

CLIMATE CHANGE CONSIDERATIONS IN MINE WATER MANAGEMENT AND ENGINEERING DESIGN FOR RECLAMATION PLANNING

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Abstract

Climate change has important implications for mine water management and reclamation engineering design. Recent provincial guidance in British Columbia has extended climate-adaptation expectations to mine reclamation. This includes the Ministry of Mining and Critical Minerals' reclamation planning guidance and the more recent edition of the Joint Application Information Requirements. So far, that guidance has emphasized the ecological side of post-mining landscapes. In parallel, Engineers and Geoscientists British Columbia (EGBC) has published professional practice guidelines on climate change in flood assessments, dam safety reviews, and infrastructure design. These engineering requirements can be aligned with closure planning through a single workflow that connects climate science, hydrologic modelling, and reclamation design. This paper describes such a workflow: characterizing historical climate and streamflow non-stationarity, selecting global climate model ensembles and emission scenarios, generating future baseline streamflow series through rainfall-runoff modelling, and propagating climate signals through site-wide water balance, groundwater, and water quality models. A central concept is the future baseline, a climate-change-affected streamflow series free of mine-induced alterations, which is the benchmark for evaluating post-closure designs. Examples from recent projects in British Columbia, Yukon, and South America illustrate typical climate-change signals at mine closure: earlier freshet, bi-modal hydrologic regimes, higher winter baseflow, and a shift in governing design events from snowmelt volume to rainfall intensity. It complements ecology-focused reclamation guidance by addressing the water-cycle foundation that post-mining landscape outcomes depend on.

Key words: climate change, mine reclamation, water management, watershed modelling, future baseline, non-stationarity.

INTRODUCTION

Climate change is the long-term shift in the Earth's climate patterns, in terms of both average and extreme conditions. Natural warming and human-driven warming since the industrial revolution have pushed global mean surface temperatures to record highs and made heatwaves, droughts, wildfires, and flooding more frequent (IPCC, 2021). For mining, the effects reach every stage of the project life cycle and are most acute at closure, when engineered systems must perform for decades to centuries with progressively less active management.

Recent reclamation-specific guidance in British Columbia has focused on the ecological consequences of a changing climate: climate-shifted ecosystem baselines, species selection for revegetation, wildlife habitat targets, and carbon as a metric of reclamation success (BC MCM, 2025; Nickels et al., 2025). That work

provides a strong foundation for the terrestrial-ecosystem side of reclamation planning. In parallel, Engineers and Geoscientists British Columbia (EGBC) has published professional practice guidelines that apply climate change to engineering design, spanning flood assessment, flood mapping, dam safety reviews, dam hydrologic loading, and infrastructure design. These are complemented by CSA Group research on climate-change adaptation for dams. The EGBC guidelines, reviewed in the next section, address the engineering side of climate adaptation but are not specific to reclamation.

Hydrology connects the terrestrial-ecosystem side of reclamation planning with engineering design. Ecological resilience in a reclaimed landscape depends on a water balance that is itself shifting over time: if hydrologic inputs to a reclamation cover change, so does rooting-zone water availability; if the fraction of precipitation falling as snow changes, so do the timing and magnitude of freshet; and if winter baseflow changes, so does the dilution of mine-affected water. Design decisions about spillways, diversions, ponds, covers, and passive treatment systems are hydrologic decisions, and they must be made considering non-stationary climate conditions.

This paper sets out a practitioner’s framework for building climate change considerations into the water-focused parts of reclamation planning. It focuses on procedures for Western Canada but these are largely universal, and it draws on recent Knight Piésold analyses at mining projects in Yukon, British Columbia, and the Andes of Argentina (Rong, 2025), and complements the ecology-focused material in Nickels et al. (2025). It follows the workflow of climate change in mining water management: regulatory drivers, historical climate characterization, future climate projection, generation of a future-baseline streamflow series, and propagation through the downstream model chain.

REGULATORY AND PROFESSIONAL PRACTICE CONTEXT

Climate change must be considered in reclamation planning under both regulation and guidance requirements and expectations. The *Health, Safety and Reclamation Code for Mines in British Columbia* (the Code) requires consideration of climate change under Conditions 10.5.2, 10.5.3, and 10.6.11, which set the design criteria and performance expectations for water management structures and reclamation measures in BC (BC MCM, 2026). The BC Ministry of Mining and Critical Minerals *Consideration of Climate Change in Mine Reclamation Planning* guidance (BC MCM, 2025) sets out expectations for climate-aware reclamation. The most recent edition of the *Joint Application Information Requirements* (JAIR) (BC MEMLCI and BC MoECCS, 2024) include several requisites relevant to water-focused climate work: Section 3.4.1 requires a summary of the predicted effects of climate change on future climate and hydrology; Section 4.4.9 requires closure designs of open pits, TSFs, dams, dumps, and stockpiles to accommodate climate change; and Sections 6.6 and 6.7 require water balance and water quality models to evaluate uncertainty under a range of hydrologic conditions, including climate variability and climate change scenarios, for each phase of mine life.

EGBC also published a set of professional practice guidelines directly relevant to mine water management and closure. The *Legislated Flood Assessments in a Changing Climate in BC* guideline (V2.1, 2018) (EGBC, 2018) sets expectations for climate-aware flood hydrology and addresses non-stationarity in climate conditions. It is complemented by the *Flood Mapping in BC* guideline (V1.0, 2017) (APEGBC, 2017); Section 3.2 requires flood maps to document how climate change has been built into the underlying hydrology, hydraulics, and design water levels. For dams, including tailings dams and water-retaining structures carried through closure, the *Legislated Dam Safety Reviews in BC* guideline (Version 4.0, 2023)

(EGBC, 2023) represents a major 2023 revision that updates dam safety review expectations. The *Determining Dam Hydrologic Loading* practice advisory (V1.0, August 2022) (EGBC, 2022) addresses sources of uncertainty in flood-magnitude estimates, including future climate change, for dam design and the hydrologic basis of dam safety reviews. The *Developing Climate Change-Resilient Designs for Highway Infrastructure in British Columbia* guideline (V2.0, 2020) (EGBC and BC MoTI, 2020) applies where mine access roads, haul roads, and culverts interact with closure drainage and must stay serviceable under projected extremes. CSA Group’s 2022 research publication on *Climate Change Adaptation for Dams* (MacTavish et al., 2022) is widely used by dam-safety practitioners and brings together climate vulnerabilities, adaptation measures, and opportunities for Canadian dams.

