Integration of Climate Analysis into a Framework for Cover Design

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ABSTRACT

Successful performance of soil cover systems depends on both physical properties (including water retention characteristics, depth, and number and arrangement of materials), which define the soil cover design, and climatic conditions. While the physical properties can be addressed by site-specific selection or completion criteria and through technical means, climatic conditions are out of anthropogenic control. Climate parameters are commonly used in the first instance to plan the cover design. However, for some climates commonly used climate indices such as the rainfall to evaporation ratio or annual means of meteorological parameters oversimplify the complexity of variable and partly erratic rainfall patterns.

In this paper we present a climate-based planning framework for soil cover systems that explicitly considers climate variability. We demonstrate our approach based on a case study using historical rainfall and evaporation data from semi-arid Mount Isa (Queensland, Australia), where highly variable rainfall events are driven by monsoonal weather situations or intense convective storms. We use Hydrus-1D to simulate the seepage from two contrasting soil materials – a unimodal silt and a bimodal waste rock material. We run the model with a number of generated climate data based on the historical climate observations, and compare the seepage patterns for the two selected soil materials with uniform distributions of rainfall and evaporation.

As hypothesised, maximum seepage events and number of large seepage events were several orders of magnitude higher for the waste rock material. Interestingly, under some climatic conditions (mainly determined by its variability) the average seepage was higher for silt material. In any case, climate variability had a great impact on the seepage patterns; i.e., the median seepage, the maximum seepage events. The number of large seepage events was several orders of magnitude higher when including the variability of events compared with the control model, where rainfall and evaporation distributions were uniform. This indicates the critical role climate variability plays for the performance of soil cover systems, and the need to implement a similar approach into post-mining planning schemes.

Keywords: soil cover systems, climate variability, planning tool, soil water modeling, waste rock material

INTRODUCTION

The objective of soil cover systems, also referred to as monolithic alternative covers or phytocaps, is to minimise drainage into the underlying hazardous wastes by maximising intercepted rainfall by vegetation, soil water storage, and evapotranspiration (ET) and thereby minimising surface runoff and seepage (Salt et al., 2011). After rainfall events cease, the loss of stored soil water through ET increases the soil water storage capacity for future rainfall events (Hauser et al., 2001; Rock, 2010). Soil cover systems are increasingly accepted for the closure of mining waste facilities (Arnold et al., 2014; Gwenzi et al., 2013). Cover materials as well as cover designs vary greatly in their characteristics and complexity and may incorporate geotextile liners, multiple soil layers with selected hydrological properties, and compacted clay layers, depending on local climate and material availability (Benson et al., 2002). While the physical soil properties can be addressed by site-specific selection or completion criteria and through technical means, climatic conditions are out of anthropogenic control. Climate parameters such as long-term average rainfall or the ratio between rainfall and evaporation (aridity index) are commonly used in the first instance to design covers. However, for some climates these climate indices oversimplify the complexity of variable and partly erratic rainfall patterns (Audet et al., 2013). Consequently, the risk of performance failure of a soil cover; i.e., deep drainage and occurrence of contaminated water, is underestimated or even ignored.

In this paper we present a climate-based planning framework for soil cover systems that explicitly considers climate variability. We demonstrate our approach based on a case study using historical rainfall and evaporation data from semi-arid Mount Isa (Queensland, Australia), where highly variable rainfall events are driven by cyclonic events or intense convective storms, and the long-term average rainfall and aridity index are 423 mm and 0.13, respectively (Halwatura et al., 2014). We use Hydrus-1D (Simunek et al., 2005) to simulate the seepage from two contrasting soil materials – a silty substrate with a uni-modal pore size distribution and a waste rock dominated substrate with a bi-modal pore size distribution. Uniform, i.e., non-structured silty substrates, are classified with medium to low values of hydraulic permeabilities (Hillel, 2004), while rock containing substrate is characterized by some proportion of coarse pores, which are highly continuous and lead to high hydraulic permeabilities (Schneider et al., 2010). The water sorption capacity of substrates is used in cover design to mitigate the impact of rainfall by designing a cover around its substrate specific water storage capacity. While the storage capacity for water may be the same or similar for different materials, the intensity parameter, like hydraulic conductivity may be greatly different (Horn et al., 2002). The objective of this paper is to investigate the consequence of different values for functional parameters to realistic climatic situations and test the performance of a cover design in respect to risk and magnitude of deep drainage. For this purpose, we run the model with a number of generated climate data based on the historical climate observations, and compare the seepage patterns for the two selected soil materials with uniform distributions of rainfall and evaporation.

