Analyzing the Effect of Climate Change on Soil Cover Performance

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Abstract

Soil-atmospheric models represent one of the tools that can be used to predict the long-term performance of soil cover systems. Soil-atmospheric models simulate the long-term water balance between the atmosphere, soil cover, and tailings mass. Current practice involves the simulation of the soil cover performance over a period of historical weather (ten or more years) with little to no consideration for how climate change might affect future soil cover performance. The Canadian Climate Change Scenarios Network (CCCSN, 2011) provides an interface for modeling climate change using a variety of global climate models (GCM) along with the Canadian Regional Climate Model (CRCM). The GCMs simulate physical processes in the atmosphere, ocean, cryosphere, and land surface to determine how climate could change in response to various predictive emission scenarios. The current study demonstrates how global climate change models can be used to prepare weather datasets for use in soil-atmospheric modeling. A comparison between soil cover performance based on historical and future weather is presented for a site in northern Canada.

Key Words: climate change, soil cover, water balance, deep percolation

Introduction

The design of a soil cover involves the use of a soil-atmospheric model to study the effect of variables related to geometry, material properties for individual soil layers, vegetation and a climate boundary condition. The soil-atmospheric simulations are used to determine the preferred soil cover system and to what extent the soil cover can be expected to limit the infiltration of atmospheric water to the underlying tailings (i.e., deep percolation). The climate boundary condition constitutes a key input to the soil-atmospheric analysis. Ten or more years of climate records are typically used to represent a range of potential weather conditions for the quantification of the soil cover performance.

Current engineering practice involves the compilation of a daily climate boundary condition from historical weather records, (e.g., Environment Canada's National Climate Data and Information Archive, Environment Canada, 2011). The design procedure may represent historical conditions but it does not integrate potential future climatic changes associated with the operational period of the soil cover. Climate change is formally recognized as an important environmental issue by federal, provincial, and territorial governing bodies. The Intergovernmental Panel on Climate Change has indicated that "warming of the climate system is unequivocal, and is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level", (IPCC, 2007) The effects of climate change are predicted to occur in the forest regions of Saskatchewan with an increase in precipitation of up to 30% and a warming of temperature between 2 ºC and 7 ºC by the 2080s (Barrow, 2009). These changes have the potential to significantly affect the performance of designed soil covers.

There is growing societal concern to adapt to climate change and to mitigate its effects. There is also new emphasis on incorporating the effects of climate change into environmental assessments to ensure that project proponents have identified and are prepared to adapt to, or mitigate climate change related risks and impacts, (CEAA 2003). This study attempts to quantify general climatic changes that may occur at the site under consideration for the period from 2071-2099. Data from climate change projections are used to evaluate the effect of primary components on water balance on soil cover performance.

Scope and Objective of the Study

The soil cover associated with the study site was designed to be an infiltration barrier that could limit deep percolation of atmospheric water. The objective of the present study is to undertake a complete soil-atmospheric modeling to determine the anticipated change in deep percolation flux and performance of the soil cover when exposed to a 16-year weather dataset that represents a variety of potential climate change ensembles. The study involved the computation of mean monthly climate change ensembles using global climate models (GCMs), the Canadian Regional Climate Model (CRCM), and a variety of potential emission scenarios available from the Canadian Climate Change Scenario Network, (CCCSN 2011). A synthesis of a 16-year projected daily dataset was prepared for each climate change ensemble. Climate classification and associated analyses were used to compare the climate change ensembles to historical weather records. A soil-atmospheric analysis was used to assess the soil cover performance for each climate change ensemble.

Generation of Climate Data

The climate data used in this study were derived from historical records (Environment Canada, 2011) and climate projections are based on Global Climate Model (GCM) and Canadian Regional Climate Model (CRCM) simulations. A historical climate dataset was compiled to obtain weather data at a daily resolution. The historical data were adapted into a future projection using general climatic trends obtained from GCM and CRCM model results. All climate datasets were then classified and assessed.

Historical Climate Observations

The historical weather data was used for soil-atmospheric modeling during the detailed design of the soil cover at the study site in northern Canada. The soil cover design served as the starting point for the consideration of future climate scenarios. The dataset included 16 years of weather records extending over a period from 1979 to 2000. More recent weather records (i.e., 2000 to 2010) contained large data gaps and were not suitable for modeling purposes. The compiled dataset included daily values for each weather parameter required in the soil-atmospheric simulations; namely, precipitation (mm), net radiation (MJ/m^2-day), maximum and minimum air temperature in degrees Celsius (°C), maximum and minimum relative humidity (%), and wind speed (m/s). The dataset was primarily compiled from weather records collected at a site weather station and an Environment Canada weather station located within 20 km of the site. Net radiation measurements were taken from an Environment Canada weather station located 500 km away, due to the lack of measurements near the site. Satellite imagery suggests that albedo values are higher near the Environment Canada station (500 km away) than near the study site. Higher albedo values meant lower overall net radiation values which would result in less evaporation when compared to the site under consideration.

Figure 1 provides a summary of the precipitation conditions at the site. The average precipitation is 530 mm/year. Approximately 385 mm/year (i.e., 70%) of the precipitation falls as rain during the active part of the year between May and October. The remaining 145 mm/year (30%) falls as snow between November and April during the inactive period. Potential evaporation ranges between 400 mm/year and 800 mm/year. The precipitation and potential evaporation information can be used to classify the climate and determine if the area experiences a net loss or net gain in water throughout the year.

