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The importance of climate for evapotranspiration cover design

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Abstract

Mine closure typically includes covering various waste facilities to stabilise landforms, control seepage, reduce erosion, and protect the environment. Commonly, evapotranspiration covers (also referred to as alternative, store and release, or water balance covers) are preferred for many mine sites. Evapotranspiration (ET) covers rely on evaporation and transpiration to reduce seepage through mine waste, which may require management or treatment to avoid adverse environmental impacts. Given ET covers rely on the natural processes of evaporation and transpiration to reduce seepage, the surrounding climate will ultimately control the performance of the ET cover. Consequently, climate is a key factor in predicting the performance of an ET cover. Several guidance documents have been published regarding best practices for the design of ET covers, although current guidance does not include comprehensive, detailed standards or best practices to develop a climate set to be used in soil-atmosphere modelling to design ET covers. This paper presents important factors to consider when compiling a climate set for soil-atmosphere modelling to design an ET cover, beyond the generalisations in current guidance documents, so that designers can make informed decisions when developing a representative climate set.

Ideally, a climate set for soil-atmosphere modelling to support ET cover design would be developed using 100-year dataset, including co-located, daily measured precipitation and estimated potential evapotranspiration (PET). Using a shorter climate set presents the risk of over- or underestimating net infiltration. Accurate simulation of the variation of both precipitation and PET at several time scales is critical for ET cover design. This includes the distribution of precipitation and PET throughout the year as well as variations over the long-term. Representing the distribution of precipitation seasonally (e.g. between winter and summer or dry and wet seasons), the number of days of precipitation in a year, the intensity of precipitation, and the frequency of storm cycles are important considerations.

The relationship between precipitation and PET is critical to understand and simulate appropriately. Because relationships between precipitation and temperature, relative humidity, wind speed, and solar radiation are complex, combining data measured at multiple sites may not represent climate at any one site appropriately. When compiling climate sets, significant preference should be given to scaling climate data from one location rather than combining data from multiple locations. Further, although many climate models have been developed, users should be aware of the basis of formulation for each model, the errors in the models, the quality of the data used to develop the model, and comparisons of the modelled data to measured data for the mine site to adjust the modelled data appropriately. Finally, developing a robust climate set with uncertainty limited to a practical extent will also serve to reduce uncertainty in predicting the potential influence of climate change.

Keywords: *evapotranspiration cover design, water balance cover design, soil-atmosphere modelling, climate for soil-atmosphere modelling*

1 Introduction

Mine closure typically includes covering various waste facilities to stabilise landforms, reduce erosion, and reduce seepage of acidic or metal-rich water in the long-term. Commonly, evapotranspiration covers (also referred to as alternative, store and release, or water balance covers) are preferred for many mine sites. Evapotranspiration (ET) covers rely on evaporation and transpiration to reduce seepage through mine waste, which may require management or treatment or may impact the environment if not contained. Given ET covers rely on the natural processes of evaporation and transpiration to reduce seepage, the surrounding climate will ultimately control performance of the ET cover. Consequently, climate is a key factor in predicting the performance of an ET cover. Several guidance documents have been published regarding best practices for the design of ET covers (e.g. Albright et al. 2009; International Network for Acid Prevention [INAP] 2017; INAP 2022; Interstate Technology & Regulatory Council [ITRC] 2003; Mine Environment Neutral Drainage [MEND] 2004), although current guidance does not include comprehensive, detailed standards or best practices to develop a climate set to be used in soil-atmosphere modelling to design ET covers.

The International Network for Acid Prevention (INAP) Cover Guidance Document states:

> *"Climate cannot be modified through engineering, at least to any large extent, and therefore it forms the basis of design." (INAP 2017, p. 21)*
>
> *Climate is the ultimate governor of cover system performance at a mine site. While certain cover system design parameters can be adjusted to a degree, the climate at a site cannot be controlled. Therefore, it is imperative that the designer fully understands the dominant climate at a site. All too often a simple average of climate parameters is an input into the models used during the cover system design process. Not only does an average value of precipitation or air temperature result in an unrealistic generalization of conditions, it fails to account for the cycles of variation inherent in all climate signals. Failure to examine the scales of variability within a climate dataset necessarily results in a spurious simplification of a complex system." (INAP 2017, p. 41)*

Precipitation, temperature, and other climate parameters vary on seasonal, annual, and decadal cycles. Consequently, the cover designer should develop long-term climatic data to represent the mine site. The INAP Cover Guidance Document (INAP 2017) includes a cover system design tool. The first step of the tool is to classify the climate for the site based on the Köppen climate classification system. This highlights the significant influence of climate on cover performance.

Similarly, the Global Acid Rock Drainage (GARD) Guide (INAP 2022) provides a caution regarding the use of annual criteria alone for ET cover design because wet/dry seasons or wet/dry months may represent periods when precipitation exceeds potential evapotranspiration (PET). Alternately, consecutive storms may limit the period during which PET can remove water stored in the near-surface between storms. The GARD Guide (INAP 2022) includes the schematic in Figure 1, which classifies potentially suitable cover types on the basis of climate types. The tri-linear plot includes climate classification, precipitation, and the ratio of PET to precipitation as well as general correlations for temperature and latitude. General cover types are indicated based on the PET ratio, with water covers indicated for climates with a PET ratio of less than 1 and 'dry' covers for climates with a PET ratio of greater than 1, while frozen covers may be appropriate in polar regions.

