario (3,850 m^3/day)

Percentage Probability Of Exceedance	Predicted Freeze-Up Date[4]	Predicted Thaw Date[4]	Number of Open-Water Days from Jan 6 to Freeze Up	Number of Rainfall Days from Thaw to Freeze-Up	Historic Precipitation (mm)						Predicted Historic Surplus (mm)						Predicted Reservoir Deficit at Freeze-Up (m^3)	Predicted Available Water Supply At Freeze-up (m^3) [4]	Predicted Reservoir Level at Freeze-Up (masl)
					Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]			
0 (Max)	06-Nov	23-May	156	94	626	393	82	189	93	92	474	154	360	155	40	78	29,406	1,261,120	111.23
5	02-Nov	27-May	150	94	586	302	73	141	84	92	431	116	238	101	39	73	37,617	1,252,909	111.20
10	29-Oct	31-May	144	93	545	210	65	93	74	92	389	77	117	47	38	69	45,829	1,244,697	111.18
25	16-Oct	04-Jun	135	84	337	160	44	67	63	58	173	62	49	22	34	35	485,047	805,479	109.73
50	14-Oct	08-Jun	127	70	332	87	33	57	58	45	151	42	14	13	18	17	553,694	736,832	109.50
75	10-Oct	11-Jun	124	64	297	74	24	45	47	34	120	24	3	4	4	8	664,042	626,484	109.11
90	05-Oct	13-Jun	121	57	267	65	17	37	32	24	75	20	3	-2	-1	7	785,283	505,243	108.67
95	04-Oct	14-Jun	118	55	226	58	13	28	31	22	50	20	2	-2	-1	5	899,451	391,075	108.24
100 (Min)	03-Oct	15-Jun	116	54	185	52	9	19	30	20	25	19	2	-2	-1	3	1,013,620	276,906	107.77

Notes:
1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total.
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
3. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m3), reservoir deficit (tabulated) and dead storage (80,667 m3) from total reservoir storage capacity (1,956,193 m^3).
4. Percentage of probability exceedance calculated using independent probability for the thaw dates and freeze up dates, meaning that the combination of thaw date and freeze update may have not occurred on the same year

6.2 Precipitation and Meteorological Surplus Required to Fill Reservoir

Using the 2019/2020 winter and 2008 through 2017 meteorological data referred to in Section 2.1.6 and water level reset function referred to in Section 2.2.2, model simulations were also carried out for the three water consumption scenarios identified in Section 2.1.5 to ascertain the quantity of precipitation that would be required from January 6 to freeze-up in order to replenish the Lake Geraldine reservoir to just below its design level of 111.33 masl. This approach was deemed necessary because insufficient meteorological surpluses in the final few open-water days before freeze-up to offset water consumption were identified in some years, regardless of the increase in precipitation. The following water supply deficits were considered acceptable buffers to establish the necessary increases in precipitation to replenish the reservoir:

- No Water Consumption Scenario – deficit of 10,000 m^3;
- 100,000 m^3/month Water Consumption Scenario – two weeks of consumption equivalent to 46,690 m^3; and,
- 115,000 m^3/month Water Consumption Scenario – two weeks of consumption equivalent to 53,900 m^3.

The following sub-sections identify relevant considerations in the interpretation of the amount of precipitation necessary to replenish the reservoir during this open-water period, discuss the approach adopted to consider these considerations and present the results relevant to each of the three water consumption scenarios.

6.2.1 Interpretation of Reservoir Filling Results

In transitioning historic precipitation data to that necessary to replenish the reservoir, the reader should be aware of a number of considerations that are fundamental to adequate interpretation of the results presented in Section 6.2.2 through 6.2.4.

6.2.1.1 Consideration of Sensitivities of Results to Meteorological Regimes

Establishing the amount of precipitation required to replenish the reservoir is complex for a number of reasons.

Firstly, the limiting effects of evapotranspiration and soil and depression storage necessarily imply that the total quantity of precipitation required to fill the reservoir needs to be greater than the reservoir deficit (i.e., soil and depression storage intercept a fraction of incident precipitation across the catchment that does not translate to inflow to the reservoir). Hence, antecedent weather conditions such as the amount and intensity of rainfall, as well as air temperature and wind conditions interceding rainfall, are important determinants to establishing to what extent soil or depression storage is exhausted or needs to fill before generating runoff that can enter the reservoir.