Thornthwaite Moisture Index is an empirical climate classification system that was developed for engineering purposes in the United States, (Thornthwaite 1948; Thornthwaite and Hare, 1955). The moisture index is computed as:

$$I_m = 100\ (P/PE - 1) \qquad \text{(Equation 1)}$$

where: I_m is the Thornthwaite Moisture Index, *P*, is the total annual precipitation, and *PE* is the total annual potential evaporation. *PE* is calculated as the summation of the Penman (1948) monthly potential evaporations.

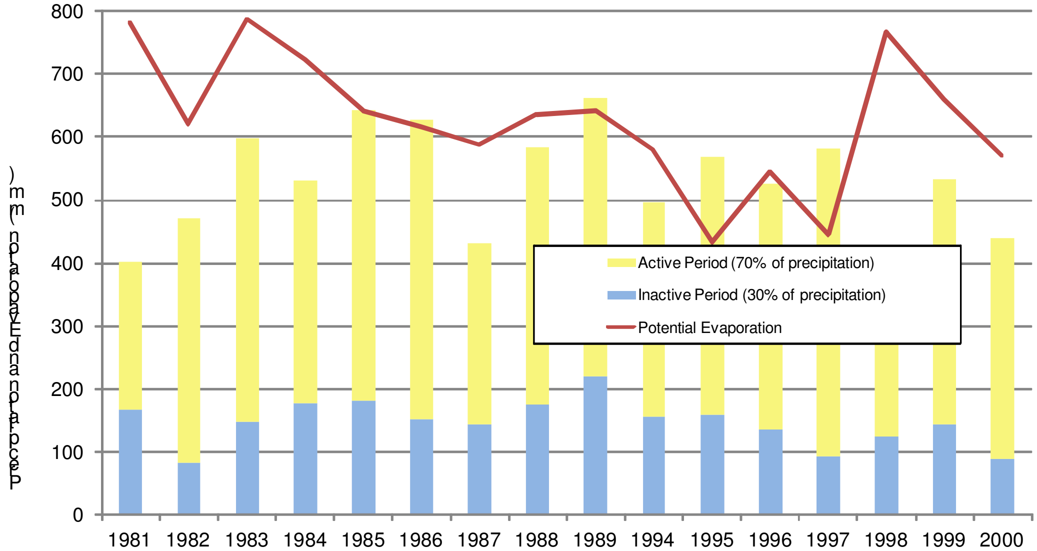

Figure 1 Distribution of precipitation between the active and inactive periods

Figure 2 summarizes the Thornthwaite Moisture Index for 16 years (over a 20-year period) based on historical observations. While *Potential Evaporation, PE,* is used for climate classification, it is *Actual Evaporation, AE,* and Transpiration, *T*, that are of greatest importance when assessing the water balance performance of a cover system.

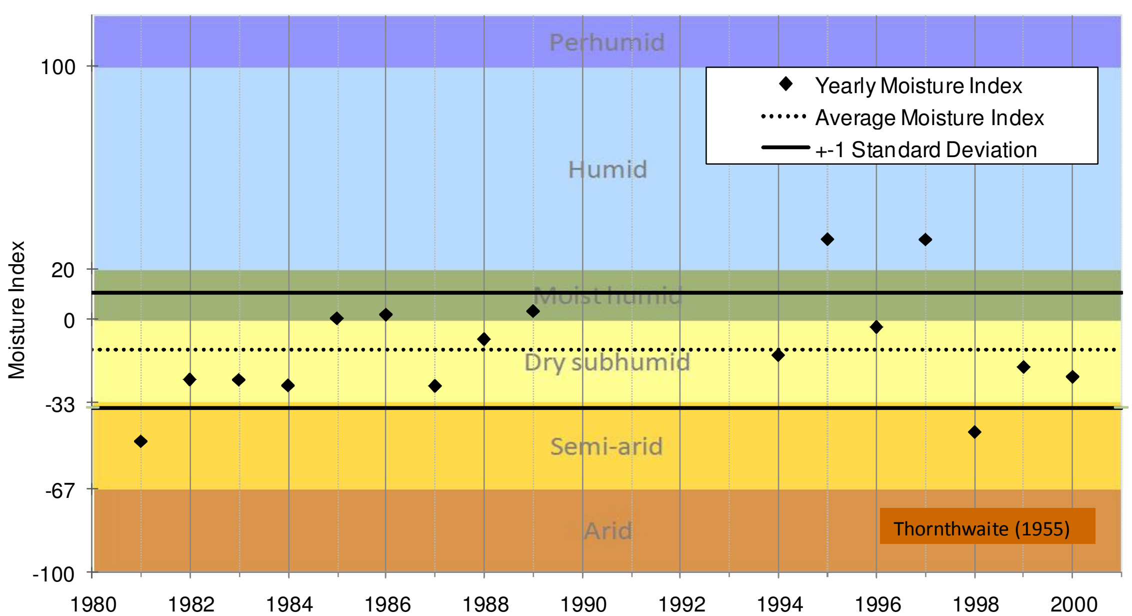

Figure 2. Classification of climate based on the Thornthwaite (1955) system

The historical climate at the site can be classified as being "dry subhumid" with an average moisture index of -12.1 based on average weather conditions. However, for 6 of the 16 years the climate classifies as “moist humid” to “humid” and for 2 of the years the climate classifies as “semi-arid”. The results show that there are considerable differences in the ground surface water balance conditions (i.e., moisture flux entering the ground surface), from one year to another. The standard deviation of the Thornthwaite Moisture Index at this site is 22.6. The mean plus one standard deviation gives a Thornthwaite Moisture Index of 10.5 (moist humid) while the mean minus one standard deviation gives -34.7 (semi-arid). The significant differences in climatic conditions from one year to the next make it necessary to undertake numerical simulations that embrace many years of weather records.