METHODOLOGY

We generated 35 time-series, each of 100 years length, using the LARS-WG stochastic weather generator (Semenov, 2008) and based on historical rainfall and evaporation data from Mount Isa, Australia (Bureau of Meteorology, 2014) (Fig. 1). Then we run Hydrus-1D (Simunek et al., 2005) with two soil materials (Table 1) and using the generated weather time series (Fig. 2) as atmospheric boundary condition (Appendix B). We assessed the frequency distributions of seepage for the two soil materials and compared them with the control scenario that ignored climate variability and was based on uniform distributions of rainfall and evaporation.

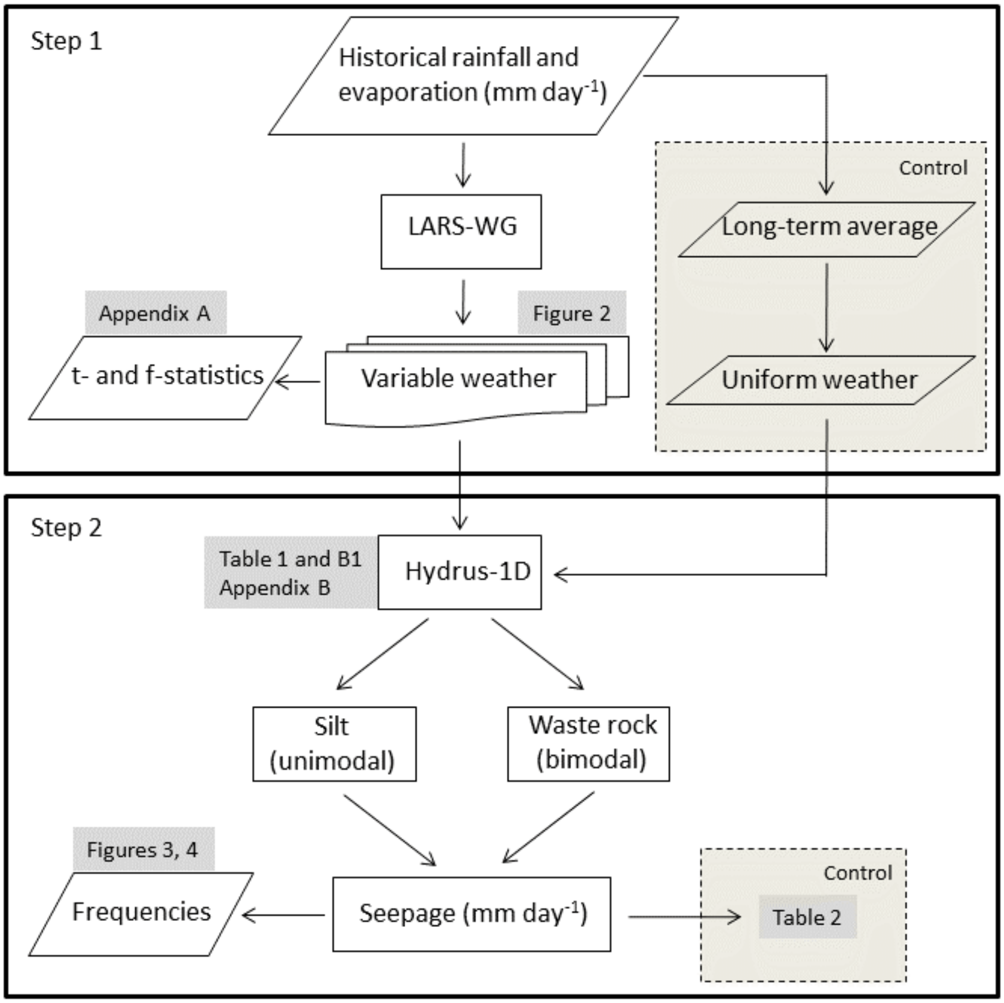

Figure 1 Schematic diagram of a climate-based planning framework for cover systems. Step 1 generates time series of rainfall and evaporation based on historical observations. Step 2 uses the generated weather data to assess frequency distributions of seepage based on selected soil materials. In total, we generated 35 time-series, each of 100 years length.