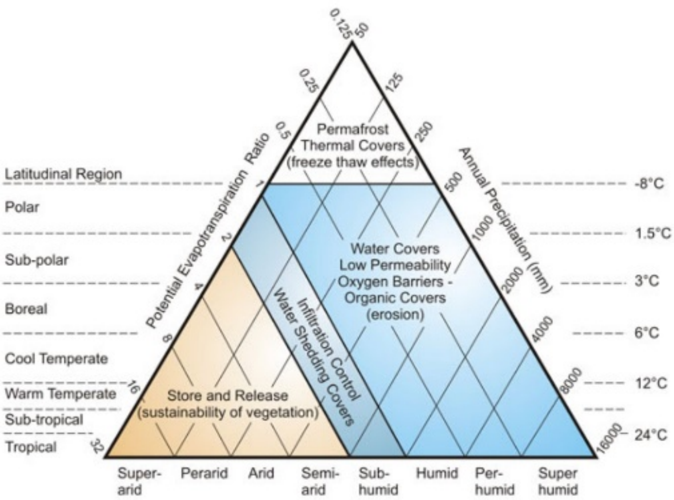

Figure 1 Cover and climate types (International Network for Acid Prevention 2022)

Finally, guidance for the solid waste industry in the United States (USA) generally states that a minimum of 20 years of climate data for the site is needed to support cover design (Albright et al. 2009; ITRC 2003). Further, cover design is typically based on defining a 'typical' year and a 'design' period that may be the wettest year on record or the 10-year period with the highest average annual precipitation. Albright et al. (2009) state simulations using longer-term records are not common due to the long run times required.

Given soil-atmosphere modelling is commonly employed to predict ET cover performance and support the ET cover design process, developing an appropriate climate set for the modelling is critical for predicting realistic and reliable cover performance. This paper presents important factors to consider when compiling a climate set for soil-atmosphere modelling to design an ET cover, beyond the generalisations in current guidance documents, so that designers can make informed decisions when developing a representative climate set.

2 Ideal climate set

Ideally, a climate set for soil-atmosphere modelling to support ET cover design would be developed using long-term, co-located, daily measured precipitation and estimated PET. PET may be estimated using a variety of methods (e.g. Allen et al. 1998 and references therein; Allen et al. 2005), which rely on daily measurements of temperature, relative humidity, wind speed, and net radiation. Alternatively, pan evaporation may be used to estimate PET, although this method is generally less desirable (Allen et al. 1998).

In the USA, Australia, Canada, and many countries in Europe, precipitation and temperature have been measured at many locations for periods approaching or exceeding 100 years. However, measurements of the climate parameters needed to estimate PET, such as relative humidity, wind speed, and net radiation, are not measured in many locations. Further, where these parameters have been measured, the periods of record may only be the past 20 to 30 years.

Mine sites are commonly located in remote areas where long-term climate data of any type may not have been measured. This presents challenges to develop datasets that would represent climate at a mine site over the periods needed to support assessments for closure. As a result, cover designers may be faced with replacing missing data, using modelled data, or compiling a synthetic climate set.

3 What is long-term?

Many mine wastes will require perpetual management, especially if the mine waste is geochemically reactive and would adversely impact the environment if not managed appropriately. Logsdon (2013) suggests a planning period of 200 years for the management of mine wastes. Further, closure planning should include a semi-quantitative assessment of the potential for significant changes between 200 and 1,000 years. Similarly, the *Uranium Mill Tailings Radiation Control Act of 1978* (Federal Government of the United States 1978) in the USA requires control of tailings "shall be effective for up to 1,000 years to the extent reasonably achievable and, in any case, for at least 200 years". The Global Industry Standards on Tailings Management (Global Tailings Review [GTR] 2020) states the design of tailings facilities should consider 10,000-year return period events for post-closure (passive care versus active care during operations and closure). Therefore, mine wastes that require an ET cover for closure and post-closure would also require the cover perform adequately over similar time periods as required for design of the facilities.

MEND (2012) recommends that cover systems are designed using a minimum 100-year design life and the design should be evaluated on a site-specific basis using a risk-based approach. MEND (2012) expands on the basis of design and states a 100-year climate set should be used, in addition to evaluating potential effects of climate change over 100 years, including the potential influence of climate change on the vegetation community. Similarly, many models used to assess climate change are projected to 2100 (e.g. Intergovernmental Panel on Climate Change [IPCC] 2014).

A climate set that is based on 100 years of climate data, at a minimum, should be developed to support ET cover design for mine sites. Further, the 100-year climate set should be suitable for use with soil-atmosphere models to support the ET cover design process. Therefore, the 100-year climate set should include precipitation and the parameters needed to estimate PET. Consequently, the climate set developed should be a *complete* climate set. Given that precipitation, temperature, and other climate parameters vary on seasonal, annual, and decadal cycles, it is critical to capture as much variation in the climate data as possible to predict cover performance in the future.

Although a minimum of only 20 years of climate data is recommended for the solid waste industry (e.g. Albright et al. 2009; ITRC 2003), landfills are located near populated areas so that any significant failures of ET covers may be repaired in a timely manner. Since many mine sites are located in remote areas, in some cases cannot be accessed reasonably year round, and few to no personnel will be present at the site during post-closure, passive care in post-closure should be assumed (GTR 2020). Consequently, closure and post-closure planning must include a long-term perspective. ET cover design must include a robust climate set that includes natural variation of climate over a time period as long as reasonably practicable.

The potential error in designing an ET cover with a short climate set may be that net infiltration (water that infiltrates the surface and is not subsequently removed through evaporation or transpiration; also referred to as deep drainage, seepage, or percolation) is over- or underestimated. Two examples are provided to illustrate the potential errors. For the first example, annual precipitation from one large city in each of the 10 western states in the USA (https://wrcc.dri.edu/) was analysed. The average period of record for the 10 cities was 108 years. The annual departure from the long-term mean of each year was calculated (the difference of the annual precipitation from the mean using the full period of record). In addition, the average of 20-year, 30-year, and 60-year periods were calculated from 1901 to 2020. The departure for the sub-period averages from the long-term mean was also calculated.

