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Climate-scaled water balance development for mine closure planning

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Abstract

Long-term (i.e. 100 year) climate predictions for high-latitude stations indicate these places may experience significant annual and seasonal changes in air temperature, precipitation and type and amount of evaporation. Such changes would have a pronounced effect on the water balances of many mine sites and strategies to manage water, effluents and environmental impacts post-closure. This paper describes methods for the development of climate-scaled water balances for mine closure planning. The methods focus on: 1) the compilation of site-specific and regional climate data; 2) usage of a weather generator to produce long-term synthetic datasets representative of the location of interest; 3) assessment of climate change scenario data (e.g. general circulation model (GCM) and regional climate model (RCM)) and the selection of data scalars for model parameters of interest; and 4) the steps to combine elements of climate variability (weather generated) and climate change to produce a climate-scaled daily dataset representative of the location. Data are presented for a case study in northern Europe. The paper concludes with a discussion of the uncertainties inherent in the approach and opportunities and limitations in applying it to other locations.

1 Introduction

There is considerable evidence that climate change will affect natural and engineered systems alike (IPCC, 2007), and these forthcoming changes (e.g. increases in temperature; changes in seasonal precipitation) are expected to be amplified in Arctic environments (ACIA, 2004). Quantitatively, general circulation model (GCM) output for northern Europe (IPCC, 2008) shows that increases in both temperature and precipitation can be expected, where increases in seasonal temperature (2–6°C) and precipitation (up to 40%) are predicted by some models and emission scenarios (Figure 1). Such changes in climatology should translate to alterations in mine site water balances, and have direct and indirect implications on the planning strategies to manage water, effluent and environmental management post-closure.

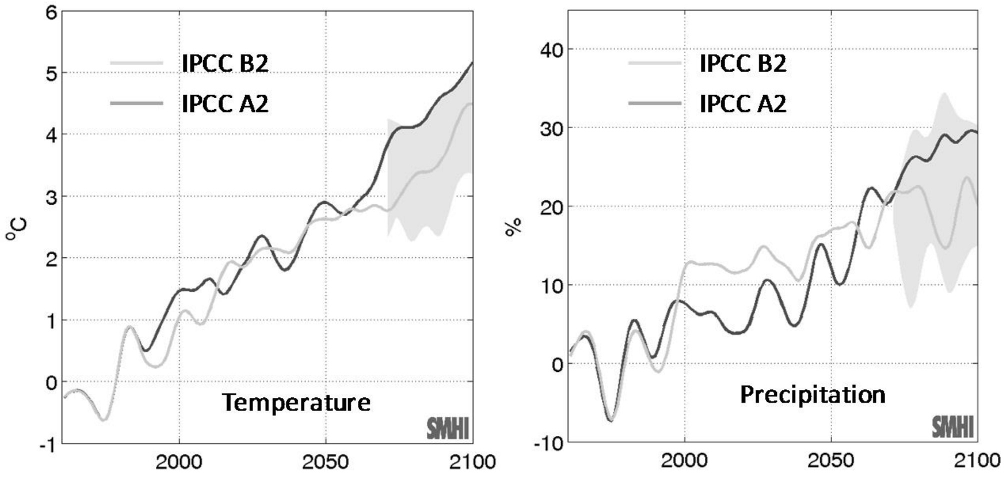

Figure 1 Temperature and precipitation predictions for northern Sweden for the period 2010 to 2100 (Source: SMHI – 2009 plotted as a function of the departure from baseline conditions (1961 to 1990). Gray shading over 2071–2100 shows the spread of four regional estimates by an atmosphere-ocean model using two different GCMs for the A2/B2 scenarios

To support a mine closure study, the water and chemical balances of two pit lakes in northern Sweden were modelled using PitMod, a one-dimensional hydrodynamic model (Crusius et al., 2002; Dunbar et al., 2004). Initial calculations revealed that pit fill times at the mine site would exceed 100 years, with time to pit-lake overflow controlled by the physical characteristics of the pits, site water balances and the water management plans assumed to be invoked at closure. Given the time scale of these pit filling scenarios, early stages of project work focused on the following: an assessment of available climate change scenario data; a translation of the effects of climate change onto the mine site water balance post-closure; and the refinement of techniques to build representative changes in climate into the input datasets that would be served to PitMod.

