Incorporating Climate Change Scenarios into Mine Design and Permitting Studies

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Abstract This paper summarizes recent experience building climate change scenario data into mine design and permitting studies in Canada and Sweden. For a proposed mine in Yukon Territory, Canada, and an existing mine in northern Sweden, this paper: 1) summarizes recent climate trends and future climate change scenario data for the two mine sites; 2) summarizes steps taken to create long-term, daily- climate datasets that account for a changing climate; and, 3) by drawing on water model results from the two sites, highlight mine-water-climate issues and general management considerations for locations likely to experience warmer and wetter climate regimes.

Key words Climate change, water balance studies, cold regions

Introduction

Recently completed studies at Coffee Gold and Aitik Mines required long-term and forward looking climate records be assembled to drive various mine-site and receiving stream water models. For the Coffee Gold Project, climate data were assembled spanning the period 2018 to 2100 inclusive (i.e., Construction 2018-2020, Operations 2021-2032, Closure 2033-42 and Post-closure 2043-2100), with assembled data used to drive the following models: a heap leach facility (HLF) water balance model (WBM), a permafrost thaw model, a MODFLOW groundwater model and a site-wide water balance and water quality model. For the Aitik Mine, climate data were assembled for a 200-yr closure timeline (i.e., 2025 to 2225) and then used as input to several assessment models: e.g., water balance and geochemical models configured for the Aitik tailings storage facility (TSF) and waste rock storage facilities (WRSF), a hydro-dynamic pit lake water quality model, as well as a recipient water quality model that was configured using GoldSim.

The Coffee Gold Mine (62° 53' N, 139° 22' W) is a proposed gold development in west-central Yukon, approximately 125 km south of Dawson, YT, Canada. Major infrastructure related to mining and processing at the Project includes: an upgraded road; a primary waste rock storage facility; several open pits; water diversion structures and storage ponds; haul roads; primary and secondary crushing facilities; a heap leach facility; a gold refinery; and an accommodation complex. Proposed infrastructure will be situated at high elevation (~1,250 m asl), where local climate conditions are as follows: average annual temperature (T) is -2.6 °C and average annual precipitation (P) is estimated to be 485 mm (65% rain, 35% snow). At the time of paper preparation, Goldcorp was preparing an environmental assessment application, with intentions to embark on more detailed permitting studies thereafter.

Boliden AB is overseeing an expansion at the Aitik Mine that will increase mining and processing capacity from 36 to 45 million tonnes per year (Mt/y). Accordingly, the Aitik Mine Closure Plan was recently updated and technical assessments were conducted in support of the undertaking. The Aitik Mine (67° 04' N, 22° 55' E) is situated near Gällivare, Sweden, and shows a subarctic climate that is characterized by long, cold winters and short mild summers. Recent climate data indicate annual P and evapotranspiration (ET) are 607 mm and 309 mm respectively for the mine site, with a mean annual T of 0.0 °C.

Data Sources

Coffee Gold Mine

Baseline climate and hydrology data collected at the Coffee Gold Mine (2011 to present), including outputs from 11 continuously recording hydrometric stations, an automated weather station and several snow courses established at multiple elevations, were available. Additionally, monitoring data from measurement networks operated by Federal and State/Territorial agencies in the YT (Environment Canada, Yukon Snow Survey Network) and Alaska (National Oceanic and Atmosphere Administration (NOAA), SNOTEL network operated by the Natural Resources Conservation Service (NRCS)) were used to frame the climate context of the baseline period in terms of broader long-term pattern/trend and range of variability. Finally, monthly climate change scenario data (2001 to 2100, CMIP3/AR4 – A2 Scenario, 2 km grid) for grid points covering the Coffee Gold Mine site (Scenario Network for Alaska and Arctic Planning) were used in this study.

Aitik Mine

Baseline data (i.e., T, P, relative humidity, solar radiation, wind speed) collected at the Aitik mine site weather station (2010 to present), were available and incorporated into the study. Historical T and P data collected at locations adjacent (i.e., Gällivare and Malberget, Sweden; within 15 km) and at further distance (Jokkmokk, Abisko, Lainio, Sweden; within 100 km) from the Aitik mine were also utilized. Furthermore, a suite of climate change scenario results provided by the Rossby Centre (SMHI 2014), including downscaled, daily- climate data (T, P, RH, radiation, wind), were available via the CORDEX (COordinated Regional climate Downscaling EXperiment) data portal.