For all 10 cities, the maximum departure for the 20-year averages is 24%, while the average is 8%. The departure for the most recent data is greater than the long-term average for nine of the 10 cities evaluated. Consequently, a climate set developed using only recent data would include wetter than average precipitation.

Figure 2 presents the calculations from a location outside Seattle, Washington, USA. The variability of averages over 20-year periods compared to 30-year and 60-year periods is shown, illustrating the potential misrepresentation of long-term climate using short-term periods. The maximum departure for the 60-year averages is 17% and the average is 6%. This indicates even a 60-year dataset for precipitation could be expected to include a 6% error compared to the long-term record and possibly more depending on the location, 17% or greater. The maximum departure for the 20-year averages is 276 mm (24%) from 1921 to 1940, while the maximum departure for the 60-year averages is 200 mm (17%) from 1901 to 1960 (Figure 2).

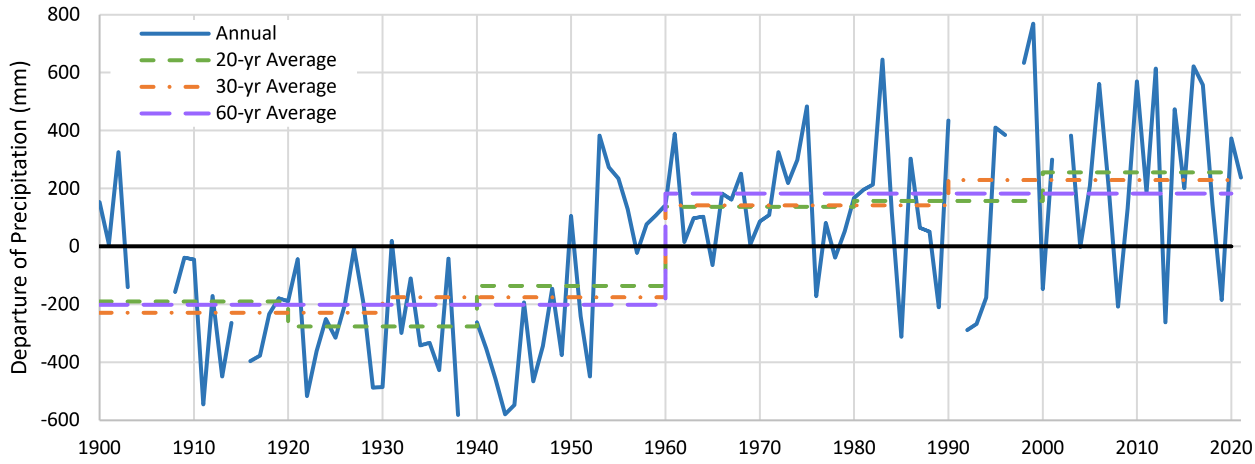

Figure 2 Departure of precipitation data from long-term average for a location outside Seattle, Washington, USA

While some may consider simulating a wetter than average climate is conservative and acceptable for design purposes, this is a source of error that could be avoided by using a longer climate set. Within the cover design process, other sources of error are present that cannot be reasonably eliminated. Consequently, accepting a known error that could be eliminated should be avoided. In addition, resources for ET covers are often scarce at mine sites, especially those that have been in operation for a long period. Top soil and organic material is commonly scarce or non-existent and fine-textured materials may also be limited. As a result, the volume of suitable cover materials available is often insufficient at many mine sites, considering the large size of many mine waste facilities. Therefore, wasting these materials in a cover design that is possibly thicker or finer than it would otherwise be if a more robust climate set had been used should be avoided.

For the second example, annual precipitation from 15 cities across Chile from 1901 to 2020 was analysed (World Bank Group, Climate Change Knowledge Portal [WBG-CCKP] 2022). Annual departure from the long-term mean was calculated as discussed above, along with the departure for the 20-year, 30-year, and 60-year averages. The maximum departure for the 20-year averages for all 15 cities is 17%, while the average is 6%. The maximum departure for the 60-year averages is 7% and the average is 3%. This indicates a 60-year dataset for precipitation could generally include a 3% error compared to the long-term record and possibly more, depending on the location, perhaps 7% or greater.

At Maule, Chile, approximately 250 km south of Santiago, the maximum departure for the 20-year averages is 116 mm (15%) from 2001 to 2020, while the maximum departure for the 60-year averages is 51 mm (7%) from 1961 to 2020 (Figure 3).