The spatial resolution of most GCMs ranges between 250 and 600 km; thus GCM output is normally downscaled to finer scales before it is used in site-specific impact modelling studies. The term 'spatial downscaling' describes techniques capable of delivering fine resolution climate information based on coarse resolution GCM output (Wilby et al., 2004). Two types of techniques are commonly recognised: 1) the use of transfer functions i.e. statistical relationships between large-scale GCM and site-specific observations; and 2) weather typing i.e. relationships between particular atmospheric circulation types and site-specific weather. An underpinning assumption behind spatial downscaling is the notion that the statistical relationships between GCM and contemporary observations will remain valid under a future climate.

Monthly climate scenario output is available for many GCM experiments, but daily output is rarely shared in the public domain. Therefore, temporal downscaling, i.e. computation of daily data from monthly or seasonal GCM output, is a routine part of impact modelling. One way to develop daily data from a climate change scenario is to apply the monthly or seasonal changes dictated by a GCM to a historical daily weather record or to a synthetic climate record produced with a weather generator. Given robust input data, a weather generator (e.g. Weather Generator (WGEN), ClimGen, Statistical Downscaling Model (SDSM)) can readily produce long- and statistically representative daily datasets for a point of interest. Monthly GCM data for climate variables such as air temperature, precipitation, and short- and long-wave radiation can then be used to perturb the synthetic dataset by the amounts and at the times dictated by the climate change scenario data. Temporal downscaling techniques and the role of weather generators are discussed extensively in the literature (Wilks and Wilby, 1999).

An alternative to downscaling GCM data is regional climate modelling (RCM – Regional Climate Model). These numerical models are similar to GCMs, but possess finer resolution and more sophisticated representation of climate since they are trained and calibrated for a specific region. Conceptually, a GCM simulates the response of the global circulation to large-scale forcings, whereas the RCM accounts for sub-GCM grid scale forcings owing to topography and land cover type. Owing to their detailed resolution, RCM simulations are computationally demanding, usually short in duration (e.g. 150 years) and typically only available for a limited subset of GCM models and emission experiments.

This paper outlines techniques that can be used to produce climate scaled datasets. Specifically, the paper: describes steps to characterise a site using contemporary climate and water balance data; outlines an approach to prepare climate scaled datasets using contemporary site data, a weather generator, and monthly climate change scenario data produced from an RCM; and compares and contrasts pit lake filling curves and modelled mine site hydrology based on non-scaled and climate-scaled datasets.

2 Data

2.1 Observational data

Observational data were used to characterise the site water balance and to generate a synthetic climate record using a weather generator called ClimGen (Nelson, 2002). The mine site was roughly 15 km from two meteorological stations maintained by the Swedish Meteorological and Hydrological Institute (SMHI). Data for climate variables such as precipitation, air temperature, wind and relative humidity have been collected at Gällivare and Malmberget dating back to the 1960s and 1970s. Radiation data were collected at Kiruna, a climate station roughly 90 km from the mine site. In addition, the SMHI provided access to radiation data generated daily using their STRÅNG model. The STRÅNG model produces hourly fields of solar radiation, photosynthetically active radiation, ultraviolet radiation, direct radiation, and sunshine duration. The model extent covers the geographic area of Scandinavia and the run-off region of the Baltic Sea with resolution of

11 km. Daily discharge data for watersheds in the vicinity of the mine (1996–2009) were also available from the SMHI.

2.2 Climate change scenario data

In the context of climate change scenario planning, different scenarios reflect futures with unique greenhouse gas emission, policy control, technological development and environmental outcome. The A2 and A1FI scenarios are associated with the largest increases in temperature over the long-term (3.5 to 4.0°C globally), whereas the B1, B2 and A1T show the smallest increases in temperature over the same time period (1.8 to 2.5°C globally). The monthly GCM data used in this study were generated with the ECHAM5 model – a Global Climate Model developed by the Max Planck Institute for Meteorology – and were based on the A1B scenario. GCM data for precipitation, air temperature, radiation, humidity and wind speed for the period 1960–2238 were obtained from the Canadian Climate Change Scenario Network at http://cccsn.ca/?page=dd-gcm. Although it is recommended practice to carry forward data and trends from a number of GCMs and climate scenarios when impact modelling, an A1B scenario (i.e. intermediate warming) and a single model (GCM developed by the Max Planck Institute for Meteorology – ECHAM5) were used to pilot concepts and scale data during scoping phases of this project.

Monthly downscaled data (1961–2100; 50 km resolution) were available for Sweden (SMHI, 2009) via the Rossby Centre RCA3 regional climate model driven by the ECHAM5 GCM. There were four RCA3 reference points near the mine site, with the closest grid cell calculation point being ~12 km from the mine site and within ~30 km of Gällivare and Malmberget. Data for the following parameters were downloaded, inspected and used to infer changes to the site water balance and to scale climate data: average, minimum and maximum air temperature; total and maximum hourly precipitation; fractional snow cover, snow water equivalent and lake ice thickness proxy; downward shortwave and longwave radiation; evaporation; and average and maximum wind speed.

