Practical Guidance for Adjusting Rainfall Annual Exceedance Probability Estimates for Climate Change

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Abstract

Mine water management infrastructure is commonly designed to pass or retain runoff resulting from a design rainfall event. The annual exceedance probabilities for these events are developed using a historical record of extreme rainfall. Extreme rainfall events are increasing in magnitude globally at a non-linear rate of approximately 7%/degree Celsius, consistent with the Clausius-Clapeyron relationship. This trend is expected to continue with projected climate change and may lead to water management upset conditions if not properly accounted for in design criteria calculations. This paper provides guidance to aid practitioners in addressing this developing issue.

Keywords: Climate change, rainfall, annual exceedance probabilities, risk management, mine water management

Introduction

The likely range of human caused warming from 1850–1900 to 2010–2019 is between 0.8 °C and 1.3 °C, with a globally averaged increase in precipitation since 1950, and a faster rate of increase since 1980 (IPCC, 2023). The globally averaged 20th and early 21st century rate of increase in annual maximum daily rainfall intensity is estimated to be 5.9 to 7.7% per °C of average near-surface atmospheric temperature warming (Westra *et al*., 2013a), with higher rates of increase noted in the high latitudes of the Northern Hemisphere and the tropics, and lower rates in the arid mid-latitudes.

The intensity of high-magnitude rainfall events is a function of the moisture content of an air mass (*i.e*., precipitable water), which in turn is a function of the air mass temperature. This relationship can be described by the Clausius-Clapeyron (CC) equation, which shows the moisture capacity of air will increase by approximately 5–8% for each 1 °C increase in temperature, depending on the baseline air temperature value. Specifically, the CC equation [Equation 1] expresses the saturation pressure of water vapour as a function of atmospheric pressure, where:

$$\ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad \text{[Equation 1]}$$

- P_1 and P_2 are vapour pressures (in standard atmospheres) at temperatures T_1 and T_2;
- ΔH_{vap} is the enthalpy of vapourization (40.7 kJ mol^{-1});
- R is the gas constant (8.3145 J mol^{-1} K^{-1});
- T_2 is equal to the vapour pressure of water (1.0 atmosphere or 1013.25 mb) at the boiling point (373 K (100°C); and,
- T_1 is set to the temperature for which the vapour pressure is to be calculated.

In general terms, the CC equation returns an exponential rise in vapour pressure with increasing air temperatures (Fig. 1), which means that with future warming, extreme precipitation events may be expected to increase in a non-linear fashion and could be higher for rarer events. Such projected increases will vary at regional scales depending on the amount of regional warming, changes in atmospheric circulation, and storm dynamics (Seneviratne *et al*., 2021). This has relevance to the design and operation of both existing and proposed mine water management infrastructure, which are commonly designed to handle runoff events that fall within the historical rainfall distribution based on annual exceedance probabilities (AEPs; e.g., 1:100-year 24-hour rainfall event).

Derivation of rainfall AEPs for current conditions are subject to several sources of uncertainty, including:

- Underrepresented spatial variability and magnitude of rainfall due to sparse monitoring networks in most regions, particularly for highly localized convective storms;
- Under catch due to wind effects and undersized gauge orifices, and relatively short-duration climate record lengths;
- Application of statistical distributions to represent high-magnitude events, particularly those located on the tails of the distributions, where representative samples from the monitoring records are limited or unavailable; and,
- A chaotic climate system exhibiting natural (internal) variability, which is intrinsic to the climate system and therefore irreducible.

Consideration of projected climate change adds further uncertainty regarding rainfall AEPs, as a changing climate may lead to changes in storm dynamics and shifts in synoptic storm tracks (e.g., atmospheric rivers, hurricanes), and therefore local rainfall distributions that deviate from historical conditions.