Predicting Future Climate

The Canadian Climate Change Scenarios Network, (CCCSN 2011) provides an interface for running a number of GCM/CRCM simulations. The GCM and CRCM model data available from CCCSN are from leading international climate models used to inform the most recent (AR4) IPCC assessment (IPCC, 2007). The models are physically based and simulate geophysical processes as well as feedbacks from the atmosphere, the ocean, the cryosphere, the terrestrial and the urban/industrial environments. The CCCSN models incorporate conditions from several projected emissions scenarios which represent “a coherent, internally consistent and plausible description of a possible future state of the world that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change” (CCCSN 2011). The scenarios were constructed using assumptions regarding socio-economic factors that will influence future global patterns of energy use and consumption, for example population distributions and growth, economic and social development, energy and technology use, agriculture and land-use practices, and global governance (IPCC, 2007).

To capture the uncertainties associated with modeling future climate and to incorporate variability of projected emission scenarios, all available models and emission scenarios under the 2007 IPCC Fourth Assessment Report (AR4, 2007) available from CCCSN that output the required climatic parameters were considered. Five specific climatic variables were used for assessment purposes; namely, precipitation, temperature, wind, relative humidity, and surface down-welling shortwave radiation. These five parameters describe the climatic conditions and are the main drivers of the local water balance. Table 1 lists the eight climate models, and three applicable emission scenarios, comprising a total of twenty three climate change ensembles.

Table 1: Climate models and emission scenarios

AR4 (2007) model	**Emission Scenario**		
	SR-A1B	**SR-A2**	**SR-B1**
BCM2.0-Run 1	✓	✓	✓
CGCM3T47-Mean	✓	✓	✓
CGCM3T63-Run 1	✓	✓	✓
CNRMCM3-Run 1	✓	✓	✓
ECHAM5OM- Mean	✓	✓	✓
FGOALS-g1.0(Mean)	✓		✓
HADCM3 – Run 1	✓	✓	✓
INMCM3.0 – Run 1	✓	✓	✓

Each climate change model begins by computing a baseline for each weather parameter. The baseline corresponds to a historical period of time which for the current study was selected to be a 30 year period between 1971 and 2000 (e.g., overlapping the period of measured data). The climate change models predict the change in each weather parameter with respect to the modeled baseline, not the measured historical data. The baseline predictions can be compared to measured historical weather data over the same period as a way of evaluating whether the climate change model is reasonably calibrated. In other words, the climate change predicted by one of the models could be viewed as being more reliable if the model provided a reasonable prediction of measured historical conditions. There is still some controversy over the practice of eliminating climate change models based on the ability to predict historical conditions. All the climate change models were considered as part of the current study, however, comparing the predicted baseline to measured historical conditions proved valuable in adjusting how the climate change was applied.

Mean monthly climate change data from the 1971-2000 baseline were collected for the twenty three simulations for the study site. Model results represent the average climate conditions over the grid cell for the Project (for example, an area of 200 x 200 km) for the period 2071-2099. The IPCC recommends the use of 30-year output periods to capture natural climatic variability and reduce the effects of inter-decadal variability (IPCC_TGICA 2007). Figures 3 through 5 compare the predicted baseline conditions to the mean monthly historical data. The comparison seems to suggest that the models predict reasonable baseline data for precipitation (Figure 3), temperature (Figure 4), relative humidity (Not shown but similar agreement as precipitation), and net radiation (Not shown but similar agreement as temperature). In general, the majority of the baseline data lies between +/-1 standard deviation. The results provide confidence that the climate change data can be applied “as-is” without the need for specialized modifications. All of the models significantly under-predict wind speed (Figure 5). Wind is highly sensitive to micro-environments and is spatially quite variable. These characteristics of wind likely contribute to the poor predications.