Federally, the Environment Canada and Climate Change (ECCC) Strategic Assessment of Climate Change gives guidance on assessing the resilience of federally reviewed projects (ECCC, 2022). International frameworks, notably the Global Industry Standard on Tailings Management (ICMM, UNEP and PRI, 2020) and the Mining Association of Canada’s adaptation guide (MAC, 2021), likewise expect projects to show that water-related infrastructure will remain fit for purpose under future climates.

The common thread in all these guidelines is the expectation of a quantitative, defensible analysis: site-specific trend analyses of historical records, consideration of multiple global climate model outputs for different emission scenarios, and the explicit evaluation of extremes and how they might change over a project’s life cycle. The workflow presented in this paper is structured to produce the hydrologic values these guidelines require.

CHARACTERIZING HISTORICAL CLIMATE CHANGE

A defensible analysis of future climate begins with a rigorous examination of the historical record. The central question is whether that record can be regarded as stationary, that is, whether the statistical properties used for design (e.g., means, variances, quantiles) remain stable over time. If they do not, the analysis must characterize the nature and expression of the non-stationarity.

Weather, Climate and Record-Length Bias

Weather and climate are different. Weather is atmospheric conditions over minutes to days; climate is long-term (typically 30 years or more) regional or global averages of temperature, precipitation, and other variables. The on-site record is often quite short (a few years at best) in mine water-resources work, so practitioners supplement it with longer regional records. Longer records add observations but also more heterogeneity, since they may span several multi-decadal climate cycles, instrument changes, or climatic regimes. However, a longer record may not always provide the best basis for assessing future conditions, as recent conditions may differ substantially than those from earlier in the period of record, though consideration must always be given to whether a short or recent on-site record is biased towards a cool-wet or warm-dry cycle, depending on when it was collected. Both conditions should be recognized when a baseline climate series is derived.

Climate Cycles, Trend Detection and Non-Stationarity

Detecting long-term trends is complicated by natural climate variability, particularly on the west coast of North America because of the effects of the Pacific Decadal Oscillation (PDO). The PDO has warm and cool phases that typically last 20 to 30 years and strongly influence temperature and precipitation patterns. Cool-phase periods bring colder temperatures and above-average precipitation, snowpack, and runoff,

while warm-phase periods bring the opposite (Mantua & Hare, 2002). The PDO can mask or amplify climate-change trends: a record spanning a warm-to-cool transition may show a declining trend even while the climate is warming. Even so, recent records show a persistent warming signal across PDO phase transitions that natural variability alone would not produce.

Formal trend testing (usually the non-parametric Mann-Kendall test (Kendall, 1945)) on regional temperature, precipitation, and streamflow records shows whether monotonic change is statistically detectable. In most mine regions of western Canada, temperature trends are now clearly detectable; precipitation and streamflow trends are often weaker, more variable in space, and scale-dependent. A common pattern in project work for these mines is that mean annual temperature, total annual precipitation, and annual rainfall all show statistically significant increases, while annual snowfall shows a small, often non-significant decline. Precipitation is therefore changing in form (more rain, less snow) and amount. Streamflow records at regional Water Survey of Canada (WSC) gauges often show no significant changes in mean annual runoff or annual peak daily flows, yet the hydrograph shape has typically shifted: the freshet occurs earlier and late-summer flows are lower, consistent with warmer spring temperatures and shifting seasonal precipitation. Figure 1 shows a typical regional analysis of mean annual discharge (MAD) trends at Water Survey of Canada gauges in a coastal-mountain mining region of northwest BC, with statistically significant increases at several stations.

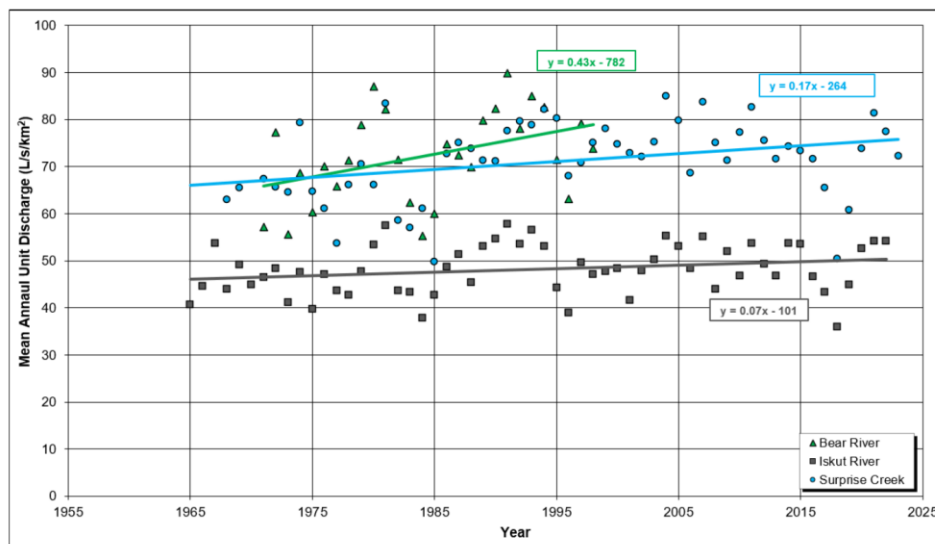


Figure 1: Regional trend analysis of mean annual discharge at WSC gauges near a coastal-mountain mining project in northwest BC. Several records show statistically significant upward trends in MAD under the Mann-Kendall test.