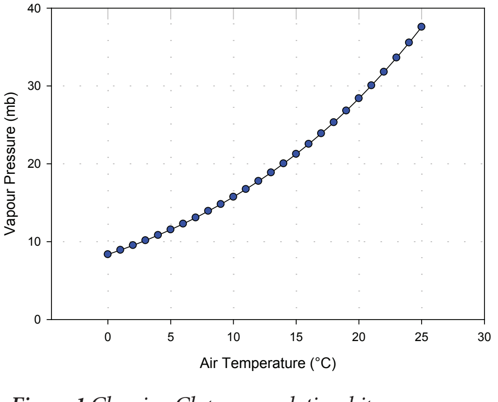

***Figure 1** Clausius-Clapeyron relationship.*

Global standards or accepted research methodology to determine how future extreme rainfall events of less than 1-day in duration may change in frequency and intensity over local areas are lacking (CSA, 2019). Furthermore, General Circulation Models (GCMs) are currently unable to fully resolve local scale convective processes and synoptic scale systems that lead to extreme precipitation and therefore, estimates of short duration rainfall derived from recent GCM outputs (at time of writing) are not reliable (Li *et al.*, 2019). Recent attempts to estimate Probable Maximum Precipitation amounts for < 1-day duration using modelling approaches have shown promise (e.g., Hiraga *et al.*, 2025), however the intensive data and modelling requirements are often not practical for use in developing inputs to mine water management infrastructure design.

The guidance outlined herein aims to address the gap between current state of knowledge with respect to the relationship between air temperature increases and precipitation event magnitude, and current approaches to developing rainfall AEP estimates, while providing practitioners a means to scale these estimates for a range of potential climate change outcomes.

Methods

There are three primary components to this guidance (Fig. 2):

1. Evaluate the original AEPs that an existing piece of infrastructure was designed to and determine whether the AEPs are appropriate for continued use.
2. Confirm the design life of the infrastructure in question.
    - If the design life < 10 years, apply an AEP scalar based on a +1 °C air temperature increase above the reference period; and,
    - If design life > 10 years, conduct a standard risk assessment for the infrastructure in question, using a probability: consequence matrix, and developing AEP scalars as outlined below.
3. Estimate future AEPs for relevant time scales and emissions scenarios.
    - Conduct a risk assessment for current conditions;

- Characterize site-specific changes to climate regime (historical and projected);
- Select a climate change emission scenario for scalar development;
- Apply climate change scalars to precipitation AEPs; and,
- Review of triggers for additional or future assessment.

The first step is the evaluation of both the original AEP estimates that the infrastructure of interest was designed to handle, and if available, current AEP estimates for the site. This should be completed by a qualified practitioner and ideally, should take into consideration all available site and regional climate data, industry best practices, technical guidance and relevant regulatory standards. If relevant to the site of interest, high-magnitude snowmelt events and the potential for overlap with extreme rainfall events should also be quantified. Next, a review of site-specific trends in air temperature, precipitation, and relevant changes in local synoptic patterns, including storm track changes, duration, and rainfall magnitude should be undertaken to provide a baseline understanding of changes already occurring.

Once the above evaluation steps are completed, a determination of the infrastructure design life should be made. Given that projected increases in air temperature and air moisture capacity are expected to progress throughout the next century (Seneviratne *et al.*, 2021), the magnitude of derived rainfall scalars are expected to increase under all emissions scenarios over the next several decades. As a result, determination of the expected design life is foundational to the recommended approach to developing rainfall AEP scalars. In summary, the longer the design life, the greater the uncertainty in climate change projections, and therefore higher emissions scenario projections are recommended for use in these circumstances.

Given the relatively low variation in projected temperature changes between emissions scenarios over the next 10-years (out to approx. 2040), a simplified approach is recommended whereby a +1 °C air temperature increase from the reference period is assumed, with scalars developed using this temperature change as input to the CC equation (Fig. 2).

If the design life is greater than 10 years, then a risk assessment is recommended to be conducted, taking into consideration the cumulative probability of exceedance (PoE) of a given rainfall AEP over the full design life (n in Equation 2).

$$\text{PoE} = 1 - (1 - AEP)n \qquad \text{[Equation 2]}$$

Accordingly, the cumulative probability of exceedance increases with each successive year of operation, such that the likelihood of failure may become relatively high, should the works be in use for a long period of time. The PoE can be applied within a risk matrix to determine the Likelihood of an event occurring (Tab. 1), which can then be cross-referenced against the consequence of infrastructure failure resulting from a rainfall event exceeding design criteria.

For example, a structure with a design life of 25 years designed to a 1:100-year event would have an expected 22% PoE over a 25-year operational period, returning a Likelihood of Unlikely (Tab. 1). The association between Likelihood and PoE is based upon standard risk assessment practices and probabilities of occurrence.

Once the risk categorization has been completed, the next step is to select the emissions scenario to be used for developing the AEP scalars. Emissions scenario selection is based upon both the design life and risk categorization for the infrastructure in question (Fig. 2).