Generated rainfall and evaporation values (step 1)

The LARS-WG stochastic weather generator generates time-series of daily weather at a single site (Semenov, 2008). Here we used 100 years of historical rainfall observations from Mount Isa, Australia, to generate 35 time-series of rainfall that have the same statistical properties (mean and variance) as the empirical observations. Likewise, we generated time-series of evaporation based on 25 years of historical records. While the generated and observed rainfall values were not significantly different (Appendix A), the generated evaporation was underestimated (Fig. 2b). Therefore we corrected each generated time-series *i* of evaporation as:

$$E_{corr_i} = (E_{g_i})^{1.22}, \qquad (1)$$

where E_{corr_i} (mm day^{-1}) is the corrected evaporation used for further simulations, and E_{g_i} (mm day^{-1}) is the evaporation generated by LARS-WG. The ensemble mean and standard deviation of all E_{corr_i} values were 4% higher and 5% lower than the observed values.

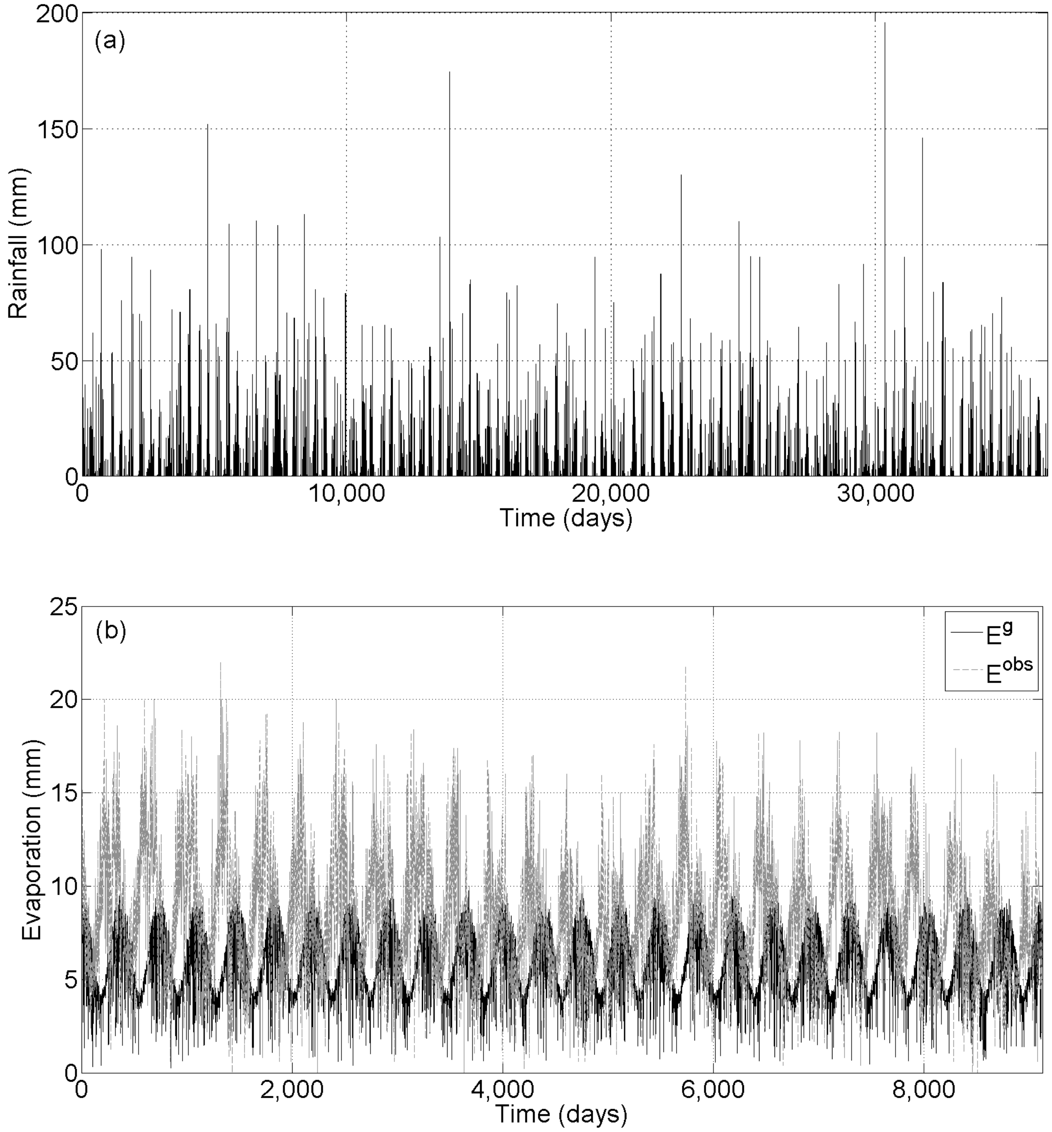

Figure 2 Examples of generated time-series of daily (a) rainfall and (b) evaporation values based on historical weather observations in Mount Isa. The generated evaporation values E^g underestimated the observed evaporation values E^{obs}.

Soil water modeling (step 2)

We used the generated time-series of rainfall and evaporation values as atmospheric boundary condition in the water flow and solute transport model Hydrus-1D (Simunek et al., 2005). We ran the model with two contrasting soil materials – a unimodal silt material reflecting a substrate with a very high water storage capacity and a bimodal waste rock material, representing a substrate with pronounced coarse and continuous pores (Table 1) – to assess the seepage patterns over a simulation period of 100 years at daily time steps. Further, we ran a control model with uniform distributions of rainfall and evaporation based on the long-term average daily records to assess the impact of climate variability on the seepage patterns of the two soil materials. For the control model, the daily rainfall and evaporation were 1.16 