Changing Extremes and the Clausius-Clapeyron Relationship

Reclamation water infrastructure design is typically governed by peak flows rather than average flow conditions. Since extreme flows are predominantly driven by extreme rainfall events, the Clausius-Clapeyron relationship provides a theoretical basis for understanding climate impacts: warmer air has the capacity to hold roughly 7% additional moisture for each degree Celsius of temperature rise (Allen and Ingram, 2002; Trenberth et al., 2003), creating a thermodynamic foundation for expecting extreme rainfall

intensity to increase with warming temperatures and generate greater flows. However, the actual relationship between atmospheric moisture capacity and rainfall intensity is non-linear and exhibits strong regional variability, influenced by storm dynamics, orographic effects, and moisture transport mechanisms (Westra et al., 2014): certain regions experience scaling rates below the Clausius-Clapeyron prediction, whereas sub-daily convective extreme events may exceed it.

Project experience illustrates this complexity. At a project site approximately 120 km north of Kamloops in south-central BC, bias-corrected CMIP6 projections yield effective scaling rates of approximately 1% to 4% increase per °C for mid-century and end-of-century extreme 1-day rainfall, which is well below the theoretical 7% per °C rate. Meanwhile, the observed record shows no statistically significant trend in annual maximum 1-day rainfall despite significant warming. This gap may reflect limits in how GCMs represent extreme rainfall processes and also the chance that warming has not yet produced detectable changes in rare extremes over the available record (though average temperatures have generally increased in western Canada over the past few decades, warming is more pronounced at daily minimum temperatures than at daily maximum temperatures).

Tools such as IDF_CC (version 8.0 and later) allow GCM-based and Clausius-Clapeyron-based adjustments of design rainfall to be compared side by side, which is useful for bounding extreme precipitation estimates at the project scale. For Probable Maximum Precipitation (PMP), the U.S. National Academies' 2024 consensus study recommends incorporating climate change directly, through near-term temperature-scaling adjustment factors and a longer-term, model-based framework that characterizes uncertainty (NASEM, 2024). Pending the development of such a framework, however, practitioners currently face the question of whether an uplift is required at all (Hultstrand & Kappel, 2020), and if so, should Clausius-Clapeyron scaling be applied to the PMP.

In support of this approach, traditional PMP estimation rests on moisture maximization, so adjusting the maximum dew-point climatology for projected warming (at roughly 7% per °C) is a clear and arguably conservative step that avoids tying a long-lived, high-hazard structure to a fixed moisture limit. Undermining this approach is the argument that the PMP is already a near-upper-physical-limit estimate, and the 7% per °C rate describes mean atmospheric moisture, not extreme intensity: the long-duration, large-area storms that govern PMP frequently exhibit sub-Clausius-Clapeyron because they are limited by moisture convergence and storm dynamics rather than capacity, effective scaling can flatten or turn negative at the highest temperatures, and a thermodynamic adjustment captures none of the projected changes in storm dynamics, tracks, or frequency (Westra et al., 2014). A full 7% per °C uplift on an already-maximized estimate therefore risks compounding conservatism, while not applying a factor of safety to account for potential effects due to warming, risks underestimation of the design event. With no consensus or current strong guidance on how best to account for potential climate change effects on the PMP, a defensible approach is to specify any thermodynamic adjustment as an explicit, documented sensitivity value, rather than a single revised design value, thereby providing the designer with a range of values that can be appropriately considered in design decisions.

Shifting Hydrologic Regime and Scale Dependence

The most visible hydrologic consequence of warming in western Canada is a shift in streamflow regime. Snow-dominated catchments tend to have annual hydrographs that evolve to having higher winter flows, an earlier onset of freshet, lower summer flows, and higher fall flows (Figure 2), as rainfall plays a bigger

part in the annual cycle and the earlier freshet depletes groundwater discharges that supply later summer flows. In some cases where the annual hydrograph is currently unimodal shaped with the annual peak flow occurring consistently in the spring, there may be a pronounced shift to a bimodal hydrograph with reduced freshet flows and peak flows occurring in both spring and fall or even primarily in the fall.

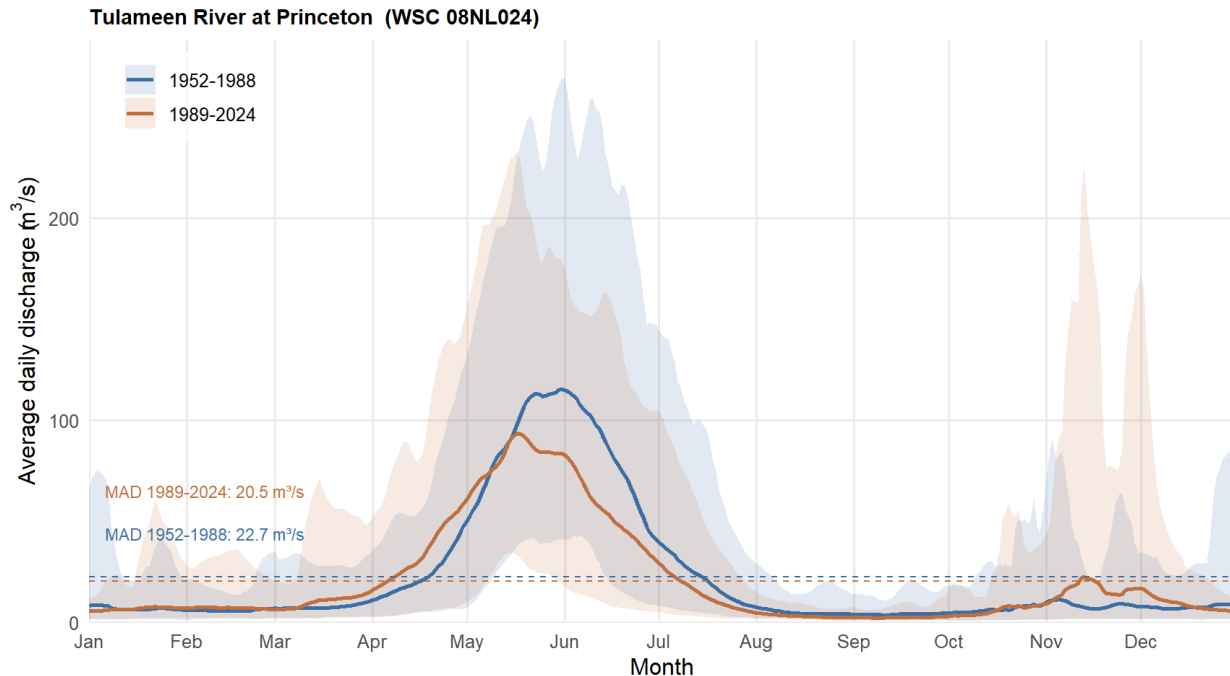


Figure 2: Illustrated shift in observed hydrologic regime under a warming climate, from unimodal freshet-dominated to bi-modal, with a larger fall rainfall peak superimposed on a smaller, earlier freshet. The record is split at its midpoint into an earlier and a later half. The shaded band is the 1st-99th percentile envelope; dashed lines are each period's mean annual discharge (MAD).