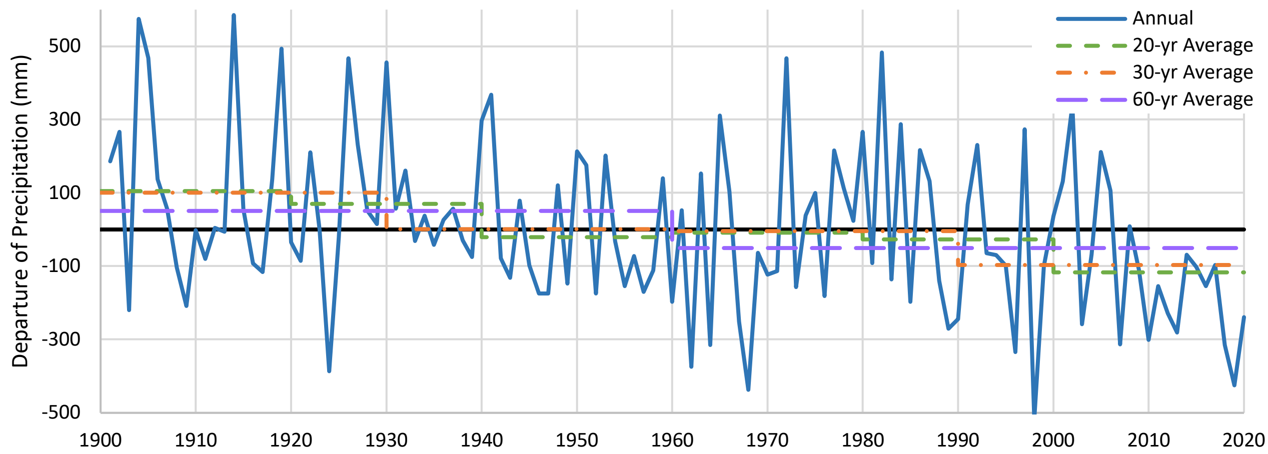

Figure 3 Departure of precipitation data from long-term average for Maule, Chile

In Chile, the departure for the most recent data is less than the long-term average for 13 of the 15 cities evaluated, the opposite of the first example. The WBG-CCKP (2022) confirms a decrease in precipitation in southern Chile from 15% to 30% in the coastal regions. Further, a severe drought influenced precipitation in Chile from 2008 to 2015 with an average decrease in precipitation of 50%, although several regions measured decreases in precipitation from 75% to 100%. Consequently, a climate set developed using only the most recent data, especially the drought from 2008 to 2015, across most of Chile would include significantly drier than average precipitation. Given the uncertainty of climate change, it is also unclear whether precipitation (and other climate parameters) will rebound or whether trends will continue. Regardless, in most of Chile, unless long-term patterns are recognised, the potential error of using only recent data is that predicted net infiltration for an ET cover would be significantly underestimated.

3.1 Climate cycles

Climate parameters vary on several cycles, not only in the long-term as discussed above but also seasonal, annual, and decadal cycles. Consequently, in order to assess cover performance adequately, a climate set developed to support soil-atmosphere modelling should represent the variation of climate within each scale of cycle. Alternately, as suggested for the solid waste industry, a shorter-term climate set may be used by defining a 'typical' year and the wettest year or a wet period to use for design. The typical year is repeated several times in modelling and used to assess long-term net infiltration, while the wettest year or wet period is used to assess maximum or upper-bound net infiltration.

This practice may present challenges for many reasons. The typical year is generally designated as the year with annual precipitation closest to the mean annual precipitation (MAP). In addition, preferably, the annual precipitation for the typical year should be greater than MAP rather than less than MAP in order to predict net infiltration for ET covers that is reasonably conservative. This approach does not typically consider seasonal variation in precipitation (e.g. summer versus winter or wet versus dry seasons), storm intensity, storm duration, the number of days with precipitation in a year, antecedent moisture conditions, or PET. If a relatively short-term period of record is available, on the order of 20 to 30 years, it may be difficult to designate a typical year that represents long-term average conditions considering precipitation and PET. In addition, it is unlikely simulating a typical year repeatedly will capture the variation in climate in the long-term. In cases where long-term climate sets are developed, the typical year is commonly used to equilibrate the soil profile to average conditions. Consequently, the designation of the typical year may still influence predicted net infiltration even when long-term climate sets are used.

To demonstrate the potential challenges of designating a typical year and using the wettest year for design, climate data from several data sources (Colorado State University [CSU] 2022; Remote Automatic Weather Stations [RAWS] 2022; United States Bureau of Reclamation [USBR] 2022) across the western USA from nearly 35 locations that classify as semi-arid and sub-humid (INAP 2022; Figure 1) were analysed. Data measured at each station varied based on the source, although precipitation and solar radiation were measured and PET was estimated using various methods at each station. The average period of record for the locations analysed is 32 years. Although the climate sets evaluated are not long-term, as discussed above, the readily available data for several locations were analysed in order to demonstrate the factors to consider, as discussed below.

Annual variation in precipitation in some locations in northern and central California is so large that each individual year can differ from MAP by a large percentage of MAP. The coefficient of variation for three stations ranges from 40% to 65%. This makes designating a typical year challenging, even with 20 to 30 years of measured precipitation. Figure 4 presents precipitation data from northern California, USA. The MAP is 708 mm, the standard deviation is 280 mm and the coefficient of variation is 40%.

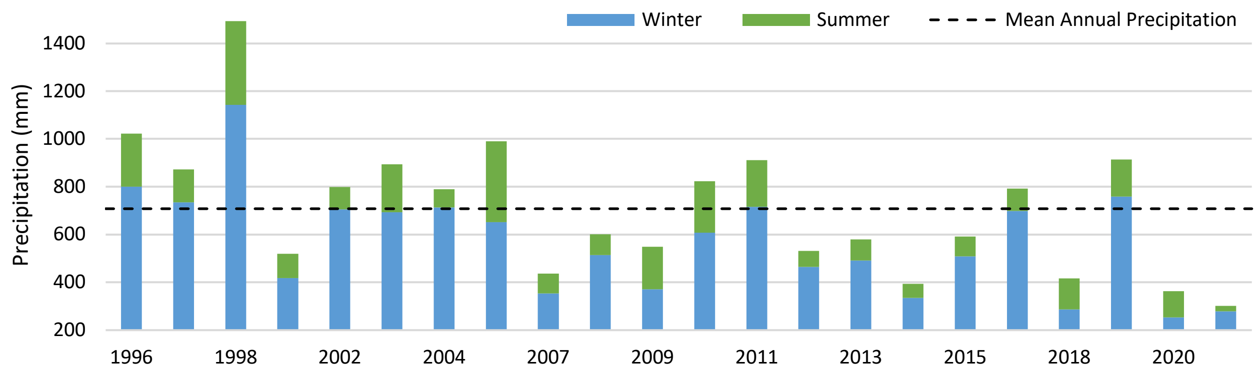

Figure 4 Annual precipitation data from northern California, USA

Both precipitation and PET should be considered to designate the typical year, otherwise non-conservative conditions may be simulated. For example, for two climate sets in Idaho and Oregon, the typical year designated based on precipitation alone includes an annual PET that is 60 mm to 110 mm (6% to 7%) above the mean annual PET. Consequently, the predicted net infiltration using these years would likely be drier than average. Although for each of these locations, another year with only slightly higher precipitation (8 mm to 13 mm and 4% to 6%) compared to the MAP included annual PET that was closer to or lower than the average. Designating these alternate years as the typical year would be more conservative while not compromising simulated average precipitation significantly.