3 Contemporary water balance and site description at closure

Based on 1961–1990 climate summaries, average precipitation at Gällivare was 554 mm per year, where 308 mm was typically realised as rain and 246 mm as snow. At the mine site, rain is primarily observed between April and November, whereas snow storage and snow melt typically dominate the water balance from October through May (Figure 2, upper left). From June through November, highest monthly precipitation amounts (50–80 mm per month) are observed, and coincide with highest annual temperatures and rates of potential evaporation. Long-term (1961–1990) annual temperature is -0.9°C, where annual maximum and minimum temperatures occurring in July (13.3°C) and January (-14.3°C) characterise the baseline for this location. Of note, mean annual precipitation and temperatures at Malmberget (1961–1990) differed from the Gällivare baseline and were 515 mm and -0.6°C respectively. Furthermore, recent annual temperatures for both these climate stations (1996–2009) were higher than the 1961–1990 baseline (i.e. 0.2 and 0.4°C for Gällivare and Malmberget respectively).

Surface water discharge records for the mine site show a pronounced snowmelt runoff signature as well as the occurrence of rainfall induced runoff events throughout the growing season (Figure 2, upper right). Mean annual discharge and runoff amounts correlated well with mean annual precipitation (Figure 2, lower left), but correlated best when precipitation was loaded based on an October–September hydrological year ($r^2 = 0.83$). For the 1996–2009 period of record, mean annual runoff was computed to be 346 mm, yielding an average annual runoff coefficient of 0.62 for the site. Detailed assessment of daily precipitation and discharge data revealed three distinct runoff conditions: 1) appreciable precipitation and low discharge when precipitation reports as snow and is held as snow storage; 2) predictable and linear relationships between precipitation and discharge during ice-free months (e.g. June to October); and 3) very high discharge associated with melt of snow storage and rain-on-snow events during freshet. In the case of discharge during freshet, the seven-day average temperature was found to be a strong predictor of runoff in this region of northern Sweden (Figure 2, lower right).