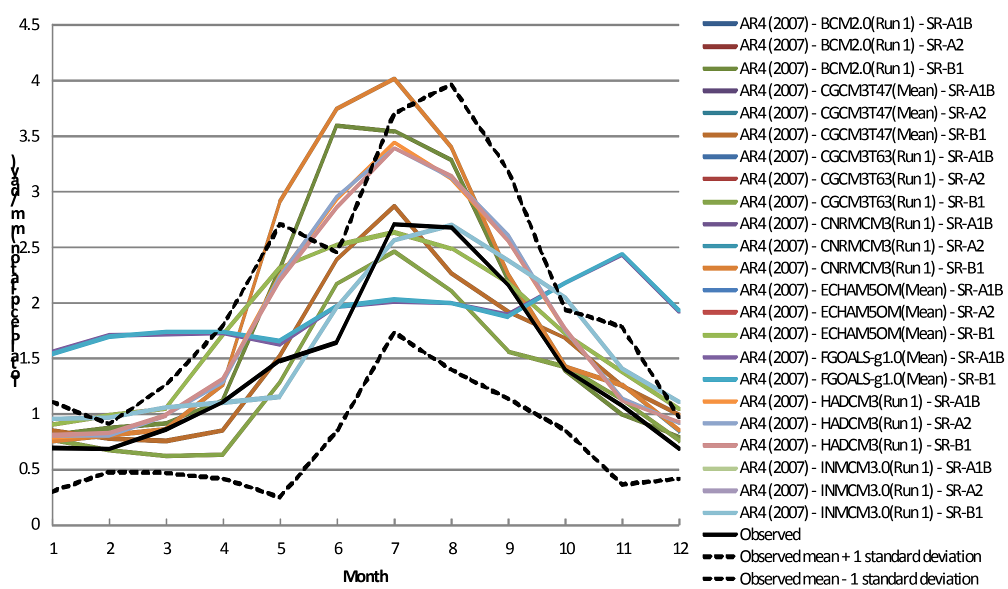

Figure 3. Predicted versus average monthly historical precipitation measurements

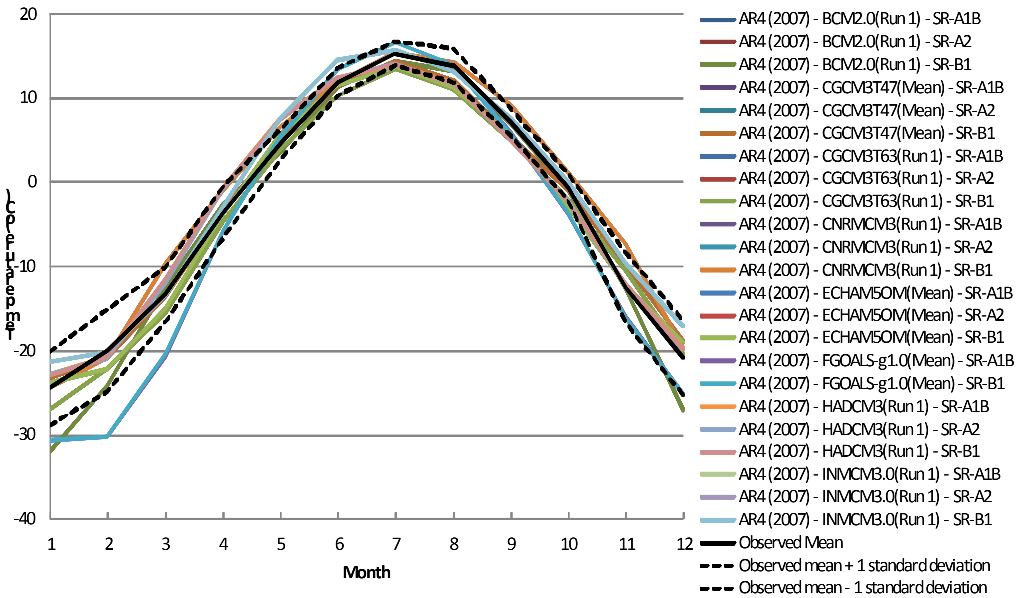

Figure 4. Predicted versus average monthly historical temperature measurements

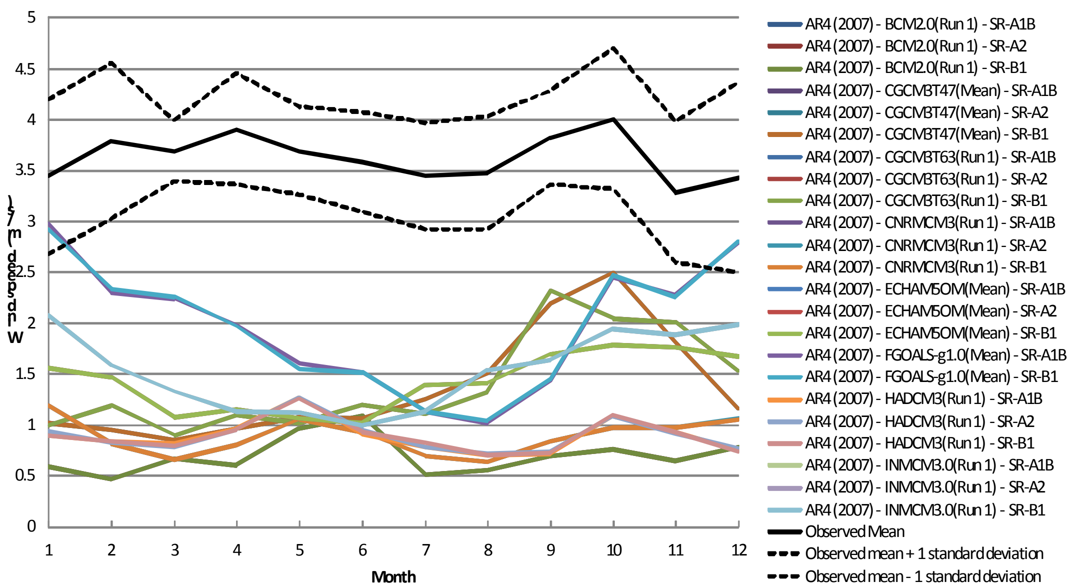

Figure 5 Predicted versus average monthly historical wind speed measurements

For this assessment the 1971-2000 baseline climate record were compared to the climate simulations for the 2071-2099 (~2080's) time period. Figure 6 presents a summary of the climate variables simulated by the climate models for each of the three scenarios. Attention should be given to the "Active Period" (May to October) because it is the time period over which detailed soil cover simulations were conducted. The model outputs and the changes predicted for 2071-2099 can be described as follows.