Climate Trends and the Instrumental Record

Baseline data were limited in their temporal extent (i.e., <5 years) and thus reliable patterns and trends were not readily discernible within this time frame. However, through a comparative process of daily, monthly, seasonal and annual climate metrics, conditions at nearest regional climate stations (e.g., McQuesten, YT – 125 km away; Gällivare, SWE – 15 km) were confirmed to be robust proxies for the mine sites. Instrumental records for McQuesten and Gällivare confirm the following climate patterns and trends for the past three decades: 1) air temperatures have increased steadily at Coffee Gold, though the overall P signature for the region is mixed and exhibits little change over the past thirty years; and 2) recent climate measurements near the Aitik mine show increasing trends for both T and P.

Climate data from nearest regional stations were also compared to other proximal regional stations, but with much longer records. Several suitable stations were identified (e.g., Mayo, YT – 85-year climate record; Jokkmokk, SWE – situated south of Aitik and shows ~150-year climate record). The results of this comparison confirmed the short-term (decadal) T and P signatures describe for McQuesten and Gällivare, but also characterized recent trends against a longer (century scale) observational timeline. Using anomaly plot format (Equation 1), positive anomalies (indicative of warmer and wetter than average conditions) and negative anomalies (indicative of cooler and drier than average conditions) were generated (Figure 1).

Anomaly (T, P) = (Observation – Mean)/Standard Deviation **(Equation 1)**

Overall, temperature anomaly plots for Mayo and Jokkmokk show strong evidence for recent warming (i.e., since the 1990s), as well, both records show a pronounced warm period which occurred in the 1930s and 1940s. The precipitation anomaly plots (Figure 1, lower plots) generally show wetter than average conditions since the 1970s at Mayo, whereas results for Jokkmokk show wetter conditions over the past 70 years (compared to the long-term average), as well as evidence for more recent P increases (since the 1990s).

Motivating Factors for Climate Change Scenario Selection

The following were motivating factors for the selection of climate change scenarios and usage of modelled future climate datasets:

- Best Practices – Several directional documents (e.g., IPCC 2013 and Comer 2007) summarize recommendations and best practices for the assembly and integration of climate change scenario data for purposes of impact modelling. As per best practices, climate change scenario data available for Coffee Gold and Aitik were ensembles, or averages, of results from multiple climate models (e.g., CMIP5/AR5, 9 model average for RCPs – Aitik Mine).

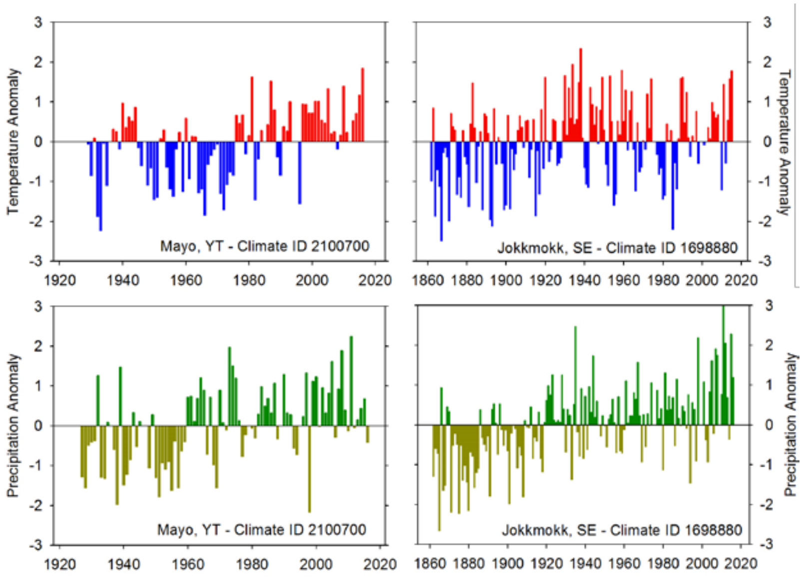

***Figure 1** Air temperature and precipitation anomaly plots for long-term monitoring stations near the Coffee Gold mine (left) and Aitik mine (right).*

- Historic and Recent Climate Trends – Patterns and trends returned by recent- and long-term monitoring data were considerations in the selection of preferential climate change scenarios. In the case of Coffee Gold, the A2 (worst case) scenario was selected in part because future T and P trends closely match trends in the instrumental record for the past 50 years.