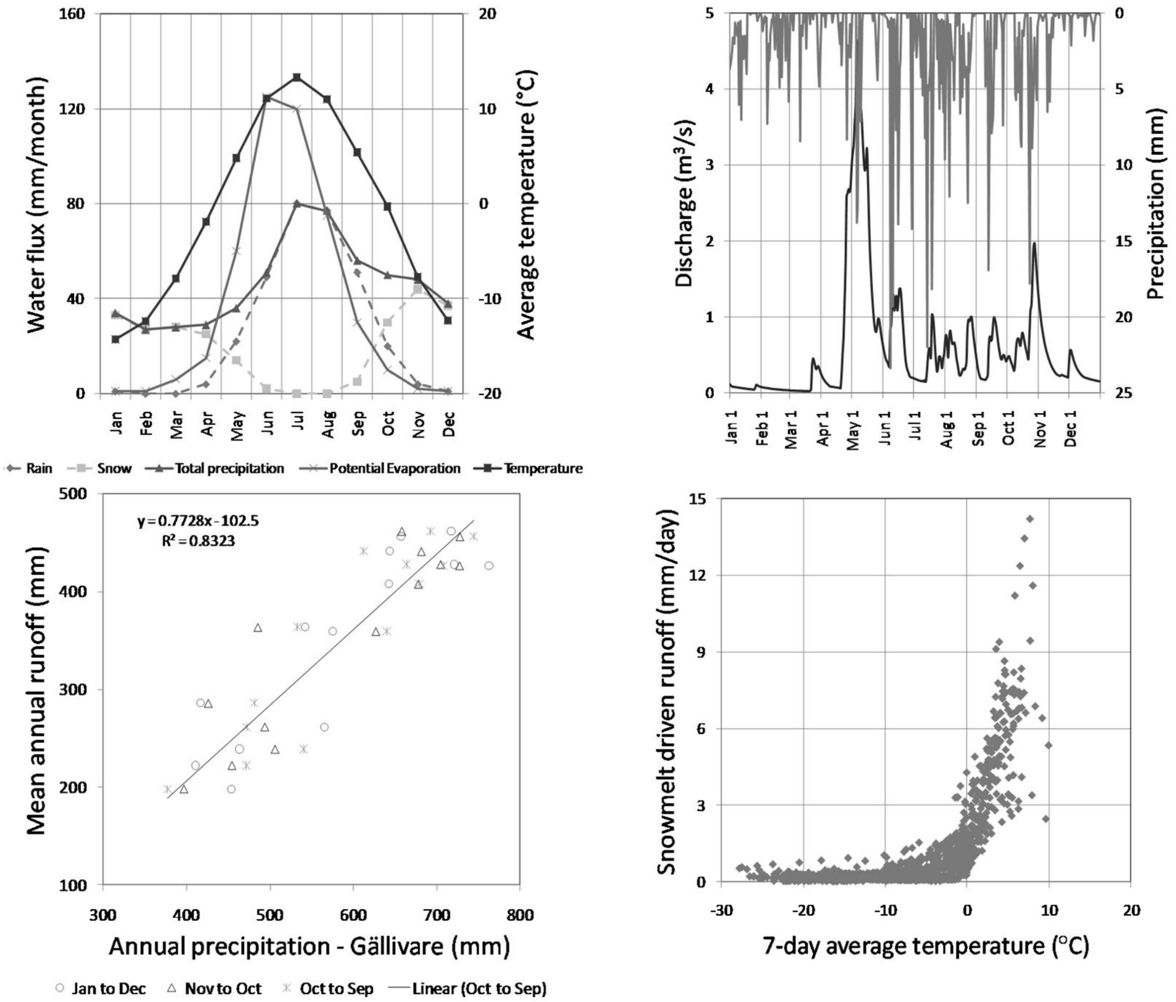

Figure 2 Summary of the regional water balance (1961–1990) for the Gällivare climate station (upper left). Daily (upper right; year 2008) and annual (lower left; period of record 1996–2009) relationships between water yield and precipitation. Relationship between snow melt driven runoff and 7-day average temperature at the mine site (lower right)

The mine site will contain two pits at closure (estimated to occur in 2030). Groundwater and surface water inputs to the main pit will result in the formation of a pit lake, occupying a void ~1 km wide, 3.5 km long and 525 m deep (maximum depth). Main pit development has resulted in the placement of waste rock around the northern, western, and eastern borders of the pit. In addition, a tailings impoundment (~14 km^2) exists down-gradient of the pit and waste rock dumps. Water inputs to the main pit will include: direct precipitation to the pit lake; pit wall runoff (i.e. precipitation falling directly on exposed pit wall surfaces); groundwater recharge; runoff from covered waste rock dumps; and runoff from the tailings management area. Evaporation from the lake surface and spillover once the pit fills are the water losses in the system.

The second pit measures 240 m deep and will occupy an area ~800 m long x ~600 m wide at closure. The catchment of this pit lake will not contain waste rock or tailings. Therefore, surface water inputs will include only direct precipitation to lake surface; pit wall runoff; groundwater recharge and surface water runoff from undisturbed areas. Losses include evaporation and spillover once the pit lake reaches spillway elevation.

4 Methodology

4.1 Overview of data scaling methods

The generation of climate-scaled data involved two main tasks (Figure 3): 1) replicating the climate variability of the site using a weather generator; and 2) generalising GCM and RCM proxies into a climate change signal that can be used to guide data scaling efforts. Assessment of RCM and GCM data for this region of northern Sweden indicated that long-term changes in air temperature, short- and long-wave radiation and precipitation are anticipated to be of greatest importance and data scaling focused primarily on these variables.