Precipitation: *The models output total precipitation as a percent change from modeled baseline conditions. Annual mean precipitation is predicted to increase an average of 16% for 2071-2099 compared to baseline conditions. The increase in precipitation is distributed relatively consistently throughout the year.*

Temperature: *The models output the predicted change in temperature in °C from modeled baseline conditions. Most models predict an overall warming at the study site with mean monthly temperatures increasing from baseline conditions an average of 3.6°C by 2071-2099. The greatest variability in predicted temperature, and the highest mean change in temperature, occurring during winter months*

Relative humidity: *The models output a percent change in relative humidity from modeled baseline conditions.* Relative *humidity is predicted to remain relatively constant over the study period, with changes falling between -7.7% and 8.3%. These changes occur relatively consistently throughout the year, however the most variability in predictions occur during April and May.*

Wind Speed: *The models output predicted change in windspeed (m/s) from modeled baseline conditions. Because wind is sensitive to micro-environments and is spatially quite variable, not all models accurately model baseline conditions. To adjust to the inaccurate baseline conditions, changes in wind speed were converted from m/s to percent change from modeled baseline. Wind speed is predicted to increase an average of 8% over the study period. Predictions are variable among the models, with minimum and maximum predictions ranging by approximately 38%-86% for any given month.*

Surface down-welling shortwave radiation: *Surface down-welling shortwave radiation is the short-wave radiation (0.3- 4 μm) reaching the soil surface in W/m^2. Predicted changes in surface down-welling shortwave radiation are presented in W/m^2 and converted to mJ/m^2·day by dividing by 11.574 W/mJ·day. On average, surface down-welling shortwave radiation is predicted to decrease during the active period (except during August), with maximum changes remaining less than 1 mJ/m^2·day. The greatest variability in predictions occurs in June and July.*