- Consultation and Engagement – It is often common practice to select climate change scenario(s) in collaboration with others (e.g., between technical leads, regulatory agencies and possibly with a broader stakeholder groups). For Coffee Gold, discussions with a First Nations technical team and guidance provided by an independent climate research centre (Pacific Climate Impacts Consortium) influenced the scenario selection process.

- Continuity – e.g., Phase 1 pit lake modelling studies at Aitik mine incorporated climate change scenario data for the A1B (middle scenario, SRES). When the pit lake model was recently updated, there were practical benefits (e.g., prior regulatory acceptance) to re-index the study to a middle climate change scenario (i.e., RCP4.5).

- Practical Purposes – For both Projects, the breadth and extent of climate change integration to the various technical assessments was balanced with project budget, scope, schedule and modelling objectives.

Future Climate Trends

At annual frequency (2000-2100), monthly climate change scenario data and predicted trends are summarized for the two mine sites in Figure 2. Plots for Coffee Gold are based on the A2 SRES emission scenario (worst case), noting that predicted changes shown below equate closely to RCP8.5 outputs which are now published but unavailable when the study was completed. By comparison, the data shown for Aitik Mine are based on RCP4.5 (middle scenario) for the 2000 to 2100 time-period.

Overall patterns and trends for the two mine sites show several similarities: 1) T and P data are indicative that future climate will be warmer and wetter at both stations, with increases being roughly 3 °C (T) and +25% (P) for each site by 2100; 2) T increases are apparent at both stations for all seasons, but the predicted T increase is greatest for winter (Dec, Jan, Feb; e.g., approximately 5 °C by 2100 for Coffee Gold); 3) plots for both Coffee Gold and Aitik Mines confirm predicted increases in seasonal precipitation by 2100, noting that P magnitude and increasing trends are greater for summer (Jun, Jul, Aug) and autumn (Sep, Oct, Nov) compared to winter (Dec, Jan, Feb) and spring (Mar, Apr, May).

Climate Datasets as Inputs to Mine Site Impact Models

Coffee Gold Mine

To generate a long-term climate record for the Coffee Gold Mine, daily climate data (i.e., T and P) from the mine site and a nearby regional station (McQuesten, YT) were assembled to create monthly predictive relationships based on periods of overlapping data. Next, the regional station (predictor) and monthly predictive relationships (e.g., for T and P) were utilized to compute a 28-year, daily- synthetic climate record representative of the mine site. To span the full Project life (i.e., 2018 to 2100), the Coffee Gold climate record was looped three times to create an 84-year, daily- climate record.