and 8.36 mm day^{-1}, respectively. More details on the configuration of the Hydrus-1D model are provided in Appendix B1. For each soil material and each generated weather situation (i.e., expressed through rainfall and evaporation values), we calculated the median seepage, and recorded the maximum seepage as well as the number of seepage events greater than 1 mm day^{-1}, which occurred over 100 simulated years.

Table 1 Hydraulic parameters of selected soils, based on (van Genuchten, 1980).

Soil Parameter	Silt	Waste rock (dual porosity)
θ_r (m^3 m^{-3})	0.034	0.05
θ_s (m^3 m^{-3})	0.46	0.28
α (cm^{-1})	0.016	(1) 1, (2) 0.01
n (-)	1.37	(1) 6, (2) 1.15
K_s (cm day^{-1})	6	1000
w_2 (-)	-	0.4

RESULTS AND DISCUSSION

Impact of climate variability on seepage

For both soil materials, climate variability had a great impact on the seepage patterns. While under uniformly distributed rainfall and evaporation the median seepage ranged between 2.84 10^{-5} and 1.42 10^{-4} mm day^{-1} (Table 2), the median seepage was several orders of magnitude higher when climate was variable, and ranged between 0.01 and 0.05 mm day^{-1} (Fig. 3). Likewise, the maximum seepage events were several orders of magnitude higher under climate variability and ranged between 0.5 and 200 mm day^{-1} (Fig. 4) compared with 2 10^{-4} to 0.06 mm day^{-1} under uniform weather conditions (Table 2). Finally, the impact of climate variability was most dramatic when comparing the number of seepage events greater than 1 mm day^{-1} between uniform and variable distribution of rainfall and evaporation. While no such events occurred under uniform conditions (Table 2), under climate variability their number increased up to 1750 events within 100 years of simulation (Fig. 5). These distinct patterns are the consequence of the different daily rainfall amounts, which are only 1.16 mm day^{-1} under uniform conditions, but can be up to 200 mm day^{-1} under variable conditions (Fig. 2a) as observed over the last 100 years (Bureau of Meteorology, 2014).

Table 2 Seepage of the control model with uniform rainfall and evaporation of 1.16 and 8.36 mm day^{-1}, respectively.