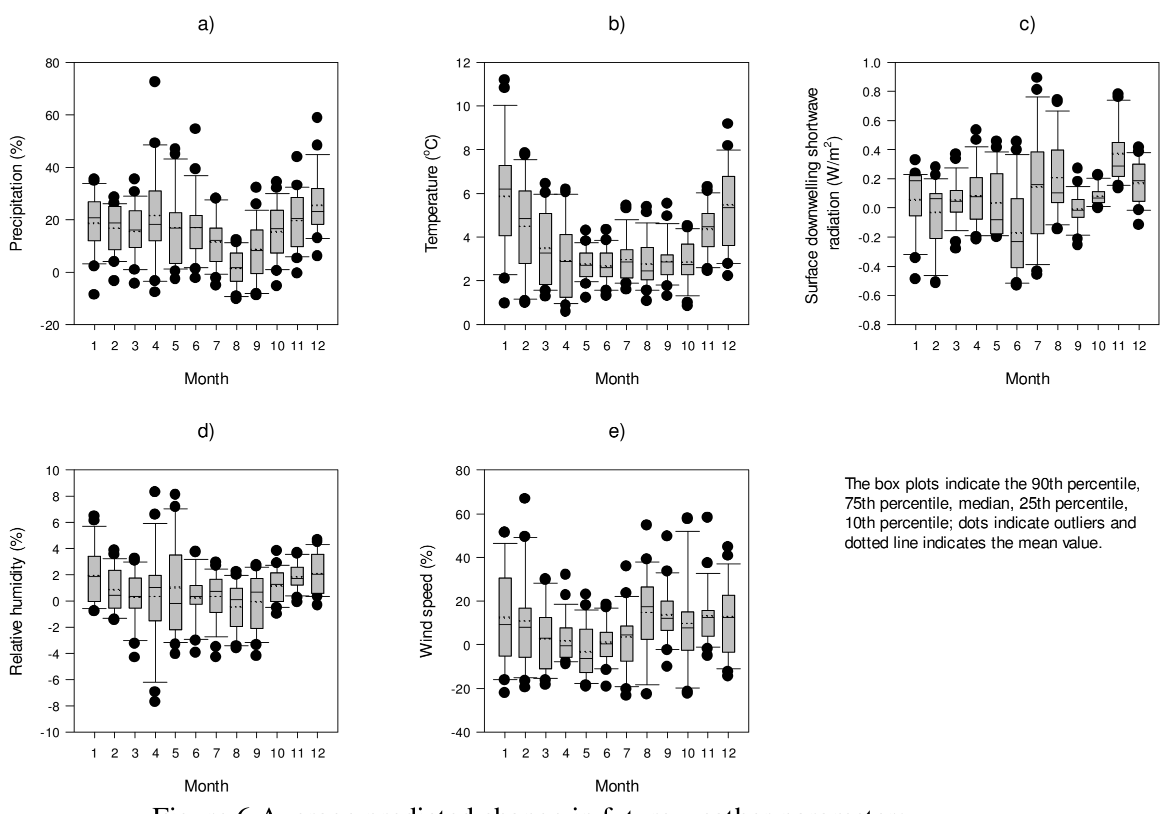

Figure 6 Average predicted change in future weather parameters

Fine resolution data are often required by practitioners so that climate change model results can be applied at a fine spatial and/or temporal resolution for detailed site-specific assessments. The soil-atmospheric modelling necessary for detailed soil cover design requires daily data and therefore temporal down-scaling of mean monthly data obtained from the climate change models. However, the methodologies and tools for down-scaling climate change data is an area requiring further development, (Barrow, 2009). For purposes of the present study, the monthly trends observed in climate change data were applied to the historical data. Using this technique, the mean monthly climate change datasets were temporally down-scaled to synthesize a 16 year daily climate dataset for each of the five parameters. In doing so, the corresponding climate change anomaly was applied to each day in the 16-year historical dataset, resulting in twenty three sixteen-year daily datasets. For example, BCM2.0-Run 1-SR-A1B projected a mean temperature change of 3.0 ºC from its modeled baseline condition for the month of July over the period 2071-2099. The 3.0 ºC temperature anomaly was applied to the historical July temperature records (i.e., the daily temperatures for each month of July were increased by 3.0 ºC).

Comparing Historical and Future Climate

A key aspect of the procedure used to predict future climate is the ability to calculate changes in individual weather parameters used in the soil cover simulations. In some cases, it is clearly understood how the change in a particular parameter might affect the climate. For example, precipitation is predicted to increase by 16% which means there is a move towards a wetter climate. However, the change in temperature, relative humidity, net radiation, and wind speed influence the amount of evaporation and are not as easy to interpret. Temperature and wind speed are both predicted to increase which could result in an increase in evaporation. However, the change in relative humidity and net radiation is expected to fluctuate providing a less definite interpretation of how evaporation will change. In general, it appears that the evaporation could increase which could tend to move the climate towards a drier condition. The increase in precipitation and the increase in evaporation are competing to change the overall climatic conditions and it is difficult to know which variable will most strongly influence the overall water balance.

The procedure used to classify the historical weather data can also be used to classify future conditions. The moisture indices can be computed for each climate change ensemble to produce twenty-three different classifications like the results shown in Figure 2. All of the classification results (historical and future) have been condensed to fit on one graph and are compared in Figure 7. For example, the historical climate classification from Figure 2 has been condensed to the box plot labelled as “Historical Climate” (HC). The line through the center of the box represents the average moisture index, the top and bottom lines of the box indicate the +/- 1 standard deviations, and the top most and bottom most lines indicate the maximum and minimum moisture indices, respectively. The remainder of the box plots are numbered according to the corresponding climate change scenario. The “Combined Climate Change” (CCC) scenario represents the average of all the climate change ensembles.

The combination of all the climate change ensembles seems to indicate that climate could move from a condition characterized by a net loss of water to a condition characterized by a net gain in water (i.e., average moisture index of 1.0, slightly greater than 0). Ensemble No. 22 predicts the largest increase in moisture index and might represent the worst case condition in terms of minimizing deep percolation to the tailings. The worst case climate change ensemble will become more apparent from the results of the detailed soil-atmospheric simulations which consider antecedent moistures conditions from year to year.

Soil Cover Analyses

Climate classifications for each of the climate change ensemble provides a high level indication that the soil cover will be exposed to wetter conditions; however, it does not provide clear evidence of how the climate changes could influence deep percolation.