One example climate set in north central Oregon, USA, is shown in Figure 5. For the 30-year dataset, the typical year designated based on precipitation alone would be 2016, although PET is much higher than average. Considering PET, 2003 could be designated as the typical year with PET closer to average, while the annual precipitation is similar to MAP. Finally, among four example climate sets, for multiple years within +13 mm of the MAP, the annual PET range is 250 mm. This also highlights the importance of considering both precipitation and PET because the variations may not correlate from year to year.

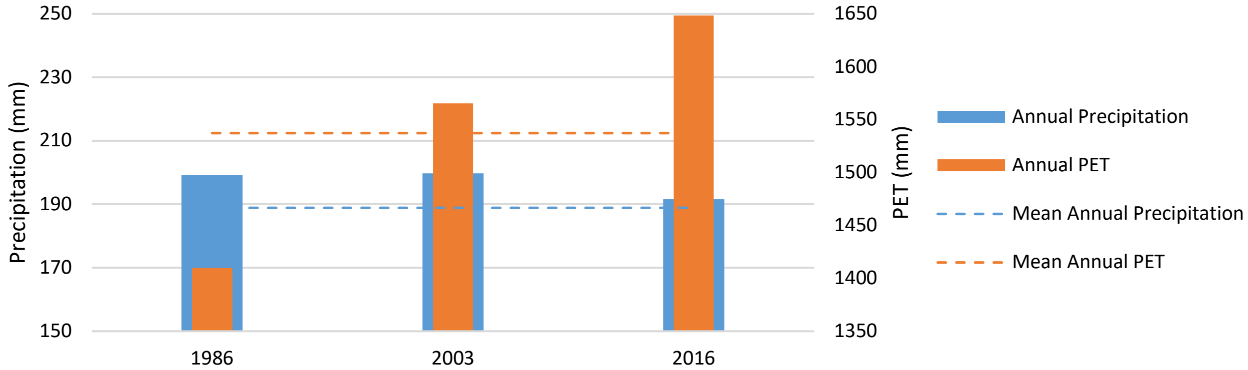

Figure 5 Precipitation and potential evapotranspiration data from north central Oregon, USA

The variation between annual precipitation and summer versus winter precipitation can heavily influence predicted ET cover performance. Therefore, the seasonality is important to simulate accurately and to consider in developing a representative climate set. Because PET is lower in the winter, higher precipitation in the winter may contribute to higher net infiltration. Consequently, the wettest year may not always lead to the highest net infiltration if the majority of precipitation occurred in the summer. In addition, the moisture condition of the soil profile can also heavily influence the net infiltration in any given year, even wet years.

A 28-year precipitation dataset from south central Idaho, USA, is shown in Figure 6. Although 1995 is the wettest year on record within the period of record with a comprehensive climate set (USBR 2022), the below average precipitation of the previous year may lead to relatively low net infiltration. The net infiltration in 1997, 2006, and 2017 may exceed that in 1995 due to antecedent moisture prior to these wet years. And although the wettest winter was recorded in 2017, the winter in the year prior was relatively dry. Consequently, the net infiltration in 1997 is likely to exceed that in 2017. This climate set demonstrates factors such as annual precipitation, seasonal precipitation, and antecedent moisture conditions that can influence net infiltration for an ET cover. Consequently, defining a typical year or a wet season without looking deeper into the dataset is likely to oversimplify these combined factors. For the same reasons, predicted net infiltration using a simplified or shortened climate set is also unlikely to represent long-term net infiltration.

Regardless of the length of climate set developed to support soil-atmosphere modelling for mine closure, cover design should include an assessment of the variation of climate over the long-term. If a complete climate set of a period shorter than 100 years is developed, the influence of natural variation in climate should be assessed by generating synthetic climate data or completing sensitivity analyses. A 20-, 30- or even 60-year climate set may not represent long-term conditions for the mine site.