The design implications are significant: the governing flow event for a spillway, diversion, or storage pond may shift from freshet to fall over the structure's design life, and volume-controlled and rate-controlled design cases may swap in importance. The same warming that reshapes the peak regime also deepens the summer low-flow trough. An earlier freshet depletes the snowpack sooner, while higher summer evapotranspiration and longer dry spells draw down late-season flows further, so the annual minimum tends to arrive earlier and run lower even where annual discharge is unchanged or higher. Lower summer flows reduce the dilution available for mine-influenced discharges during the warm season, and they coincide with higher stream temperatures and lower dissolved oxygen, which can stress temperature- and flow-sensitive aquatic habitat and fish-bearing reaches downstream. On the positive side, higher winter base flows may enhance overwintering habitat for aquatic species and increase the bio-productivity of a stream. Changes in the timing of stream flows may require changes to the management of mine effluent.

Climate-change signals in streamflow are also scale-dependent. Larger watersheds integrate a broader climatic footprint and tend to show smaller fractional changes than smaller, more homogeneous catchments. This matters for mine reclamation because most long-record Water Survey of Canada flow records are for relatively large rivers, whereas mine catchments are typically situated in small watersheds. Inferring small-

catchment response directly from large-catchment trends can therefore understate the change at the scale of reclamation design.

PROJECTING FUTURE CLIMATE

Once historical climate and flow patterns and trends are characterized and understood, the next step in a climate change assessment is to predict potential future patterns. For climate change modelling, this involves the selection of three primary model parameters: the global climate model (GCM) ensemble, the emission scenario(s), and the time horizon(s).

Model Ensemble Selection

There are approximately 30 GCMs around the world that are broadly used by the scientific community to simulate potential future climate conditions (Eyring et al., 2016), and these models can produce a wide range of results for the same inputs. As such, the average results from a selected ensemble of models are typically used to project future climate conditions. The results from the full model ensemble of the Coupled Model Intercomparison Project Phase 6 (CMIP6), an international collaborative framework that coordinates climate model experiments across modeling centers worldwide, runs approximately 0.2-0.7 °C warmer than the Intergovernmental Panel on Climate Change (IPCC) AR6 assessed warming, which draws on several lines of evidence (paleoclimate, surface-temperature and ocean-heat observations, and process models); this gap comes from several high-sensitivity “hot models” included in the CMIP6 ensemble (Hausfather et al., 2022). Using the full ensemble therefore builds in a known bias toward too much warming. As such, it is good practice to use an ensemble limited to the models most applicable to the region of interest, and which produces results consistent with the “very likely” range of Earth’s equilibrium climate sensitivity in AR6.

For projects in northwestern North America, the BC Ministry of Forests has recommended curated 13-model and 8-model ensembles that remove the worst-biased models (Figure 3) (Mahony et al., 2022; Mahony & Foord, 2021).

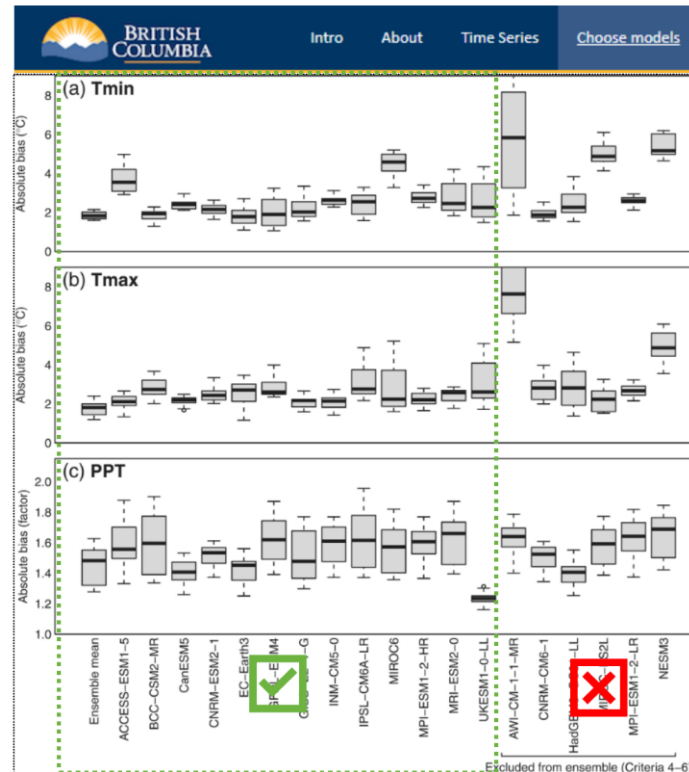


Figure 3: Recommended GCM ensembles for northwestern North America (BC Ministry of Forests). Curated ensembles exclude high-sensitivity models whose projected warming is inconsistent with the multi-line-of-evidence AR6 assessment.

For projects located in Canada, ECCC’s Canadian Downscaled Climate Scenarios, Multivariate CMIP6 (CanDCS-M6) dataset, developed jointly by ECCC and the Pacific Climate Impacts Consortium (PCIC), provides statistically downscaled daily projections at approximately 10 km resolution using 12 of the 13 recommended models. For international projects, the principle is the same: drop models with large positive or negative biases, and where possible use an ensemble recommended by the host jurisdiction or a relevant peer-reviewed synthesis.