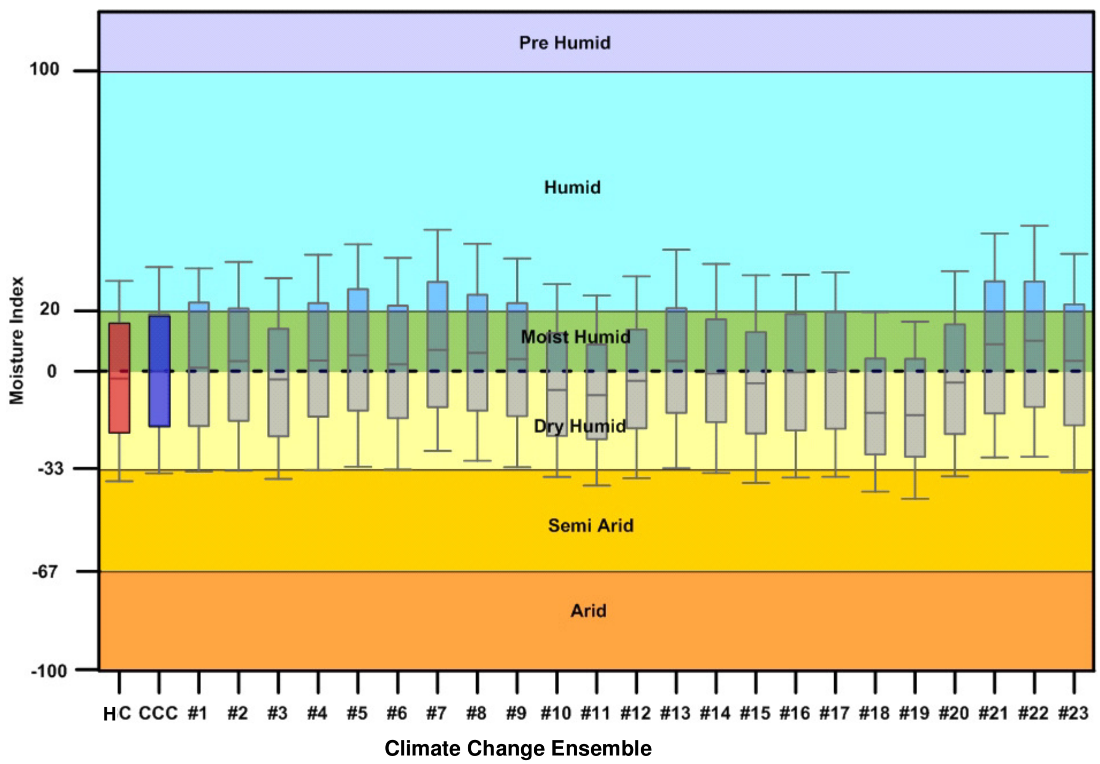

Figure 7. Climate classification for future climate change ensembles.

The climate classification does not take the soil conditions at the ground surface into consideration (e.g., runoff or soil storage). Also, the climate classification is based on *Potential Evaporation* which is greater than *Actual Evaporation*. A soil-atmospheric analysis can be used to provide a more detailed analysis of the water balance throughout the soil cover profile. The water balance computed by a soil-atmospheric analysis can be described according to Equation 2:

$$DP = P - AE - R - \Delta S \qquad \text{(Equation 2)}$$

where, DP is deep percolation below the soil cover, P is precipitation, AE is *Actual Evaporation*, R is runoff, and ΔS is change in storage within the soil cover. The soil cover at the test site is designed as a barrier system to minimize the deep percolation of precipitation to the underlying tailings. Runoff occurs in the simulations primarily because a phreatic surface develops on top of the barrier layer and periodically rises to the ground surface. The runoff occurs because the storage in the surface layer is overcome and is not a result of high intensity rainfall events or because the ground is frozen.

The same soil cover conditions were analyzed for the twenty three different climate change ensembles. The analyses did not include vegetation, nor did it include intensity induced runoff and spring runoff. The simulations were conducted under one-dimensional conditions (i.e., no interflow associated with sloping subsurface layers.). The vegetation and runoff conditions are selected to provide less, rather than more water removal. Less water removed from runoff and vegetation results is a more conservative assessment of deep percolation through the cover system.

The water balance components presented in Equation 2 were used to compare the behaviour of the soil cover during exposure to historical weather versus the climate change ensembles. The effect of the climate change is presented in terms of the *change in the water balance parameters* (Figure 8). For example, the amount of precipitation applied to the soil cover increases for all climate change ensembles when compared to historical conditions. The increase in precipitation ranged from approximately 30 mm for Ensemble No. 3 and No. 12, to 140 mm for Ensemble No. 22. The change in *Actual Evaporation*, runoff, storage, and deep percolation indicate how the additional water is being managed by the soil cover system. The performance of the soil cover is basically the same in all cases; namely, 1) there is a small essentially insignificant increase in deep percolation (i.e., 1 mm/year on average), 2) the majority of the water is re-directed as runoff, 3) *Actual Evaporation* increases and is the second largest factor contributing to the change in the water balance, and 4) soil cover storage remains essentially unchanged and does not play a primary role in how the extra rainfall is managed.