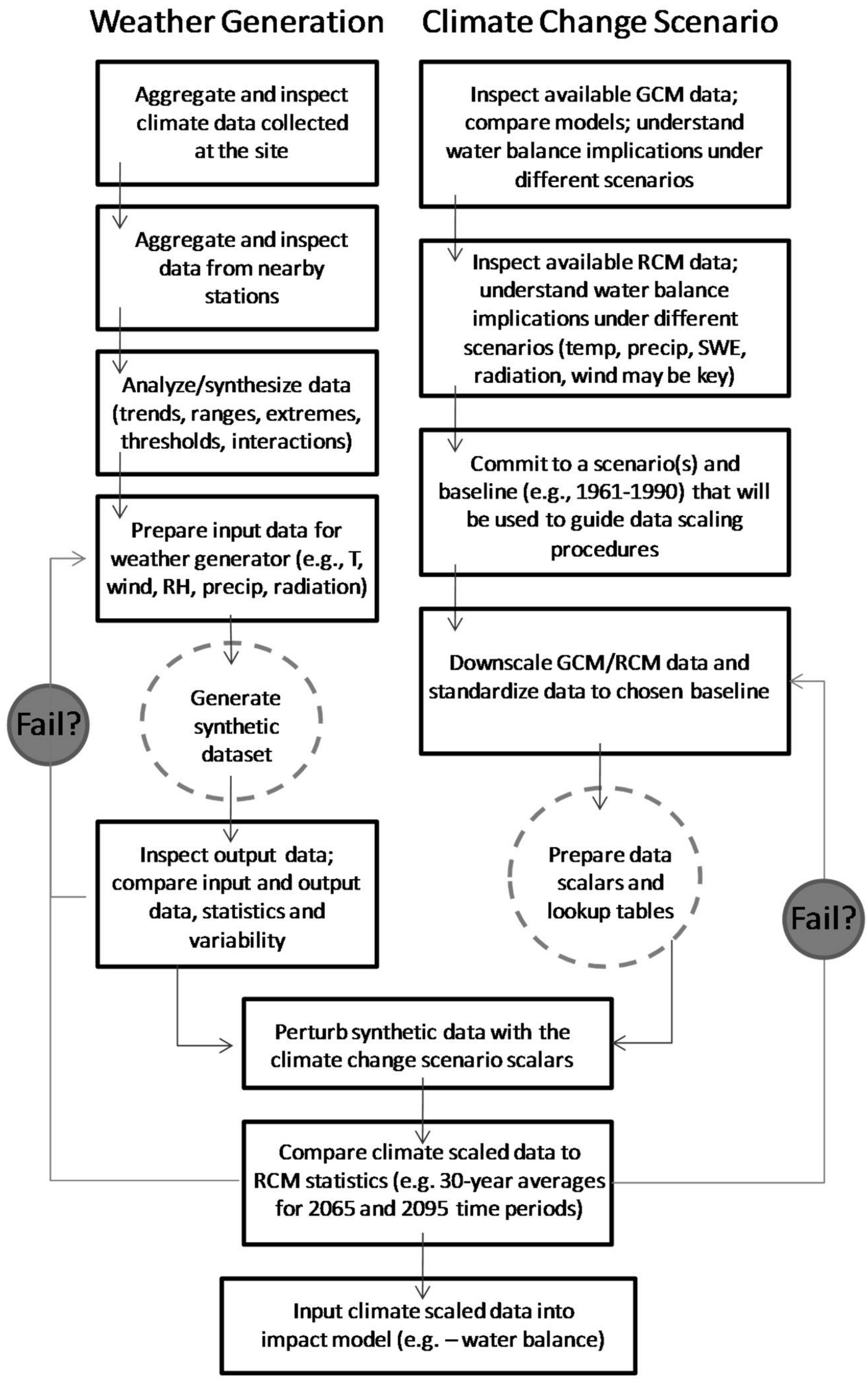

Figure 3 Flow diagram summarising steps to scale climate data

Specific steps included the following:

1. Site- and climate station data were aggregated and inspected to identify data trends, statistical extremes, critical thresholds and inter-variable interactions.

2. A set of input data (e.g. daily precipitation, air temperature, shortwave radiation, wind and relative humidity observations) was fed into a weather generator and a 200 year synthetic dataset was produced.
3. GCM and RCM climate change scenario data were inspected to understand site water balance implications under different scenarios. A scenario (e.g. A1B) and baseline period (e.g. 1961–1990) were selected to guide data scaling procedures.
4. Downscaled RCM output for each month of the year was used to depict the climate change signal and to preserve seasonal shifts and trends in parameters. Monthly data scalars were prepared against the baseline 1961–1990.
5. The climate variability (weather generated) and climate change (RCM) signals were combined to create a climate-scaled daily dataset. Prior to using the climate-scaled data as model input, scaled data were compared to RCM statistics (e.g. 30 year averages for 2065 and 2095 time periods) as validation.

4.2 Relevant water balance computations

4.2.1 Direct precipitation to pit lake and pit wall runoff

200 year synthetic and climate scaled datasets were applied to the pit lakes to represent water fluxes reporting as direct precipitation to the lake and contributions from pit wall runoff. Direct precipitation to the lake was computed using daily precipitation values and lake surface area, i.e. surface area-depth curve inferred from the pit bathymetry. Precipitation contacting pitwalls was treated as pitwall runoff when temperature was greater than 0°C, and held as snow storage below this threshold.