Soil material Seepage	Silt	Waste rock
Median (mm day^{-1})	2.84 10^{-5}	1.42 10^{-4}
Maximum (mm day^{-1})	0.06	2 10^{-4}
Number of event greater than 1 mm day^{-1}	0	0

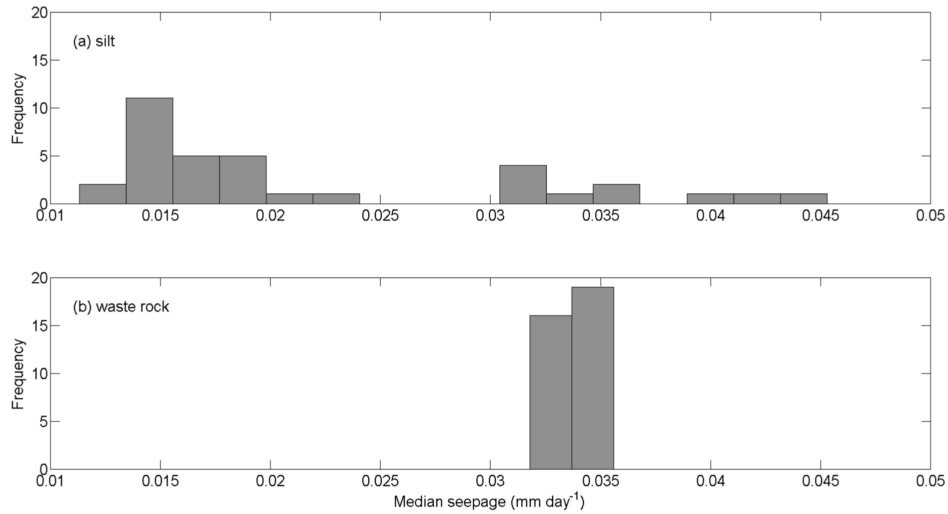

Figure 3 Frequencies of median seepage for (a) unimodal silt and (b) bimodal waste rock material and variable climatic conditions (based on 35 generated time-series, each of 100 years length).

Seepage patterns of two contrasting soil materials at variable climatic conditions

In general, seepage was lower for silt than for waste rock material. While for most of our simulations the maximum seepage for silt material was less than 1 mm day^{-1} (Fig. 4a), for waste rock material the maximum seepage ranged between 140 and 200 mm day^{-1} (Fig. 4b). Consequently, the frequency of seepage events greater than 1 mm day^{-1} ranged from 10 to 70 for silt (Fig. 5a), and from 1450 to 1750 for the waste rock material over the period of simulated 100 years of variable rainfall (Fig. 5b). The high number of seepage events >1 mm in the waste rock is a consequence of the bimodal pore system, consisting of a small proportion of wide and continuous pores and a majority of pores of medium to fine size. Water flow in coarse pores may only occur at rainfall events, which are sufficiently intensive to saturate these pores. For the majority of rain events these pores will not be filled and may not participate to downward flow because they function as a capillary barrier. Only if the soil is saturated or close to saturation, these pores will participate in the water flow. When averaging rainfall events across a large time scale, high intensive rainfall situations will be overlooked. For pore structures with a bimodal pore system and macro-pore flux, the consequences of water flow at saturated conditions will be ignored (i.e., higher maximum seepage events for silt rather than waste rock material (Table 2)).

At annual time scale, the median seepage ranged from 7 to 23 mm year^{-1} for silt (2-5 % of annual rainfall), and 175 to 229 mm year^{-1} for waste rock (44-50 % of annual rainfall). Interestingly, at a daily time scale, the median seepage ranged from 0.01 to 0.05 mm day^{-1} for silt (Fig. 3a), and 0.03 to 0.35 mm day^{-1} for the waste rock (Fig. 3b). That is, on a daily time scale and under same climatic conditions (variability), the average long-term seepage was higher for silt than for waste rock material. This finding is critical for the planning of soil cover systems and underpins the importance of using well-defined target parameters or closure criteria; i.e., whether average seepage or single seepage events should not exceed threshold values. In this regard, our case study of the climate in Mount Isa depicts that silt material much better reduces the probability of large seepage events (Figs. 4 and 5) at the expense of potentially higher average long-term seepage (Fig. 3).