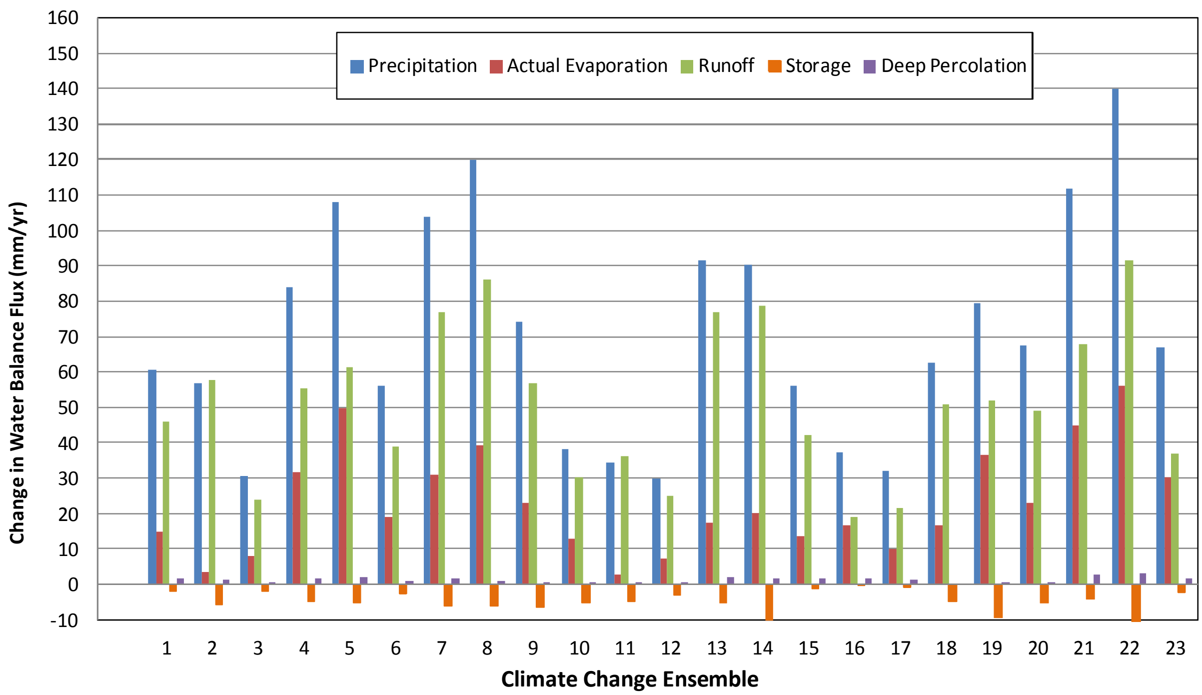

Figure 8. Change in soil cover water balance based on future climate change ensembles.

Table 1 provides a summary of the data presented in Figure 6 showing the values of flux associated with the *Minimum Change*, the *Average Change*, and the *Maximum Change* in each of the water balance parameters. The change in deep percolation is of particular interest because it is the primary means for evaluating soil cover performance. In the best case ensemble, deep percolation remains unchanged and in the worst case ensemble deep percolation is computed to increase by 3 mm/year. An increase of 3 mm/year indicates that the soil cover can be expected to perform within the range of the original design when exposed to the weather conditions predicted by current climate change ensembles.

The maximum increase in deep percolation occurs for Ensemble No. 22 which also corresponds to the case with the maximum increase in precipitation. It is interesting that the minimum change in precipitation is predicted by Ensemble No. 3 but the minimum change in deep percolation is computed from Ensemble No. 18. The misalignment between the minimum change in precipitation and deep percolation shows that the timing of precipitation events and antecedent moisture conditions play a role in soil cover performance over and above the absolute quantity of precipitation.

Table 1: Change in soil cover water balance parameters resulting from climate change.

Water Balance Parameter	Minimum Change (mm/year)	Average Change (mm/year)	Maximum Change (mm/year)
Precipitation	30	71	140
Runoff	19	51	91
Actual Evaporation	3	23	56
Storage	-11	-5	0
Deep Percolation	0	1	3

Current climate change algorithms predict more precipitation and overall wetter climate conditions at the test site. Detailed water balance assessment indicates marginal increases in deep percolation. The simulations provide evidence that the soil cover will continue to control deep percolation at levels consistent with the original soil cover design when exposed to long term climate change conditions. The ability to hold the extra precipitation near the ground surface promotes a condition where: 1) more water is available for evaporation, and 2) the storage in the surface layer is more readily overcome which promotes more runoff. The majority of the additional precipitation is redirected as runoff, shifting the focus toward the longevity of the landform design. Landforms designed using a geomorphic approach are likely to perform well when subjected to a changing environment. The philosophy behind the geomorphic approach suggests that the landscape will evolve slowly with time and climate change, and should include self-healing qualities that remain resistant to erosion. Self healing qualities can include vegetation sacrificial armouring and the conservative selection of overall design parameters.

Some conveyance systems of the landform might be designed considering the 24-hr 1:25 year and 24-hr 1:100 year rainfall events. The climate change algorithms do not output information directly related to specific return periods. In other words, the climate change algorithms do not indicate that the flow rate for a particular return period event should be increased by a certain value. The climate change algorithms output information related to precipitation intensity (e.g., 5 day maximum precipitation (mm), number of days with precipitation events greater than 10 mm/day, a simple daily intensity Index (mm/day), and total precipitation per year). The parameters provide some indication to help determine whether the intensity of precipitation events could increase or decrease.

Observations

The study presents a methodology for assessing soil cover performance when exposed to future weather conditions predicted using accepted climate change algorithms. Climate change algorithms can be used to compute the change in the weather parameters which in turn are used to conduct detailed soil atmospheric simulations. The weather parameters evaluated are: precipitation, temperature, relative humidity, wind speed, and net radiation. Changes in each of the weather parameters are computed at a monthly resolution and can be used in combination with a period of historical weather records to prepare the boundary conditions required for the soil atmospheric simulations. Each month of the historical weather record is shifted by the computed change in the weather parameter. The future weather record ends up being the same length as the historical weather record. For the current study, each climate change boundary condition was 16 years long, the same length as the historical weather record. The only difference is that the climate change boundary conditions have been shifted according to the change in each weather parameter.

The current study considered 8 climate change algorithms combined with 3 different carbon emission scenarios resulting in 23 different climate change boundary conditions (one climate change algorithm only provides two Carbon emission scenarios.). The performance of the soil cover was assessed for all 23 climate change boundary conditions and the following conclusions were arrived at:

1. The climate change ensembles indicate that in general precipitation will increase by approximately 16% and the climate will move toward an overall wetter condition.
2. At a maximum, deep percolation is expected to increase in the order of 3 mm/year which was considered to be within an allowable range for the intended design.
3. Situations where extra precipitation will be diverted as runoff and should be considered as part of the landform design.

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