Emission Scenarios

Emission scenarios have evolved from SRES families (AR4) through Representative Concentration Pathways (RCPs, AR5) to the current Shared Socio-economic Pathways (SSPs, AR6). The SSPs combine a narrative of socio-economic development with an end-of-century radiative forcing target (Figure 4). For practical application in reclamation planning:

- **SSP1-2.6** (sustainability-focused, 2.6 W/m² by 2100) is useful as a low-emission sensitivity case.
- **SSP2-4.5** (“middle of the road”, 4.5 W/m² by 2100) is typically adopted as the base case because it most closely tracks current global emission trajectories.
- **SSP3-7.0** (regional rivalry) is an unlikely but plausible pessimistic sensitivity case given current geopolitics.
- **SSP5-8.5** (fossil-fueled development, 8.5 W/m² by 2100) is now widely regarded as implausible (Burgess et al., 2021; Hausfather & Peters, 2020; Pielke et al., 2022) and has been formally retired

from the CMIP7 scenario set, as discussed in the next section. It should only be retained, if at all, as a clearly flagged stress test.

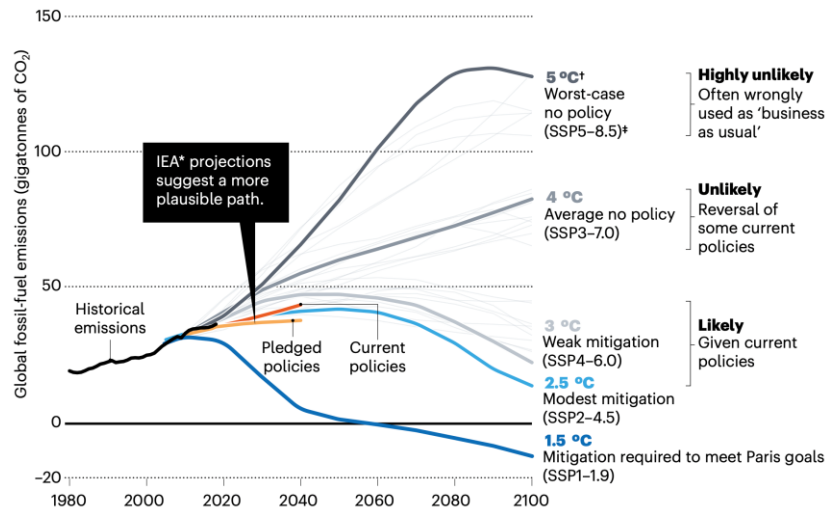


Figure 4: Emission scenarios and their assessed likelihoods, after Hausfather & Peters (2020). Original data sources: historical emissions, Global Carbon Budget (2019); SSP data, Rogelj et al. (2018) and the SSP Database (v2); and International Energy Agency projections.

Together, SSP1-2.6, SSP2-4.5, and SSP3-7.0 provide a full range of optimistic, neutral, and pessimistic but still plausible emission trajectories. Because the scenarios diverge meaningfully only around 2040, use of SSP2-4.5 alone is often enough for near-term (2030s) and mid-century (2050s) work. A defensible reclamation analysis reports a base case with bracketing sensitivities, not a single “worst case.”

The scenario framework is not static and a major development occurred while this paper was being prepared. In April 2026, the Scenario Model Intercomparison Project for the seventh Coupled Model Intercomparison Project (ScenarioMIP-CMIP7) published the scenario set that will underpin the IPCC Seventh Assessment Report (AR7) (Van Vuuren et al., 2026). The most important change for practitioners is that the highest-emission scenario of the CMIP6/AR6 era, SSP5-8.5 (and its precursor RCP8.5), has been judged implausible and removed from the core set. The new upper-bound scenario tops out near the former SSP3-7.0 level, well below SSP5-8.5. The CMIP7 authors state explicitly that “the CMIP6 high emission levels (quantified by SSP5-8.5) have become implausible, based on trends in the costs of renewables, the emergence of climate policy and recent emission trends.” (Van Vuuren et al., 2026)

The CMIP7 set includes seven scenarios named by emission trend rather than by radiative-forcing target, from Very Low to High. The new High scenario reaches approximately 6.7 W/m² in 2100, below the former SSP3-7.0 and far below SSP5-8.5, and it is framed explicitly as an exploratory “what-if” that assumes a rollback of current climate policy, not a business-as-usual projection. Two method improvements further lower projected warming relative to AR6: most scenarios are now run in emission-driven mode, which represents carbon-cycle feedback explicitly, and emissions are tied to observed 2023 data rather than the 2014 data used in CMIP6. The set spans a future temperature projection of roughly 1.5 to 3.5 °C of warming in 2100 relative to 1850-1900, a narrower and lower range than the AR6 SSPs.

This retirement confirms a conclusion the peer-reviewed literature (Burgess et al., 2021; Hausfather & Peters, 2020; Pielke et al., 2022) and British Columbia’s own provincial guidance had already reached. The BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) model- and scenario-selection guidance for the ClimateBC tool (Mahony & Foord, 2021) underpins much of the downscaled climate data used in the province. It recommends SSP1-2.6, SSP2-4.5, and SSP3-7.0 as the optimistic-neutral-pessimistic set, and it advises that SSP5-8.5 “should be used with caution,” calling its emissions pathway “extremely unlikely” on essentially the grounds later adopted by CMIP7. SSP5-8.5 persists in assessment and financial-risk frameworks largely because it was long mischaracterized as a “business-as-usual” pathway (Hausfather & Peters, 2020), which drew an outsized share of research attention and embedded it in the guidance based on that work. Where a regulator or reviewer still requests SSP5-8.5, it should be reported openly as an implausible upper bound, not adopted as a design expectation.

For now, practitioners should not abandon the AR6 SSPs. The downscaled, bias-corrected datasets and tools that mine-scale work depends on (CanDCS-M6, the PCIC Climate Explorer, IDF_CC, and ClimateNA) are all built on CMIP6 SSP projections, and equivalent CMIP7-based products are several years away, since CMIP7 Earth system model runs are only beginning in 2026. The defensible interim position is to keep using AR6-based downscaled data weighted toward the lower and middle scenarios, and to revisit these assumptions when CMIP7/AR7-based datasets become available.