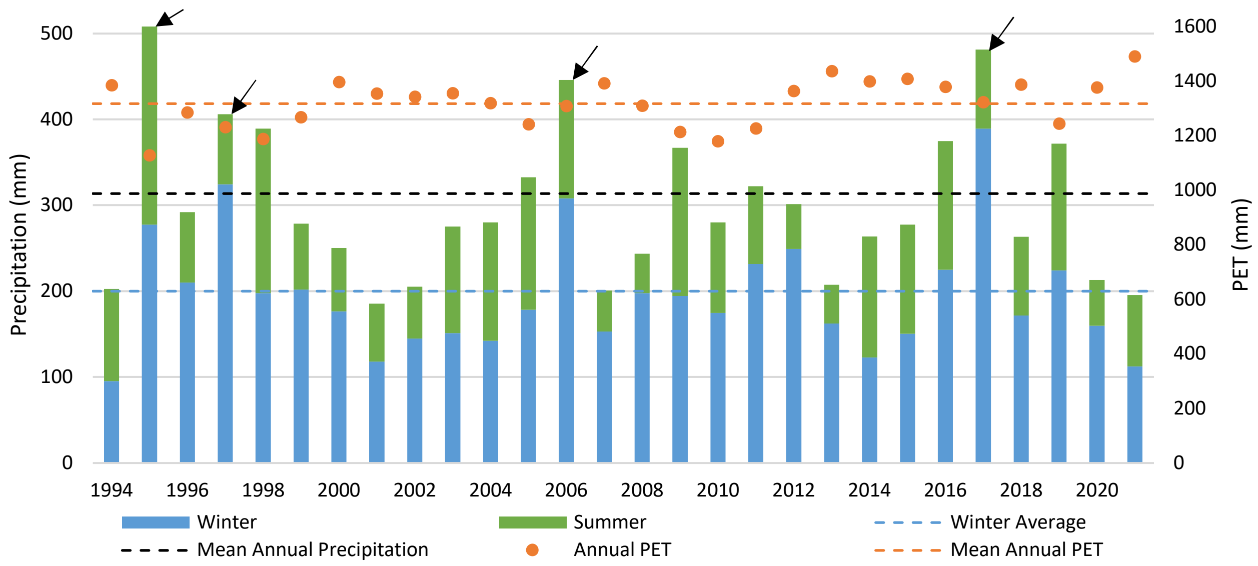

Figure 6 Precipitation and potential evapotranspiration data from south central Idaho, USA

4 The influence of storms

4.1 Precipitation and potential evapotranspiration

Representing the relationship between precipitation and PET in a climate set for soil-atmosphere modelling is critical to accurately simulate evaporation and transpiration, the 'release' mechanisms for an ET cover. Typically, due to limited data for the climate parameters needed to estimate PET, various methods are often used to replace missing PET data, generate synthetic data, or use modelled data. Some of these methods do not maintain the relationship between precipitation and PET that is found in the measured data. Therefore, it is important to understand the relationship between precipitation and PET in a region to make appropriate decisions when compiling a climate set for soil-atmosphere modelling. Compromising the relationship between PET and precipitation on a daily or storm-event basis in a climate set compiled for soil-atmosphere modelling may result in significant errors in predicted net infiltration.

Comprehensive climate data were reduced from several data sources (CSU 2022; RAWS 2022; USBR 2022) across the western USA to assess the relationship between precipitation and PET. Daily data from 50 locations that classify as arid, semi-arid, and sub-humid (INAP 2022; Figure 1) were analysed. Data measured at each station varied based on the source, although precipitation and solar radiation were measured and PET was estimated using various methods at each station. The average period of record for the locations analysed is 25 years.

Two-sample *t*-tests assuming unequal variances were used to compare various climate parameters. The statistic was calculated assuming the means of various subsets of the data were not equal and compared at the 5% significance level. The mean of each climate parameter for the entire dataset was compared to the means for days in which precipitation occurred (wet days) and days in which precipitation did not occur (dry days). As expected, the mean solar radiation for the full dataset at each location was not equal to the mean on wet and dry days, with two exceptions for which the significance level was 10% instead of 5%. Similarly, the mean PET for the full dataset at each location was not equal to the mean on wet and dry days, with only one exception for which the significance level was 25% instead of 5%.

This pattern is expected: solar radiation will generally decrease on wet days compared to dry days, which will influence PET similarly. In addition, the mean for the full dataset at each location for temperature, relative humidity, and wind speed was not equal to the mean for wet and dry days generally to a statistically significant level. This indicates an annual average of nearly any climate parameter does not represent the variation between wet and dry days.

These relationships – or the lack thereof – are critical to consider when compiling datasets. Any annual average will not represent the complexity inherent in climate – all parameters vary seasonally and are affected by storm cycles. Further, a pattern that may not be expected is that in some climates, solar radiation may be highest on days following wet days. This occurs because on the day following a storm event, skies are generally clear and solar radiation is higher compared to most dry days.

This relationship is demonstrated for a site near Denver, Colorado, in Figure 7. The plot includes the mean solar radiation for the complete dataset ('All Data'), along with mean solar radiation for wet days, dry days following wet days ('After Wet'), and dry days not following wet days ('Dry'). The mean solar radiation for days following wet days is significantly higher compared to most dry days. In addition, the mean solar radiation on days following wet days is statistically significant to the 0.05% level compared to each of the three remaining means included in Figure 7. The same pattern, and statistical significance of the means, occurs for estimated PET as well. On days following storm events, the moisture content in an ET cover in the near-surface would be wetter than average. Higher solar radiation following wet days also means evaporation and transpiration may be very effective at removing water that has infiltrated the near-surface. Consequently, an ET cover in this climate is likely to be more effective than an ET cover in a climate in which solar radiation following wet days may not be higher than average, assuming all other aspects of the climate are equivalent.