4.2.2 Calibrating a runoff model to produce unit runoff

Local climate and hydrometric data enabled a description of the runoff processes at the site based on runoff coefficients, daily precipitation values and a temperature record. For the 1996–2009 period, runoff coefficients ranged from 0.44 to 0.72 and averaged 0.62, where highest runoff coefficients corresponded with maxima in annual precipitation. Runoff coefficients were estimated for each year between 2030 and 2230 using both non-scaled and scaled precipitation records as the predictor (r-square of 0.79). In the runoff model, precipitation was converted to runoff when air temperature was greater than 0ºC. When air temperature was less than 0ºC, precipitation was held as snow storage and subsequently discharged according to the relationship between discharge and 7-day average temperature relationship (Figure 2). Unit runoff computed this way was used to represent runoff from natural areas of the catchments.

4.2.3 Runoff from covered waste rock dumps

At closure, waste rock dumps were assumed to be covered (shallow organic and vegetation horizon, i.e. 30–50 cm overlying ~1 m of till. At closure, design specifications for the cover system aim to limit infiltration to one-sixth of the regional discharge signal. Therefore, unit runoff values derived by the runoff model were partitioned in ratios of 1:6 and 5:6 to represent waste rock seepage and surface water runoff from the covered waste rock dumps, respectively.

5 Results

Thirty year summaries of temperature, precipitation and runoff are shown in Figure 4 and are illustrative of the non-scaled and scaled datasets driving PitMod simulations. Relevant statistics are summarised in Table 1. For temperature, precipitation and runoff, non-scaled inputs (Figure 4, left) are statistically identical to the input data, demonstrating that the synthetic data produced by the weather generator are robust. Scaled temperature data show progressively higher temperatures with time, where increases are most pronounced in the winter- and winter shoulder periods (Figure 4, right upper).

Scaled precipitation data capture both the long-term increases as well as seasonal patterns dictated by the climate change scenario data (Figure 4, right middle). The changes in runoff resulting from these adjustments in temperature and precipitation show a progressive shift of freshet from May to early March; the presence of elevated discharges in winter months in the future; and a sequential 'flattening' of the annual hydrograph as winter sees more frequent snowmelt events and winter precipitation reporting as rainfall (Figure 4, right lower).