Time Horizons

Three time horizons are in common use in climate change assessments: near-term (2021-2040), mid-century (2041-2060), and end-of-century (2081-2100). Uncertainty grows rapidly beyond 2100, and both the IPCC and most practical projection tools stop at that year. The BC MCM guidance (BC MCM, 2025) explicitly recommends that reclamation projections be limited to 2100. Table 1 gives the IPCC AR6 assessed warming for each SSP at these three horizons (Lee et al., 2021).

Table 1: IPCC AR6 (Working Group I) assessed change in global surface air temperature (GSAT, °C relative to 1850-1900) at the near-, mid-, and end-of-century horizons, across the Shared Socio-economic Pathways (Lee et al., 2021). Values are best estimates, with very likely ranges in parentheses.

SSP scenario	Near-term (2021-2040)	Mid-century (2041-2060)	End-of-century (2081-2100)
SSP1-1.9	1.5 (1.2 to 1.7)	1.6 (1.2 to 2.0)	1.4 (1.0 to 1.8)
SSP1-2.6	1.5 (1.2 to 1.8)	1.7 (1.3 to 2.2)	1.8 (1.3 to 2.4)
SSP2-4.5	1.5 (1.2 to 1.8)	2.0 (1.6 to 2.5)	2.7 (2.1 to 3.5)
SSP3-7.0	1.5 (1.2 to 1.8)	2.1 (1.7 to 2.6)	3.6 (2.8 to 4.6)
SSP5-8.5	1.6 (1.3 to 1.9)	2.4 (1.9 to 3.0)	4.4 (3.3 to 5.7)

It makes clear two points that are central to horizon selection. Firstly, the scenarios barely diverge in the near term, with all of them sitting near 1.5 °C by 2021-2040, but they spread widely by the end-of-century, from about 1.4 °C under SSP1-1.9 to about 4.4 °C under SSP5-8.5. Scenario choice therefore matters most at the longer horizons. Secondly, the very likely range within each scenario is itself substantial, reinforcing the base-case-plus-sensitivities approach noted above. Where regulators or other stakeholders raise specific concerns about conditions beyond 2100, the preferred response is not to force projections past the horizon of model confidence, but to agree on a framework for revisiting those concerns against the latest climate science later, when better models and a longer record have reduced the uncertainty.

FROM CLIMATE TO STREAMFLOW: ESTABLISHING A FUTURE BASELINE

A watershed model links climate projections to reclamation design. The framework here is tool-agnostic: the same principles apply whether the practitioner uses Raven (Craig et al., 2020), HEC-HMS, GoldSim, MIKE SHE, PRMS, or any other physically based or semi-distributed model.

The Historical and Future Baselines

A watershed model is first calibrated against the historical record. This historical baseline is the foundation of credibility; without it, future projections have no anchor. What makes it defensible is largely independent of the model: a calibration period long enough to sample year-to-year variability, regional supplementation where on-site records are short, and a clear demonstration that the calibration period represents the longer climatological record (or, if it does not, a statement of how it differs).

Reclamation planning asks a counterfactual question: *what would the hydrology of the site look like at closure and beyond, if the mine were not there?* Answering this question requires a **future baseline**, a climate-change-affected streamflow series that is free of any mine-induced alterations. The future baseline is distinct from both the historical baseline (observed, pre-change) and the operational or post-closure case (which includes mine landforms, pit lakes, diversions, and active or passive water management).

Climate change and mine effects act on the same water balance and can compound. A climate-driven drop in summer low flows, for example, can add to a mine-driven loss of dilution, so the combined closure condition may be worse than either effect alone. Assessing the mine against the future baseline, rather than the historical record, is what exposes this compounding.

Generating a Future Baseline

Two approaches are widely used to translate GCM output into forcing for a calibrated watershed model:

1. **Delta-change (or climate-change factor) methods**, in which monthly or seasonal changes in temperature and precipitation from the GCM ensemble are applied to the observed historical data. This preserves observed sequencing and variability but does not introduce changes in the structure of variability itself.
2. **Bias-corrected, statistically downscaled GCM outputs**, used directly as model inputs. The Quantile Delta Mapping (QDM) method (Cannon et al., 2015), used by ECCC and PCIC to produce the CanDCS-M6 dataset, is a widely adopted approach that aligns downscaled model data with local station observations to ensure historical and future projections are directly comparable on a like-for-like basis. This approach preserves some of the projected changes in variability and extremes, at the cost of introducing the biases and dependencies of the downscaling procedure (Cannon et al., 2015; Wang et al., 2016).

Each approach has trade-offs in variability, extremes, inter-variable consistency, and bias. The choice usually depends on ensemble size, availability of downscaled data, and the downstream model's sensitivity. In many reclamation applications, delta-change methods are adequate for seasonal water balance work, while bias-corrected downscaling is preferred when extremes matter.

What a Future Baseline Reveals

Across mine projects in western Canada, future baseline streamflow series show a consistent set of signals: an earlier freshet; lower freshet peaks as snowpack accumulation declines; lower summer flows; larger fall rainfall peaks; and higher winter baseflow. Figure 5 illustrates this at a partially glaciated coastal-mountain project in northwest BC. In the baseline condition (grey line), the annual peak flow is the spring freshet. Under each SSP, the freshet peak shrinks and arrives earlier while the fall rainfall peak grows, so that by end-of-century the governing peak flow event shifts from the spring freshet to fall rainfall.