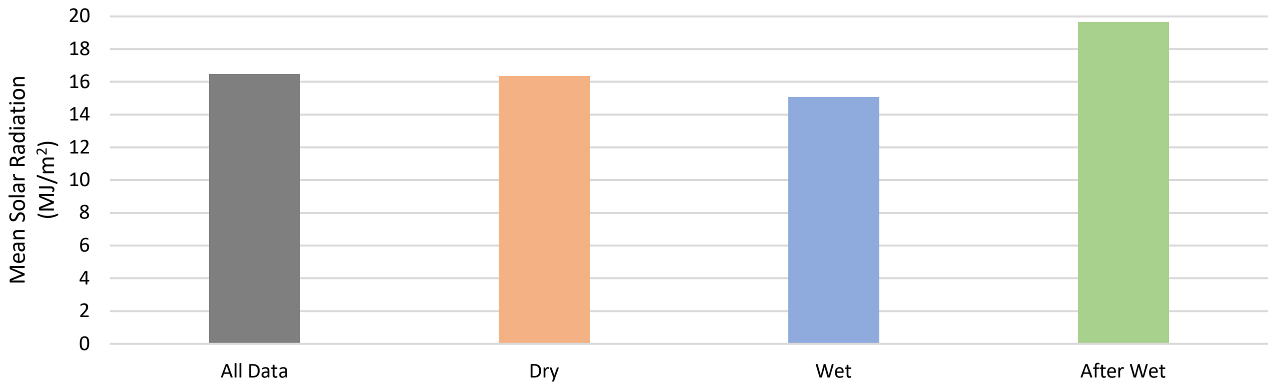

Figure 7 Mean solar radiation for a location north of Denver, Colorado, USA

It is critical to represent this relationship where it occurs because transpiration and evaporation will be most effective at removing water that has infiltrated the surface immediately following a storm, when water is near the surface in the soil profile. In subsequent days following storm events, water is likely to penetrate the soil profile to greater depths; consequently, transpiration and evaporation would not be as effective. In cases when missing climate data are replaced, synthetic data are generated, or modelled data are used that do not represent this pattern, the predicted net infiltration from soil-atmosphere modelling may be overestimated.

4.2 The importance of co-located data

The dependence of climate data on storms discussed above highlights the importance of using data that have been measured in the same location. To assess the variation of climate parameters on a local scale, six locations north of Denver, Colorado, USA, were compared (CSU 2022; National Centers for Environmental Information National Oceanic and Atmospheric Administration 2022). Precipitation from five stations was replaced with the precipitation from a primary station. Two-sample *t*-tests were then conducted for each of the five datasets in which precipitation had been replaced and using the same criteria discussed above. The five stations range from 0.4 km to 13 km from the primary station. The maximum elevation difference among the five stations compared to the primary station is 38 m.

In each case, the means of the estimated PET using data that had been replaced were not equal to the means using the estimated PET for the primary station for days following wet days. The mean PET for dry, wet, and 'after wet' days at the primary station is presented in Table 1, along with the mean PET using precipitation from five local stations. By replacing precipitation at the primary station with precipitation from a local station, the dry, wet, and after wet days may differ, hence the mean for each type of day may also differ. Table 1 demonstrates the pattern shown in Figure 7 for the primary station in which PET is significantly higher for days following precipitation. The difference is statistically significant to the 0.05% level for the primary station.

The table also demonstrates PET on days following precipitation is actually lower than dry days using the replaced data from four of the five stations. For the remaining station, although PET on days following precipitation is higher than on dry days, the significance level is only 40%. Consequently, the pattern presented in Figure 7 is not represented using the replaced data. This demonstrates using data from multiple stations may not represent climate in one location, even when the stations are relatively close together. Although the pattern demonstrated in Figure 7 is not universally applicable, this relationship is demonstrated as an example of the dependence of multiple climate parameters on storm cycles. Consequently, other locations may exhibit an unexpected pattern that may be broken when combining data from multiple locations. Given a choice between combining measured data from multiple locations or scaling data from one location to the site of interest, the latter may represent a complete climate set more accurately than the former.

Table 1 Mean potential evapotranspiration for dry, wet, and after wet days for six stations near Denver, Colorado, USA

Station	Primary	1	2	3	4	5
Distance (km)	–	8.8	13	4.8	0.4	4.7
Elevation difference (m)		35	3	37	−9	38
Mean PET (mm/day)						
Dry days	4.07	4.27	4.20	4.10	4.10	4.29
Wet days	3.78	3.84	3.47	3.14	3.25	3.33
After wet days	4.56	4.06	4.22	4.02	4.07	4.18

5 Factors to consider for missing data

Since solar radiation is not generally measured in many locations or for long periods of record, multiple models have been developed to estimate solar radiation (Mirzabe et al. 2022), mostly intended for energy-related applications. Users of any modelled data must be aware of the basis for developing the model. For example, one popular model, WGEN, which is incorporated into software such as the Hydrologic Evaluation of Landfill Performance Model and GoldSim, generates synthetic data based on dry and wet days only (Richardson & Wright 1984). Consequently, the pattern shown in Figure 7 would not be represented.

Further, errors are inherent in all models (Mirzabe et al. 2022; Richardson & Wright 1984; Sengupta et al. 2018). The most recent update of the National Solar Radiation Database (NSRDB) for the USA is reported to include average errors of 5% for solar radiation for hourly, daily, monthly, or annual data, although the error for hourly data can reach up to 20% (Sengupta et al. 2018). Further, Sengupta et al. (2018) state the error in western areas of the USA may be higher due to high occurrence of clouds, snow, and bright surfaces, especially at the stations in South Dakota and Colorado, which were used to compare measured to modelled data.

Modelled data from the NSRDB were compared to the measured data at a location north of Denver, Colorado, USA (CSU 2022). For the period of record available for the most recent update of the NSRDB (1998 to 2020), solar radiation from the NSRDB is on average 5% higher than the measured data. The difference in daily solar radiation data is an average of 12%, while 3% of the daily data exceed a difference of 50% between the two datasets. Modelled relative humidity from the NSRDB is generally 6% lower than measured data and does not represent well the range of minimum and maximum daily values in the measured data. Modelled daily wind speed from the NSRDB is generally 54% higher than measured data. Although the NSRDB temperature data also differed compared to measured data, modelled temperature data is least likely to be used for climate sets compiled for soil-atmosphere modelling given the high number of stations globally that measure and record temperature.

The variation between measured and modelled data in solar radiation, relative humidity, and especially wind speed may influence simulated net infiltration if used in a climate set. Users of modelled data should be aware of the range of errors and assess the influence of the errors on the predicted net infiltration or other aspects of cover performance such as soil moisture content, which may be critical if oxygen transport is a performance objective for the ET cover.