Forward looking projections of future climate outcomes are generated using GCMs, which are driven by greenhouse gas forcings. These forcings are based upon scenarios that envision various Shared Socioeconomic Pathways (SSPs). These emissions pathways begin in 2015 and are summarized below for the scenarios recommended for use in this guidance:

- SSP2-4.5: Intermediate greenhouse gas emissions, with CO_2 emissions remaining around current levels until mid-century, then decreasing;
- SSP4-6.0: Higher emissions than SSP-4.5, with CO_2 emissions peaking in 2050 and declining thereafter;

Table 1 Likelihood and Cumulative Probability of Exceedance.

Likelihood	Cumulative Probability of Exceedance
Almost Certain	≥ 95%
Likely	≥ 75% to < 95%
Possible	≥ 25% to < 75%
Unlikely	≥ 5% to < 25%
Highly Unlikely	≥ 0.1% to < 5%
Extremely Remote	< 0.1%

- SSP3-7.0: High greenhouse gas emissions, with CO_2 emissions doubling from current levels by 2100; and,
- SSP5-8.5: Very high greenhouse gas emissions, with CO_2 emissions doubling from current levels by 2050.

These SSPs translate to projected global average temperature increases of 1.5 °C over the near term (all SSPs; 2021–2040), a range of 1.6 to 2.4 °C over the mid-term (2041–2060), and a range of 1.4 °C to 4.4 °C over