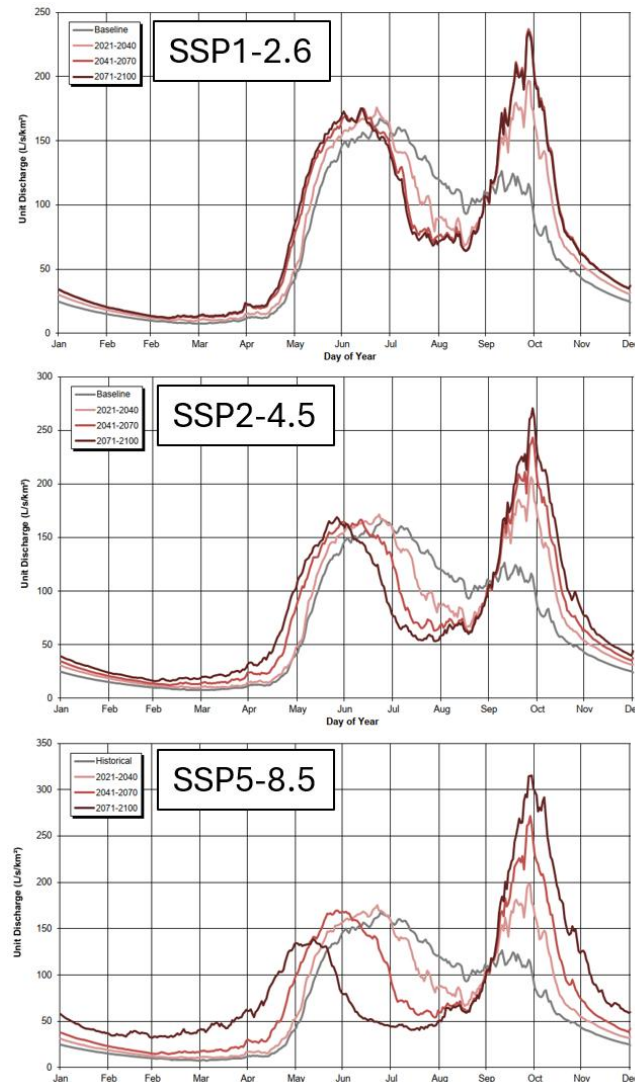


Figure 5: Simulated future baseline streamflow at a partially glaciated coastal-mountain project in northwest BC under SSP1-2.6, SSP2-4.5 and SSP5-8.5. The baseline (grey) peaks at the spring freshet; under the SSPs the freshet peak shrinks and arrives earlier while the fall rainfall peak grows to become the annual peak flow.

These projections come with an important caveat: watershed models calibrated on a historical record are being asked to simulate climate outside their calibration range. Hydrological processes may not respond linearly to shifts in snow fraction, to glacier loss, to degrading permafrost, or to vegetation phenology, and the calibrated parameters carry no information about thresholds that have not yet been crossed. This is an unavoidable feature of climate-change work, not a reason to avoid it: end-of-century projections should be reported with explicit acknowledgement of structural uncertainty and should not be relied on alone for design.

Propagation Through the Downstream Model Chain

A climate signal does not stop at streamflow. In a typical mine closure prediction framework (Figure 6), streamflow output from the watershed model is an input to the site-wide water balance, which in turn drives water quality predictions; groundwater models provide baseflow partitioning that both feeds and is fed by surface hydrology; dam-breach and flood-routing models depend on peak-flow characteristics that shift with the regime; and geochemistry and water-treatment assumptions depend on concentrations set by dilution flows. A climate signal introduced only at the top of this chain, without flowing through to the downstream models, produces internally inconsistent closure predictions.

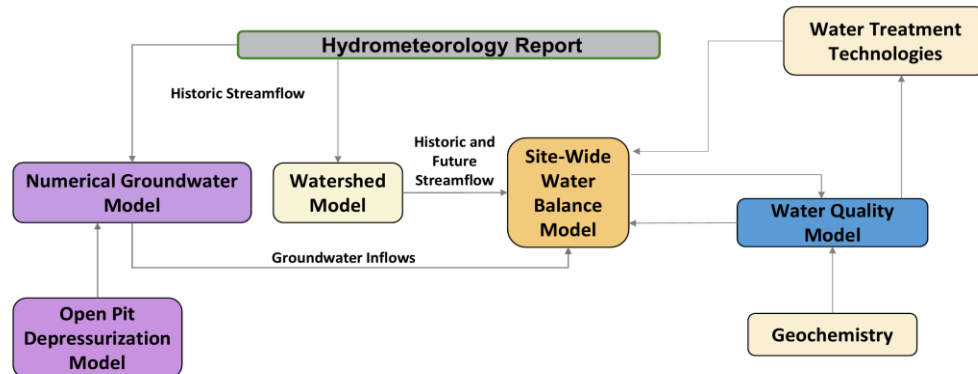


Figure 6: Interaction of climate-affected streamflow with downstream models in a typical mine water-management prediction framework.

Figure 7 shows the practical implementation used at the coastal-mountain project: a matrix of calibrated watershed model runs across SSPs and time horizons, each producing a streamflow realization that is then passed to the downstream water balance/water quality model. The same structure applies whether the downstream models are GoldSim, a custom spreadsheet water balance, MODFLOW, or a combination thereof.

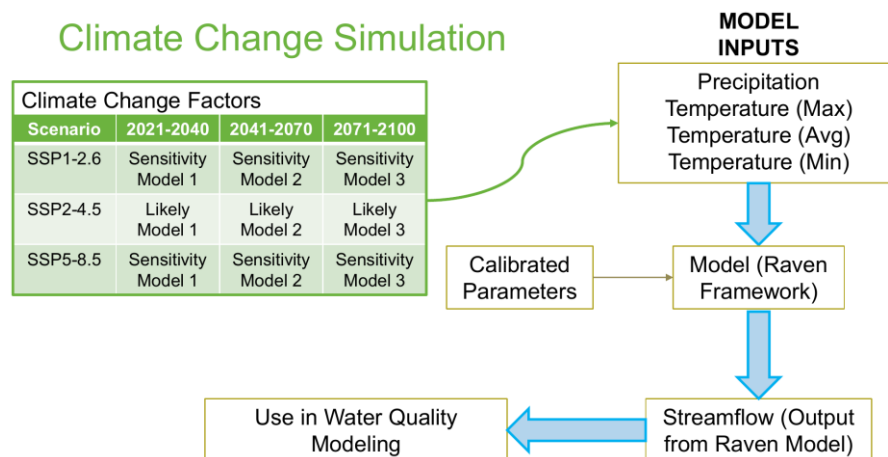


Figure 7: Climate-change simulation framework for the watershed model: matrix of $GCM \times SSP \times$ time-horizon realizations fed to downstream models.