Secondly, this complexity is compounded by the rate of precipitation delivery to the system. The same monthly precipitation amount can yield entirely different quantities of inflow to the reservoir depending on the distribution and intensity of precipitation delivered to ground surface. For example, 100 mm of rainfall uniformly distributed across a month would typically result in lower total monthly runoff volumes than the same quantity off rainfall over a day. In the latter case, evapotranspiration would have insufficient opportunity to affect soil and depression storage volumes in a meaningful way.

Lastly, the duration of the ice-free period loosely determines the number of rainfall days available to replenish the reservoir. In other words, an early winter would conceivably require higher average daily precipitation amounts than the precipitation amounts required to replenish the reservoir before a late winter.

6.2.1.2 Distribution of Historic and Necessary Precipitation and Surplus Amounts

By supplementing the amount of historic rainfall with that required to replenish the reservoir, the probability distribution of decadal rainfall becomes considerably contracted relative to that for measured conditions. Accordingly, it is important to note that the monthly percent probability values presented in Table 7, 9 and 11 may not be directly compared to the monthly percent probability values in Tables 3, 4 and 5. In rare cases, a small decrease in monthly required precipitation values may be apparent. Accordingly, average monthly precipitation requirements are presented in each sub-section in Tables 6, 8 and 10.

6.2.2 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under No Water Consumption Scenario

Table 6 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 7 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to a deficit of 10,000 m^3) from an initial water level of 110.56 masl under the no consumption scenario, for an average ice-free period (thaw to freeze-up). Relative to average annual precipitation amounts measured between 2008 and 2017, average ice-free precipitation amounts would need to increase by approximately 1% in order to generate the necessary meteorological surplus to replenish the reservoir to a deficit of 10,000 m^3.

Despite featuring less precipitation than in August, the effect of cooling air temperatures on the proportion of precipitation converted to meteorological surplus in September is conspicuous in its effect on the ratio between precipitation and meteorological surplus. In contrast, the lowered ratio in October is likely attributed to a relative increase in ET losses from soil and depression storage.

Table 6: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under No Consumption Scenario

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
January 6 to Freeze-Up (Varies)[1]	359	187	52%
January 6 to end of June (January 6 to Thaw day) (Thaw day to end of June)	*172* *(134)* *(38)*	*109* *(51)* *(58)*	*63%*
July	68	26	38%
August	57	19	34%
September	51	28	55%
October 1 to Freeze-Up (Varies)[1]	11	5	43%
November 1 to Freeze-Up (Varies) [1,2]	1	0	36%

Notes:

1. Effective length of ice-free period (i.e., the number of days since thaw day to estimated freeze up day) differs between years.
2. The 63% of precipitation converted to surplus by the end of June includes recorded snow accumulation between November 1, 2019 and January 6, 2020 and is the reason more surplus than precipitation is delivered for the period immediately after thaw.
3. Rounding errors over a short period in 2010 mean a meteorological surplus is higher than tabulated.

Given the considerations previously presented in Section 6.2.1, the results in Table 7 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 7 exhibit no significant precipitation and meteorological surplus change relative to average measured historic conditions (see Table 3).

Table 7: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under No Water Consumption Scenario

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m^3)	Predicted Total Surplus Required to Replenish Reservoir (mm)						Predicted Total Precipitation Required to Replenish Reservoir					
			Open Water Period (Jan 6 to) Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Open Water Period Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]
0 (Max)	06-Nov	6,193	10	20	2	-2	-1	6	146	57	9	21	30	20
5	02-Nov	6,193	24	20	2	-2	-1	7	154	61	13	29	31	22
10	29-Oct	6,193	38	20	3	-2	-1	7	163	65	17	37	32	24
25	16-Oct	6,609	88	24	3	4	4	8	191	74	25	45	50	35
50	14-Oct	7,626	116	42	14	13	18	17	219	87	33	57	58	47
75	10-Oct	9,110	131	62	51	22	34	35	250	160	44	67	63	58
90	05-Oct	11,014	243	77	116	47	38	69	273	210	65	93	74	92
95	04-Oct	17,397	324	116	238	101	39	73	310	302	73	141	84	92
100	03-Oct	23,779	405	154	359	155	40	78	346	393	82	189	93	92

Notes:

1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total..
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

6.2.3 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under 100,000 m^3/Month Water Consumption Scenario

Table 8 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 9 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to within a two-week consumption deficit) from an initial water level of 110.56 masl under the 100,000 m^3/month consumption scenario, for an average ice-free period (thaw to freeze-up). Relative to average annual precipitation amounts measured between 2008 and 2017, average ice-free precipitation amounts would need to increase by approximately 48% in order to generate the necessary meteorological surplus to replenish the reservoir to a two-week deficit within approximately 46,700 m^3.