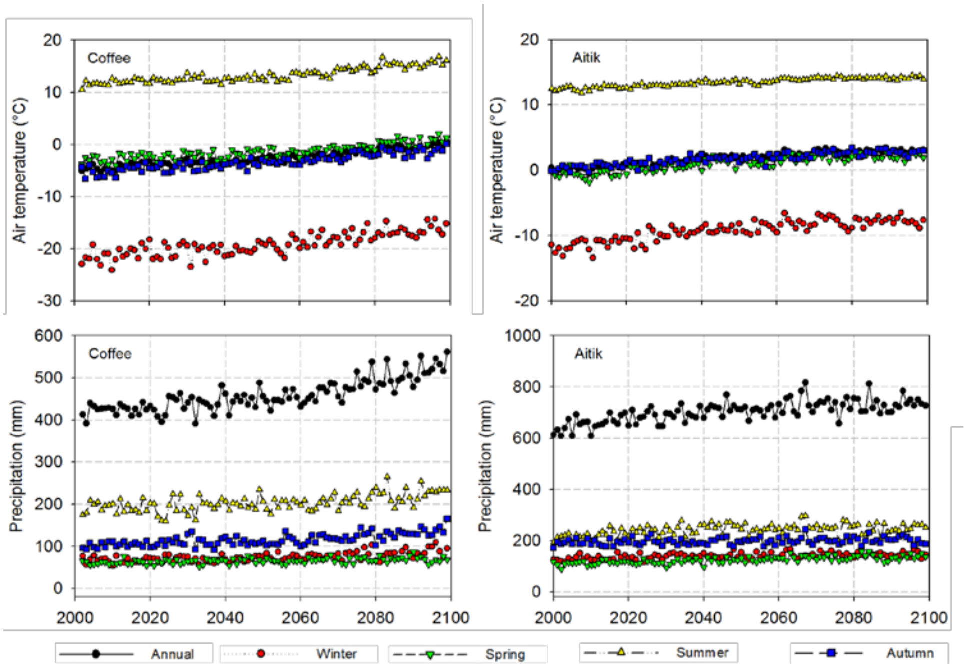

Figure 2 *Climate change scenario data for the Coffee Gold Mine (left) and Aitik Mine (right). Predictions are shown for T and P to year 2100.*

To represent a plausible future condition, climate change scenario data were downloaded from the Scenario Network for Alaska and Arctic Planning. Monthly T and P predictions (2001 to 2100, CMIP3/AR4 – A2 Scenario, 2 km resolution) for grid points covering the mine site extent were downloaded, averaged and then used to scale the 84-year daily climate record. The resultant time series (T and P shown) is shown in Figure 3 to illustrate the range of variability and trends with time (i.e., increasing T and P) that are inherent in the synthetic dataset.

Aitik Mine

For the Aitik Closure Plan, down-scaled, daily- and monthly future climate data for grid cell locations nearest to the mine site were available for download from the CORDEX data portal. Predicted air temperature and precipitation data for the four nearest grid cells to the mine site were downloaded and inspected to confirm consistency between points for RCP4.5. Once satisfied as to their consistency, daily climate data for the closest grid cell to the Aitik mine were downloaded for RCP4.5, EC-EARTH for key water balance variables:

e.g., wind speed; air temperature, precipitation, atmospheric pressure, specific humidity, energy balance terms and potential evaporation (computed using modified Penman-Monteith formulation). The downloaded climate data were used directly to represent the 2025 to 2100 timeframe. To extend the climate record to the year 2225, the data for the period 2065 to 2100 were repeated to cover the period from 2100 to 2225.

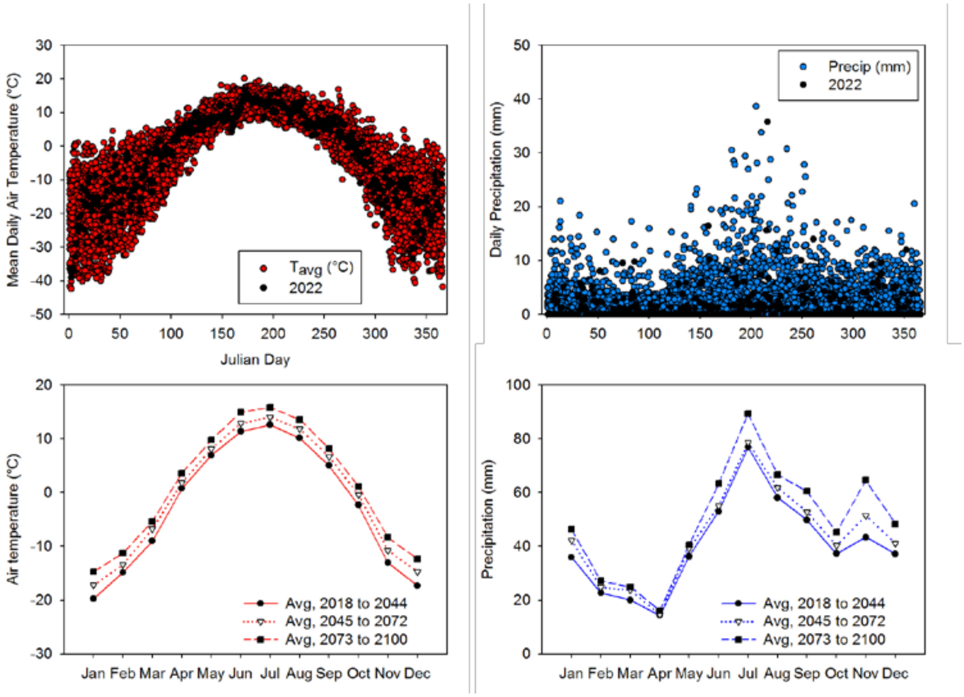

Figure 3 *Time series data from the Coffee Gold Mine water balance model. In the upper portion of the figure, daily time series data (2018-2100; year 2022) are shown for T and P. In the lower two panels, monthly average T and P trends are shown for three time periods.*