Four propagation pathways deserve attention. In the **site-wide water balance**, shifts in seasonality change the timing of storage filling and drawdown. Larger, earlier freshet volumes combined with larger fall peaks may exceed design storage under stationary assumptions, while drier mid-summer periods may reduce supply to passive treatment or reclamation irrigation, and annual totals alone are insufficient. For **groundwater**, changing snow fraction, earlier snowmelt, and degrading permafrost at northern sites alter recharge partitioning and baseflow; baseflow is frequently the dominant winter source of water for water-quality dilution and for persistence of wetlands and pit lakes in closure, and small fractional changes in baseflow can produce large changes in winter low-flow concentrations of water quality constituents. For **dam breach and flood design**, when the governing peak flow event shifts between freshet and fall rainfall, the characteristics of the design event (volume, duration, instantaneous peak, and antecedent conditions) all change. Environmental Design Flood (EDF) and Probable Maximum Flood (PMF) selections made against a stationary climate may then no longer identify the actual governing case. Finally, for **water quality**, winter low flows typically govern predicted concentrations of mine-influenced constituents; because winter low flows are projected to increase at many northern sites, climate change is in some cases a dilution benefit rather than a penalty for water quality, but this is site-specific and must be demonstrated rather than assumed.

CASE STUDIES AND LIMITATIONS

Case Studies

The climate change assessment framework has been applied to four projects spanning a wide range of climatic and geographic settings.

The **coastal-mountain project (BC)** lies in a partially glaciated, transboundary watershed in the Coast Mountains of northwest BC and supports fish-bearing reaches near its mouth. Regional WSC records (Bear River, Iskut River, Surprise Creek) show a statistically significant upward trend in mean annual discharge, and future baseline projections predict that the annual hydrograph will have an earlier freshet, lower freshet peaks, and larger fall rainfall peaks across all SSPs.

The **high-latitude project (Yukon)** lies in an area of Yukon with discontinuous permafrost. The limited on-site climate record required extensive regional and reanalysis supplementation, and climate change conditions are pronounced as polar amplification has produced one of the fastest observed warming signals in Canada. The watershed model had to represent active-layer behaviour with temperature-dependent soil parameters, with sensitivity analysis allowing a 10-30% increase in percolation to reflect permafrost degradation. A deeper challenge at this project is that few hydrologic models can represent *changing* permafrost: conventional calibrated parameters treat frozen-ground extent as fixed and cannot simulate the progressive thaw, deepening active layer, and shifting recharge expected over the projection period. Model availability for evolving permafrost is therefore itself a factor in model selection for high-latitude closure work; where it is lacking, the permafrost response is best bracketed by sensitivity analysis rather than direct modelling. Future baseline projections predict that the annual hydrograph will remain freshet-dominated but with an earlier freshet of similar peak magnitude, alongside higher summer and fall flows from increased rainfall and higher winter baseflow across all SSPs.

The **interior plateau project (BC)** lies in the Thompson-Nicola region of south-central BC, which has a continental interior setting with a mainly snowmelt-driven regime. Long-term records (1935-2025) show

significant warming and precipitation increases, while streamflow shows stable annual totals but a clear shift towards an earlier freshet and lower late-summer flows. A key result at this project is that the projected increase in extreme rainfall scales well below the Clausius-Clapeyron expectation of about 7% per °C of warming, so design rainfall rises more slowly than warming alone would imply. Future baseline projections predict that the annual hydrograph will shift toward an earlier, somewhat smaller freshet as the snowfall fraction declines, with lower late-summer flows under higher evaporative demand and higher winter flows from the shift to rain across all SSPs.

The **high-altitude Andean project (Argentina)** lies in an arid zone of the Andes Mountains, where the framework was applied to water balance modelling under international emission scenarios, with ensemble selection following the host-jurisdiction principle of dropping models with large equilibrium climate sensitivity biases. A key consideration here was retreating glaciers: glacier- and snowmelt-fed flows that sustain dry-season water availability are expected to decline as the ice reserve is depleted, so the future baseline must account for the loss of this glacial buffering rather than assume a stationary glacial contribution. Future baseline projections predict that the annual hydrograph response will vary across the watershed: glacier-fed catchments lose their spring-summer melt peak and shift toward winter-weighted flow as the ice reserve is depleted, while higher non-glacial catchments see modestly increased flows as warming reduces snowfall and sublimation losses, across all SSPs.

All four projects involved modelling of the SSP5-8.5 scenario, which reflects that the work predated the CMIP7/AR7 guidance that has since judged the pathway implausible, and that stakeholders and regulators asked for the high-emission case to be carried as a conservative bound. If the same studies were initiated today, SSP5-8.5 would be reported only as a clearly flagged stress test, not as a design scenario.

Across these projects, the common outcome is the same: the future baseline conditions differ materially from the historical baseline conditions, the directions and sizes of the changes are site-specific, and downstream water balance and water quality predictions are sensitive to how the future baseline simulations are built.

Uncertainty and Limitations

Climate-aware reclamation water-resources work carries uncertainty at every step: the GCM ensemble, the emission scenario, the downscaling, the watershed model structure and parameters, and the downstream models that use the future baseline simulations are all uncertain. The best approach for assessing future climate conditions and their potential effects is not to seek a single “right answer,” but to characterize the uncertainty in the estimates, usually through a matrix of SSPs and time horizons reported with a clear base case and bracketing sensitivities. Early, open engagement with regulators, Indigenous communities, and independent reviewers on the assumptions behind the future baseline assessment is essential; these assumptions almost always matter more than the choice of modelling platform.

CONCLUSION

Assessing potential climate change effects is no longer optional in reclamation planning; it is a core input to water-resources characterization and engineering design. Practices built on stationary-climate assumptions will often underperform under projected conditions, either by mis-sizing water infrastructure for a shifted peak regime or by mistaking mine-related changes for climate-driven ones. The framework outlined here is to (i) characterize historical non-stationarity, (ii) select a defensible set of GCMs, scenarios,

and time horizons, (iii) generate a future baseline streamflow series, (iv) propagate it consistently through the downstream model chain, and (v) use it to inform reclamation design. This approach provides a defensible basis for meeting the regulatory and professional expectations now in place in British Columbia, in Canada, and internationally. Used with the ecology-focused frameworks in Nickels et al. (2025) and BC MCM (2025), it supports the development of reclamation landscapes that remain fit for purpose through the end of the 21st century.

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