Compared to the results presented in Table 6, on average (arithmetically), a 43% increase in precipitation relative to the no consumption scenario would be necessary to replenish the reservoir before freeze-up, resulting in a 50% increase in surplus over the January 6 to freeze-up period relative to historic conditions The beneficial effects of exhausted soil and depression storage within the catchment are notable when comparing the results in Table 8 with those previously presented in Table 6.

Table 8: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under 100,000 m^3/Month Consumption Scenario

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
January 6 to Freeze-Up (Varies)[1]	514	280	55%
January 6 to end of June (January 6 to Thaw day) (Thaw day to end of June)	*241* *(183)* *(57)*	*135* *(59)* *(76)*	*56%*
July	96	44	45%
August	84	42	50%
September	76	51	67%
October 1 to Freeze-Up (Varies)[1]	16	8	54%
November 1 to Freeze-Up (Varies) [1,2]	1	1	91%

Notes:

1. Effective length of ice-free period (i.e., the number of days since thaw day to estimated freeze up day) differs between years.
2. The 63% of precipitation converted to surplus by the end of June includes recorded snow accumulation between November 1, 2019 and January 6, 2020 and is the reason more surplus than precipitation is delivered for the period immediately after thaw.
3. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

Given the considerations previously presented in Section 6.2.1, the results in Table 9 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 9 exhibit increased precipitation and meteorological surplus amounts relative to average measured historic conditions (see Table 4).

Precipitation over open water period (thaw to freeze up) would need to increase between 0 and 120 mm to generate the additional surplus required to full the reservoir to within 46,690 m^3 (equivalent to two weeks water consumption) of its storage capacity.

These results should be interpreted with caution, particularly for more extreme probabilities (e.g. the 75 to 100 percent probabilities). On average (Table 8), 29% of all open-water rainfall falls during the month of July, with only 5% of rainfall falling during the final month of October before freeze-up.

The paradox of estimating the necessary precipitation increases over the open-water season as a whole is that the increase over historic precipitation required to offset consumption and, to a lesser degree, evaporative losses during the month of October is necessarily large thus leading to oversupplies within, and overtopping of, the reservoir during the typically rainier months of July, August and September for some of the ten year records.

While estimates of seasonal increases therefore provide somewhat misleading information, the key conclusion from these results is that supplementation (or an increase in precipitation) in the final month before freeze-up would be most efficient provided sufficient water supplies in nearby water bodies are available. Notwithstanding the potential regulatory challenges of sourcing adequate supplementation volumes from nearby waterbodies, pumping during the final month before freeze-up may deliver a more efficient supplementation strategy, owing to advantages of (i) improved knowledge of residual deficits as well as reduced evaporative losses which are shown to increase with water level (Section 5).

With these notable benefits in mind, the risk of postponing all supplementation until the last month before freeze-up is expected is elevated given that the date of freeze-up over the 2008 through 2017 period evaluated has varied by over a month. As such, a balanced approach to offsetting the risks and maximising the benefits of delayed supplementation is advisable. It is understood that a separate analysis of monthly basin yields in the nearby River Apex, a potential source for supplemental water, is currently being undertaken by Nunami Stantec. Accordingly, the results of Nunami Stantec's work should be carefully considered as part of the planning process to verify which supplementation strategy would best suit the City's supplementation needs.

Table 9: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under 100,000 m^3/month Water Consumption Scenario (3,335 m^3/day)

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m^3)	Predicted Total Surplus Required to Replenish Reservoir (mm)						Predicted Total Precipitation Required to Replenish Reservoir					
			Open Water Period Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Open Water Period Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]
0 (Max)	06-Nov	16,110	163	27	4	3	1	1	233	87	14	39	47	24
5	02-Nov	26,133	173	28	6	3	5	4	245	101	21	43	51	31
10	29-Oct	36,157	183	29	7	3	10	7	257	114	28	47	56	38
25	16-Oct	347,909	190	40	17	8	19	22	310	131	32	67	64	49
50	14-Oct	412,954	204	47	28	34	34	49	340	143	56	91	86	73
75	10-Oct	517,135	223	64	95	43	63	78	365	225	66	103	105	104
90	05-Oct	648,402	250	90	148	106	84	93	383	274	81	162	112	122
95	04-Oct	764,888	328	122	254	130	86	101	390	333	115	176	113	123
100	03-Oct	881,375	406	154	360	155	89	109	398	393	148	189	114	124

Notes:

1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total.
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

6.2.4 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under 115,000 m³/Month Water Consumption Scenario

Table 10 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 11 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to within a two-week consumption deficit) from an initial water level of 110.56 masl under the 115,000 m³/month consumption scenario, for an average ice-free period (thaw to freeze up). Relative to average annual precipitation amounts measured between 2008 and 2017, average annual precipitation amounts would need to increase by approximately 57% in order to generate the necessary meteorological surplus to replenish the reservoir to a two-week deficit within approximately 53,900 m³.