This comparison also demonstrates the need to compare measured data at a mine site, even limited periods of record, to modelled data to assess differences that may require adjustment prior to incorporating into a climate set. Further, even though modelled data of relatively high quality have been generated recently, these datasets are available only from 1998 to 2020. Previous versions of the NSRDB have been developed, although the quality of the previous databases is limited (Sengupta et al. 2018 and references therein). Consequently, lack of long-term solar radiation data is commonly the greatest limitation to developing a long-term climate set to support soil-atmosphere modelling for mine sites.

Finally, if sufficient climate data are not available, known errors should be assessed in a sensitivity analysis. As mentioned previously, this includes whether the period of record accurately represents long-term average conditions and the variation of climate on many scales, as well as uncertainty due to replacing missing data.

6 Solar radiation versus net radiation

Most methods to estimate PET assume a constant albedo of 23% (Allen et al. 1998 and references therein; Allen et al. 2005). While this assumption is appropriate for managed crops (for which most of the methods were developed), it is not typically appropriate for vegetation on ET covers, especially in arid and semi-arid environments where some bare ground is expected. Further, this assumption is not appropriate in the winter or other times when some or all vegetation may be dormant. Albedo also varies significantly if snow is present. Depending on the soil and vegetation, albedo for many ET covers likely ranges from 15 to 30% when the ground is not covered in snow (SolarGIS 2022). When snow is present, the albedo could be much higher and ranges from 75% to 95% for fresh snow and 40% to 60% for old snow (Solar GIS 2022). Consequently, if solar radiation is measured rather than net radiation, the climate set should include an estimate for albedo, which varies daily.

Albedo is included in the NSRDB, with estimates representing 1 km grids for an 8-day period. To evaluate the influence of modelled or measured albedo compared to the assumption of a constant value of 23%, the daily albedo from the NSRDB was used to calculate PET using the ASCE method (Allen et al. 2005) for the climate station north of Denver, Colorado, USA (CSU 2022). On average, annual PET was 3% higher using the albedo from the NSRDB compared to a constant value of 23%. The difference in the daily values when snow was not present was 8% on average and ranged up to 34%. While the difference is larger when snow is present (on average 64%), as expected, this difference would not likely influence predicted net infiltration assuming PET is adjusted to a low or zero value when snow is present, depending on the vegetation. Regardless, the difference when snow is not present (up to 34% difference for daily values) could influence predicted net infiltration. This highlights the importance of measuring or estimating net radiation for the vegetation cover expected during closure conditions rather than assume a constant value that represents managed crops.

7 Assessing climate change

Given the long-term perspective required to assess performance for mine closure and post-closure, the potential influence of climate change should also be included in assessing cover performance (MEND 2012). The climate set developed for soil-atmosphere modelling will form the basis of assessing climate change. The potential influence of climate change represents another uncertainty to consider. Consequently, developing a robust climate set with uncertainty limited to a practical extent will also serve to reduce uncertainty in predicting the potential influence of climate change.

Similar to developing primary climate sets, the largest uncertainty in predicting the influence of climate change will be changes in PET in the future. This is because most climate change scenarios focus on changes expected for precipitation and few models include temperature (e.g. IPCC 2014). The inclusion of additional parameters in climate change modelling is not typically completed due to computational demand. Consequently, while variation in precipitation is defined in most global circulation models, variation in PET is far less certain. Temperature is only one parameter needed to estimate PET. Relative humidity, wind speed, and net radiation are also needed to estimate PET.

Uncertainty related to the parameters other than temperature may not be resolved with models in the future. Therefore, the influence of climate change may be restricted simply to changes in precipitation and temperature based on current models, and possibly inference of potential changes in the remaining parameters without global circulation models as a guide.

8 Conclusion

Ideally, a climate set for soil-atmosphere modelling to support ET cover design would be developed using long-term, co-located, daily measured precipitation and estimated PET. Given that many mine sites will require perpetual management after closure is complete, the design of facilities and closure planning should include assessments for a period of 200 years.

A climate set that is based on 100 years of climate data, at a minimum, should be developed to support ET cover design for mine sites and should include precipitation as well as the parameters required to estimate PET. Using a shorter climate set presents the risk of over- or underestimating net infiltration.

Accurate simulation of the variation of both precipitation and PET at several scales is critical for ET cover design. This includes the distribution of precipitation and PET throughout the year as well as variations over the long-term. In the short-term, representing the distribution of precipitation seasonally (e.g. between winter and summer or dry and wet seasons), the number of days of precipitation in a year, the intensity of precipitation, and the frequency of storm cycles are important considerations. In the long-term, cover performance will also depend on annual and decadal variations as well as potential variation due to climate change.

The relationship between precipitation and PET is critical to understand and simulate appropriately on the same scales as discussed for precipitation. This includes the relationship between precipitation and temperature, relative humidity, wind speed, and solar radiation. The dependence of temperature, relative humidity, wind speed, and solar radiation to wet and dry conditions is complex. Therefore, data measured at multiple sites may not represent climate at any one site appropriately.

When compiling climate sets, significant preference should be given to scaling climate data from one location rather than combining data from multiple locations. Further, although many climate models have been developed, users should be aware of the basis of formulation for each model, the errors in the models, the quality of the data used to develop the models, and comparisons of the modelled data to measured data for the mine site to adjust the modelled data appropriately.

Finally, assessing climate change should be included in ET cover performance assessment. The climate set developed will form the basis of assessing the influence of climate change. Developing a robust climate set with uncertainty limited to a practical extent will also serve to reduce uncertainty in predicting the potential influence of climate change.

The next step in understanding the influence of climate sets developed for soil-atmosphere modelling is to quantify the error in predicted net infiltration of the factors discussed above for a range of climate sets. This will be discussed in Greaser et al. (2022, in press) for the climate sets presented above.

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