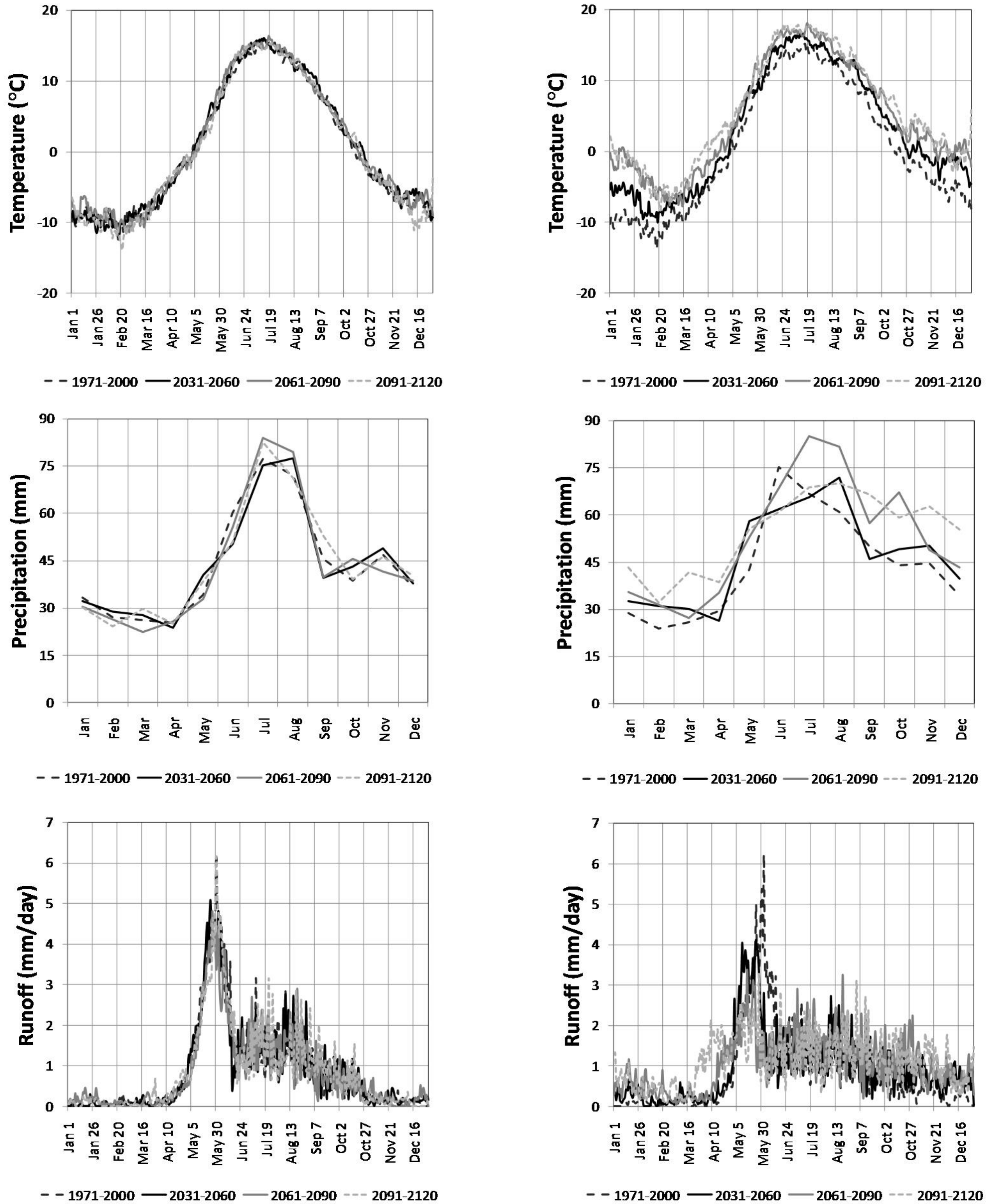

Figure 4 **PitMod input data for temperature, precipitation and runoff under non-scaled (left plots) and climate-scaled (right plots) conditions. 30 year average conditions are shown for 1971–2000, 2031–2060, 2061–2090 and 2090–2121**

Table 1 Summary of scaled and non-scaled climate statistics for temperature, precipitation and runoff

Variable	1971–2000	2001–2030	2031–2060	2061–2090	2091–2120	2121–2150	Average
Temperature (°C)	0.5	0.7	0.7	0.9	0.4	0.8	0.7
Scaled temperature (°C)	0.7	1.3	2.9	4.8	5.5	6.5	
Precipitation (mm/yr)	523	505	525	522	531	519	521
Scaled precipitation (mm/yr)	527	520	562	635	655	662	
Runoff (mm/yr)	303	286	304	302	309	299	300
Scaled runoff (mm/yr)	301	296	334	384	406	411	

PitMod predictions of pit lake filling based on non-scaled and scaled input data are compared in Figure 5. The scaled climate data foster a shorter filling time from 134 to 96 years (a relative percent difference of 33%). Once filled, the trajectories of surface water flows (e.g. direct precipitation, pit wall runoff, pit lake overflow) are greater for the scaled versus non-scaled PitMod model output. These trajectories are reflective of the site hydrology expected ~100 years post closure.