Compared to the results in Table 6, on average (arithmetically), a 51% increase in precipitation relative to the no consumption scenario would be necessary to replenish the reservoir before freeze-up, resulting in a 58% increase in surplus over the January 6 to freeze-up period relative to historic conditions. The beneficial effects of exhausted soil and depression storage within the catchment are notable when comparing the results in Table 10 with those previously presented in Tables 6 and 8.

Table 10: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under 115,000 m³/Month Consumption Scenario

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
January 6 to Freeze-Up (Varies)[1]	544	296	54%
January 6 to end of June (January 6 to Thaw day) (Thaw day to end of June)	*254* *(194)* *(60)*	*137* *(60)* *(77)*	*54%*
July	101	46	46%
August	89	47	53%
September	82	55	68%
October 1 to Freeze-Up (Varies)[1]	17	9	54%
November 1 to Freeze-Up (Varies) [1,2]	1	1	91%

Notes:
1. Effective length of ice-free period (i.e., the number of days since thaw day to estimated freeze up day) differs between years.
2. The 63% of precipitation converted to surplus by the end of June includes recorded snow accumulation between November 1, 2019 and January 6, 2020 and is the reason more surplus than precipitation is delivered for the period immediately after thaw.
3. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

Given the considerations previously presented in Section 6.2.1 and further discussed after Table 8, the results in Table 11 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 11 exhibit increased precipitation and meteorological surplus amounts relative to average measured historic conditions (see Table 5).

Precipitation over open water period would need to increase between 0 and 146 mm to generate the additional surplus required to full the reservoir to within 53,900 m^3 (equivalent to two weeks water consumption) of its storage capacity.

These results should be interpreted with caution, particularly for more extreme probabilities (e.g. the 75 to 100 percent probabilities). On average (Table 8), 29% of all open-water rainfall falls during the month of July, with only 5% of rainfall falling during the final month of October before freeze-up.

The paradox of estimating the necessary precipitation increases over the open-water season as a whole is that the increase over historic precipitation required to offset consumption and, to a lesser degree, evaporative losses during the month of October is necessarily large thus leading to oversupplies within, and overtopping of, the reservoir during the typically rainier months of July, August and September for some of the ten year records.

While estimates of seasonal increases therefore provide somewhat misleading information, the key conclusion from these results is that supplementation (or an increase in precipitation) in the final month before freeze-up would be most efficient provided sufficient water supplies in nearby water bodies are available. Notwithstanding the potential regulatory challenges of sourcing adequate supplementation volumes from nearby waterbodies, pumping during the final month before freeze-up may deliver a more efficient supplementation strategy, owing to advantages of (i) improved knowledge of residual deficits as well as reduced evaporative losses which are shown to increase with water level (Section 5).

With these notable benefits in mind, the risk of postponing all supplementation until the last month before freeze-up is expected is elevated given that the date of freeze-up over the 2008 through 2017 period evaluated has varied by over a month. As such, a balanced approach to offsetting the risks and maximising the benefits of delayed supplementation is advisable. It is understood that a separate analysis of monthly basin yields in the nearby River Apex, a potential source for supplemental water, is currently being undertaken by Nunami Stantec. Accordingly, the results of Nunami Stantec's work should be carefully considered as part of the planning process to verify which supplementation strategy would best suit the City's supplementation needs.

Table 11: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under 115,000 m^3/month Water Consumption Scenario (3,850 m^3/day)

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m^3)	Predicted Total Surplus Required to Replenish Reservoir (mm)						Predicted Total Precipitation Required to Replenish Reservoir					
			Open Water Period Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]	Open Water Period Jan 6 to Freeze-Up	January 6 to Thaw[1]	Thaw to End of June[1]	July[1]	August[1]	September[1]
0 (Max)	06-Nov	29,406	179	30	5	3	1	1	233	95	15	39	52	24
5	02-Nov	37,617	187	30	7	4	6	4	258	109	23	45	54	30
10	29-Oct	45,829	194	30	9	6	10	7	282	123	31	51	56	37
25	16-Oct	485,047	206	42	17	11	20	23	337	135	33	74	68	50
50	14-Oct	553,694	221	47	30	41	37	54	361	153	60	100	93	80
75	10-Oct	664,042	238	64	96	47	82	86	386	244	70	112	107	113
90	05-Oct	785,283	265	94	156	103	92	102	396	299	81	158	120	133
95	04-Oct	899,451	335	124	257	129	92	110	407	346	120	174	121	133
100	03-Oct	1,013,620	405	154	359	155	93	119	419	393	158	189	121	134