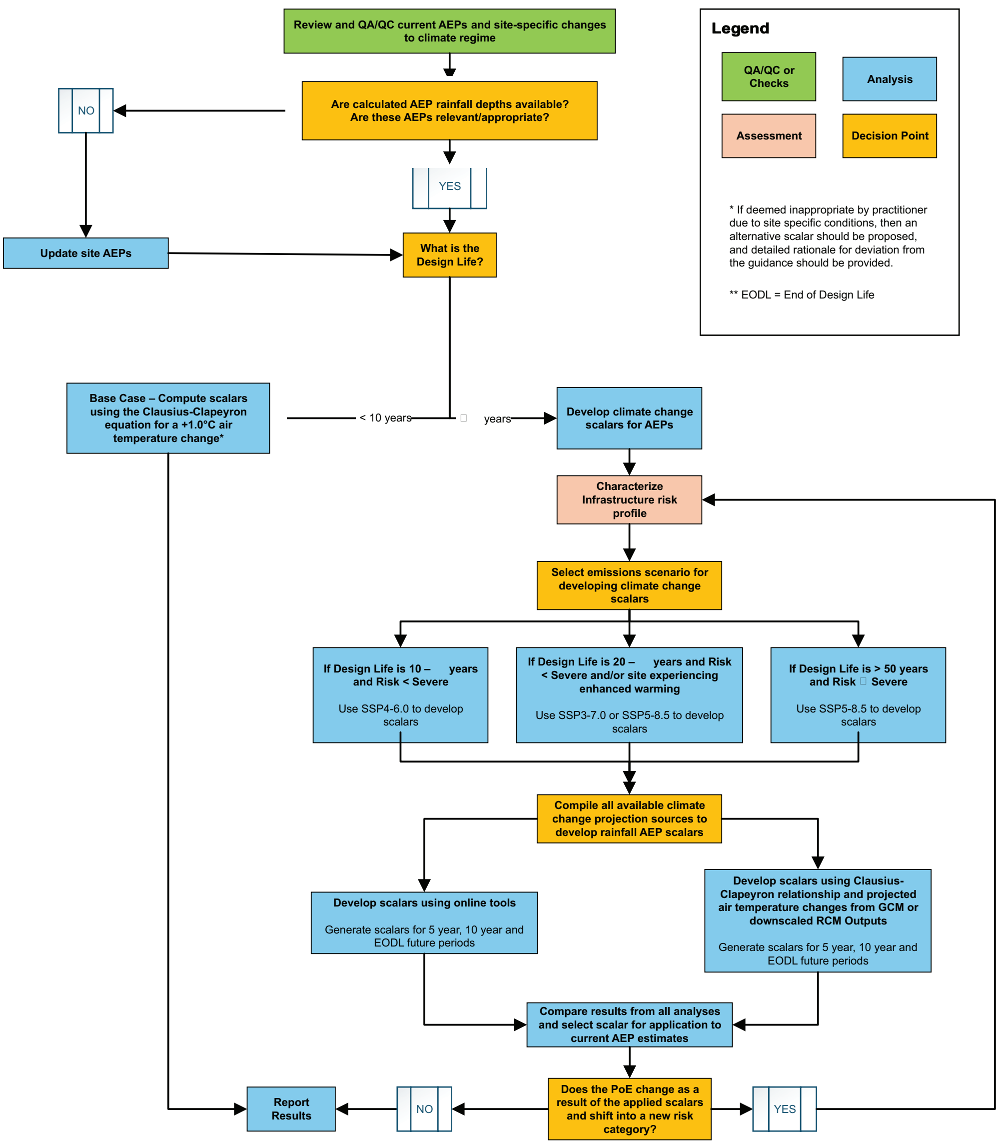

Figure 2 Decision tree showing assessment process for scaling rainfall annual exceedance probability estimates for projected climate change based on the infrastructure design life.

the long-term (2081–2100). These projected temperature increases are directly linked to the atmospheric moisture capacity, as defined by the CC equation.

Minimal difference in the projected global temperature change by 2050 is expected between emissions scenarios, but beyond this point, divergence between scenarios becomes pronounced. By the end of this century, the projected global temperature increase is approximately 2.8 °C for the SSP2-4.5 scenario, and 4.7 °C for the SSP5-8.5 scenario. Therefore, the recommended conservative approach to selecting emissions scenarios is based primarily on the design life of the structure. A shorter design life is linked to lower emissions scenarios, and a longer design life (i.e., > 20 years) linked to higher emissions scenarios (Fig. 2). In cases where the design life is > 50 years, the SSP5-8.5 scenario is recommended outright, in alignment with the guidance in ECCC (2020).

Once the emissions scenario has been selected, rainfall AEP scalars are derived using the following methods:

1. Using downscaled projection data for the study region supplied in online tools (if available); and,
2. Applying the Clausius-Clapeyron equation to local estimates of air temperature change.

It is assumed that the practitioner will apply professional judgement when assessing the utility of available online tools. If no downscaled products providing climate change scaled estimates of precipitation are available for the study area, then the current AEPs can be adjusted using the air temperature change projections and the CC relation as a conservative, physically based approach. The CC equation is applied to calculate the potential vapour pressure of an air mass at a given temperature, which is directly proportional to the precipitation depths that air mass can generate. This is recommended to be done for the current reference period, and for the future periods that scalars are required for (generally for the 5-year, 10-year and end of design life periods). Once these vapour pressure potential values have been generated, a scalar can be developed by:

$$Climate\ Scalar = \frac{Future\ Vapour\ Pressure\ Potential}{Current\ Vapour\ Pressure\ Potential} \qquad \text{[Equation 3]}$$

This approach should also be taken as a check on scalars derived from online products. Once this has been done, the practitioner should compare the results from all analyses (e.g., online tools, CC equation) and select the most appropriate scalar values to be applied to the current AEP estimates.

After the current AEPs have been scaled for projected climate change under the selected emissions scenario, a final check should be conducted to determine whether the updated AEPs shift the Likelihood into a higher category (Tab. 1) and therefore have the potential to increase the assessed risk profile for the infrastructure (Fig. 2).

The state of knowledge surrounding climate change induced increases in extreme rainfall is continually evolving. Similarly, mine sites and associated water management infrastructure are in a constant state of flux. Accordingly, the following events should be considered as triggers for revisiting the rainfall scalar assessment:

- An increase in structure design life of > 10 years;
- Future IPCC assessment reports provide significantly different (i.e., higher) temperature delta predictions;
- An update to the risk assessment matrix used in the analysis or underlying components; and,
- The occurrence of one or more significant rainfall event(s) that alters the underlying frequency distribution, and therefore the current AEP estimates.

Conclusions

It is likely that rainfall AEPs developed using historical data will not be representative of future conditions as the global climate continues to warm. Given the importance of these values for the safe design and operation of mine water management infrastructure, it is critical that a science-based methodology be employed to develop robust estimates of future rainfall magnitude.

A methodology is presented herein to guide practitioners through the process of developing future scalars for rainfall AEPs based on infrastructure design life considerations, standard risk assessment practices, climate change projections from the International Panel on Climate Change's Sixth Assessment Report, and the well-established relationship between air temperature, moisture capacity and extreme rainfall depths.

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