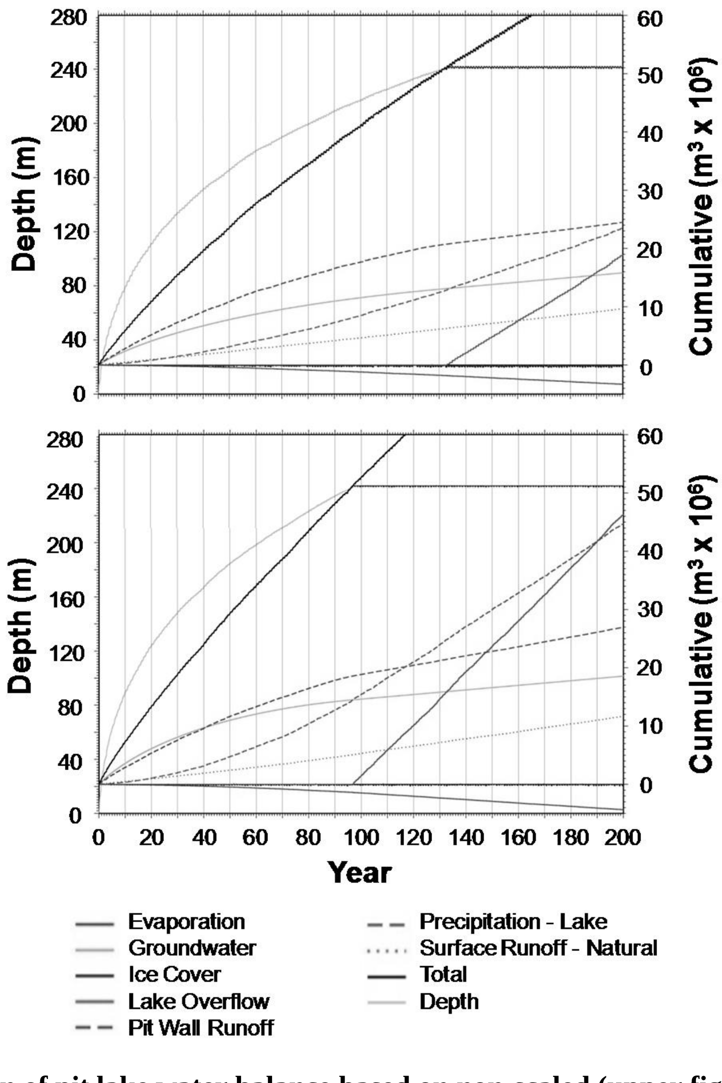

Figure 5 Comparison of pit lake water balance based on non-scaled (upper figure) and scaled (lower figure) climate inputs for the 2030–2230 modelling period. Data for the small pit are shown

6 Discussion

6.1 Commentary on data scaling techniques

As a back-check on the integrity of the scaling efforts, scaled precipitation, temperature and radiation datasets were compared to RCM data at decadal intervals to ensure per cent and magnitude changes within the climate scaled dataset agreed with climate scenario data. In doing so, the methods replicated long-term trends contained within RCM and GCM proxies reasonably well ,e.g. RCM data showed a temperature increase of 2.6°C for the 2030 to 2100 period, whereas the climate scaled data showed an increase of 2.7°C for the same time period.

On an annual basis, scaled precipitation results compared well to the timing and magnitude of changes dictated by the climate change scenario data. However, the techniques were less successful in reproducing the monthly distribution of precipitation for the baseline (i.e. Figure 4 – precipitation plots – dashed black line) compared to temperature. These differences in precipitation baseline are attributed to the representation of precipitation in the RCM dataset, more so than being an issue with the data scaling approach. The use of more sophisticated downscaling, i.e. simple linear downscaling techniques were used in this study may improve the representation of scaled precipitation in future phases of modelling.

Any downscaling or data scaling approach assumes that the variability seen in the instrumental record (and which is built into synthetic data) appropriately represents the variability that can be expected in the future. However, there is suggestion (IPCC, 2007) that climate change may bring increased occurrence of extreme events such as large storms or prolonged heat and drought. The scaling techniques described here could be used to test whether shifts in variability of a climate parameter may have important consequences for a mine site water balance. To do this, synthetic data produced from the weather generator could be analysed, re-sampled and re-run to create a new synthetic dataset that better captures an anomaly of interest.

6.2 Implications for the mine closure process

The water balances of the sites were sensitive to the effects of climate change. Expected shifts in temperature, radiation and precipitation affected all aspects of the pit lake water balance (e.g. surface runoff, pit wall melt and runoff, evaporation, fill times; Figure 5). In addition to ‘amplifying’ the site water balance, a changed climate will indirectly affect other dimensions of the mine closure process. The data presented here show a shift in the timing of freshet (i.e. earlier in the year), a flattening of the hydrograph on an annual basis, and the occurrence of higher flows in the winter owing to more frequent winter-melt events and increased winter precipitation. Present day information shows winter to be the time of year when flows are lowest and adverse surface water quality conditions to be most probable. In this light, climate scaled model runs suggest careful scrutiny of the policy and engineered strategies employed to manage water quality at closure.

6.3 Considerations for application in other regions

To carry out scaling procedures at another location (e.g. Canada), the following is required: instrumental data that characterises site-specific variability of the local environment (i.e. precipitation, temperature, radiation, wind, humidity data); and open access to downscaled climate scenario data from a regional climate model with grid resolution <50 km. In the absence of RCM output, effort may be placed on downscaling GCM output to the site of interest.

With respect to downscaled regional climate model output, the Canadian Climate Change Scenario Network website (http://www.cccsn.ca/) indicates that Canadian Regional Climate Model data (CRCM 4.2.0 – 45 km resolution; for Quebec – SRES A2 for 1961–2100 and for North American – SRES A2 scenario for 2040–2070) at monthly, seasonal and annual scales can be downloaded from the Canadian Centre for Climate Modelling and Analysis website. Licensing agreements may limit the ease and timing to carry out comparable data scaling measures for an industry-led impact modelling exercise, although it appears that the required ingredients exist to scale input data in a manner similar to that used for northern Sweden. In Canada, scaling efforts will most likely be limited by the ability to characterise site climate variables defensibly.

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