Notes:

1. Monthly precipitation and surplus values are based on independent probability distributions for examined month and cannot be summed to derive the corresponding period total.
2. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the preceding discussion of results and previously noted assumptions and limitations the following conclusions are summarised:

1) The open-water period available for replenishment of the reservoir (predicted thaw to predicted freeze-up) ranges from 116 to 156 days (predicted thaw dates ranges between May 18 to June 10 while freeze-up dates range between October 3 and November 6).

2) The assessment of recent meteorological conditions (2008 to 2017) suggests that, on average, 52% of the measured precipitation falling between January 6 and predicted freeze-up results in meteorological surpluses that enter the Lake Geraldine reservoir. Given the paucity of meteorological surpluses in the final days before freeze-up for some of these years, however, reservoir losses attributed to evapotranspiration and water consumption mean the reservoir cannot always be filled to its entirety. In order to establish a target water reservoir level for freeze-up, the following permissible deficits were selected:

    a. A 10,000 m^3 storage deficit was selected as appropriate for the no water consumption scenario; and,

    b. Storage deficits equivalent to two weeks of water consumption were selected for the 100,000 m^3/month (46,690 m^3) and 115,000 m^3/month (53,900 m^3) water consumption scenarios.

3) For the three consumption rates evaluated, the predicted water supply deficit ranges as follows:

    a. The no water consumption scenario incurs a water supply deficit between 6,200 m^3 and 23,800 m^3, with a 50th percentile of 7,600 m^3;

    b. The 100,000 m^3/month water consumption scenario incurs a water supply deficit between 16,100 m^3 and 881,400 m^3, with a 50th percentile of 413,000 m^3; and,

    c. The 115,000 m^3/month water consumption scenario incurs a water supply deficit between 29,400 m^3 and 1,013,600 m^3, with a 50th percentile of 553,700 m^3.

4) The assessment of meteorological surpluses for the January 6, 2020 to 2020 freeze up period (assessment period) indicates that, relative to the measured 2008 through 2017 arithmetic average precipitation amount (357 mm), arithmetic average precipitation amounts required to achieve close to maximum water supplies by freeze-up would need to increase to:

    a. 359 mm for the no water consumption scenario;

    b. 514 mm for the 100,000 m^3/month water consumption scenario; and,

    c. 544 mm for the 115,000 m^3/month water consumption scenario.

5) The assessment of meteorological surpluses from thaw to freeze up period (open-water period) indicates that, relative to the measured 2008 through 2017 arithmetic average precipitation amount (223 mm), arithmetic average precipitation amounts required to achieve close to maximum water supplies by freeze-up would need to increase to:

    a. 226 mm for the no water consumption scenario;

    b. 330 mm for the 100,000 m^3/month water consumption scenario; and,

    c. 350 mm for the 115,000 m^3/month water consumption scenario.

6) It should be noted that the total open-water precipitation requirements detailed under Conclusion 5 should be interpreted with caution because the distribution of rainfall is such that a disproportionate amount of these totals would fall across the months of July, August and September with losses due to reservoir evaporation and reservoir overflows increasingly likely the earlier during the season that supplementation or rainfall occurs. Given the discussion of results presented at the end of Sections 6.2.3 and 6.2.4 and pending the results of Nunami Stantec's investigations of monthly basin yields in the nearby River Apex, specific consideration regarding the benefits and risks of delaying supplementation until the later portion of the open-water season are recommended as part of the water supply planning process currently being conducted by the City.

7) Given some differences in active storage estimates between Nunami Stantec (2019) and Golder (2013), it is recommended that the City of Iqaluit verify the current stage-storage relationship of Lake Geraldine via a bathymetric survey so that appropriate updates to the model and, fundamentally, the City's understanding of storage volumes and predicted water supply deficits may be made.

8.0 CLOSURE

We trust that the information provide din this technical memorandum meets your immediate needs and appreciate the opportunity to contribute to your interesting work. Please contact the undersigned if you have any questions or concerns regarding any of the content documented in this technical memorandum.

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