Management Considerations

Adopting Climate Change as Base Case – For both Coffee Gold and Aitik Mines, climate change was adopted as Base Case, rather than considering future climate change as a sensitivity analysis or *a posteriori* evaluation. In both Yukon Territory and Sweden, climate change scenario data are readily available to end-users and are easy to incorporate into mine impact models.

Expectations of Regulators, Stakeholders – Building climate change into mine site evaluations as Base Case can build trust with regulators and stakeholders. The Yukon Government for example, regularly reports on past, present and future climate trends and a general expectation for environmental assessment applications is a comprehensive consideration of climate change. Outright omission of climate change from a water modelling assessment would be potentially viewed as a notable regulatory submission gap.

Warmer and Wetter Climate Future – Assessments at Coffee Gold and Aitik indicate that warmer and wetter climate conditions will impart changes on the behaviour of mine facilities and adjacent receiving streams, compared to model outputs based on stationary (i.e., no trends) assumptions for climate conditions.

- For the Aitik Pit Lake model, warmer and wetter conditions returned a shorter fill time (by ~15 years) owing mainly to increased amounts of contact water (WRSF) and natural runoff generated by contributing areas adjacent to the pit. Higher rates of precipitation to the pit lake surface (with time and owing to a wetter future) also expedite filling, but potential gains are offset by enhanced rates of lake evaporation under future warmer conditions.

- For the Coffee Gold Project, the long-term rate of seepage from the reclaimed HLF following drain-down and closure is predicted to increase in magnitude through the Post-closure phase (2043-2100) of the Project. Further, assumed increases in precipitation to 2100 return increased production of contact water (e.g., pit wall runoff that reports to filling and spilling pit lakes; seepage that reports from the toe of the main WRSF proposed for the Project).

- Receiving stream assessments conducted for the two mine sites confirm the following runoff/streamflow changes under a warmer and wetter future climate regime: 1) progressive and earlier onset of freshet, later occurrence of autumn freeze up, and a longer ice-free season; 2) shifts with time to the proportions of P realized as rain vs. snowfall; 3) increases in baseflow conditions and likelihood of mid-winter melt events; and, 4) progressive increases in receiving environment flows with time.

Populating Models, Range of Variability and Future Trends – For northern environments that are predicted to be warmer and wetter in the future, there is clear value (i.e., regulatory acceptance; risk management for proponent) in demonstrating that closure plans and associated mitigations remain robust when tested against a broad range of climate conditions. While guided by single emission scenario (Coffee Gold) or RCP scenario (Aitik), daily climate inputs, that account for the full range of variability per parameter, were assembled and used to drive an array of mine impact models.

Conclusions

To drive hydrological and/or geochemical models, technical evaluations undertaken for the Coffee Gold Project and Aitik Mine required assembly of long-duration and forward looking climate datasets. Instrumental records at stations adjacent, or near, the two mine sites show evidence of increasing trends in air temperature and precipitation. Furthermore, downscaled climate change scenario indicate future climate will be warmer and wetter at both stations, with increases being roughly 3 °C (T) and +25% (P) for each site by 2100.

To ensure consistency with respect to the climate data used by the various modelling teams, a common climate dataset was assembled for each project that specifically accounted for predictions of climate change for the local region. For the Aitik mine, closure plan assessments drew upon readily available and high-quality information generated by the SMHI and the Rossby Centre, including modelled daily climate data and runoff data specific to the site. In contrast, necessary climate inputs for the Coffee Gold Mine were synthetically generated by combining baseline, regional and downscaled climate change scenario data. The climate-water issues were unique to each mine site; however, robust management responses and defensible plans were successfully defined for Coffee Gold and Aitik Mines while considering climate change as Base Case.

Acknowledgements

The authors thank two anonymous reviewers who provided comments on an earlier draft of this paper. Baseline hydro-meteorology data for the Coffee Gold Mine was provided by Ken Nordin, Laberge Environmental Services – Whitehorse, YT.

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