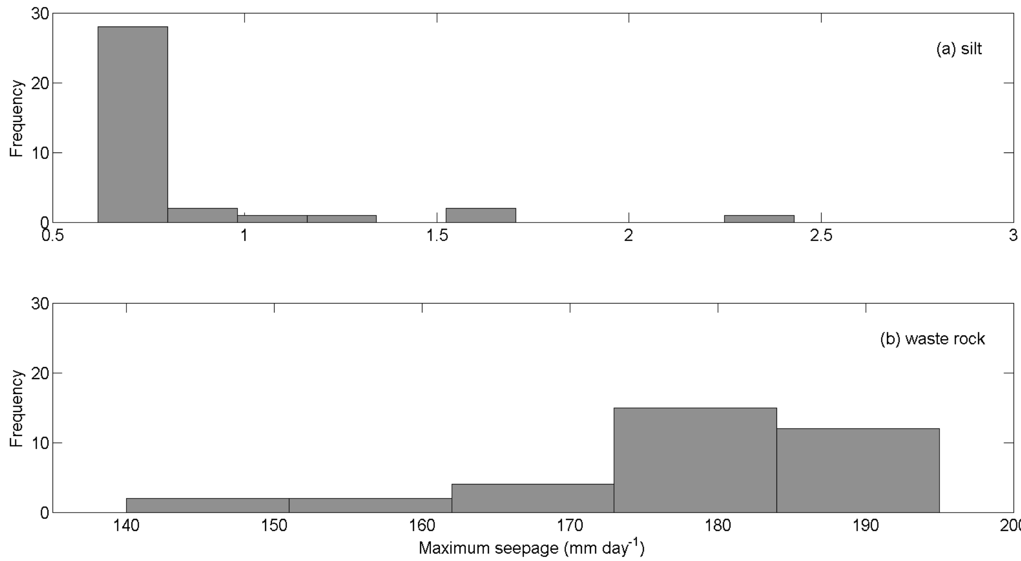

Figure 4 Frequencies of maximum seepage for (a) unimodal silt and (b) bimodal waste rock material and variable climatic conditions (based on 35 generated time-series, each of 100 years length). Note the scale differences.

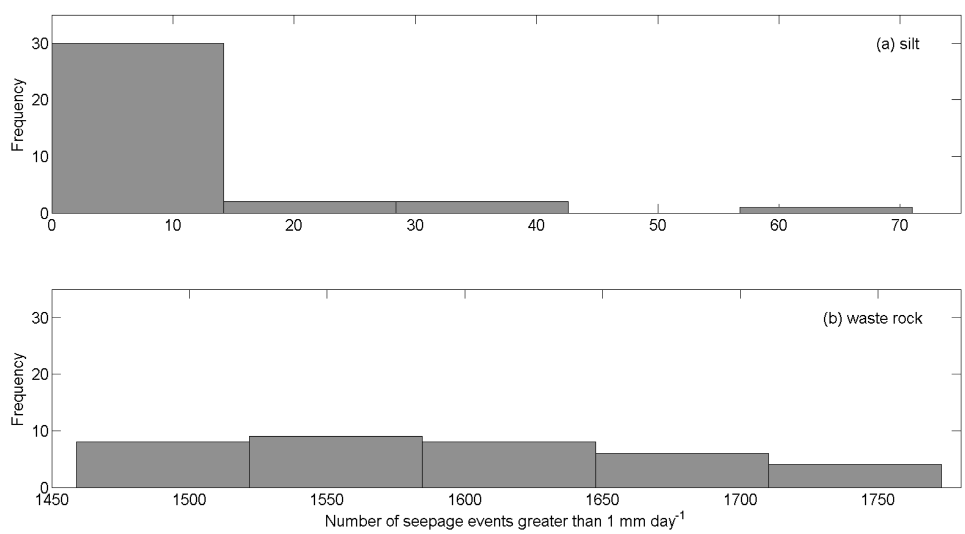

Figure 5 Frequencies of number of events with seepage greater than 1 mm day^{-1} for (a) unimodal silt and (b) bimodal waste rock material and variable climatic conditions (based on 35 generated time-series, each of 100 years length). Note the scale differences.

CONCLUSION AND FURTHER DIRECTIONS

A main consideration of our analysis is that the regional intensity, seasonality, and extremity of rainfall should represent a primary determinant of the design of soil cover systems. Our case study of climate in Mount Isa, Australia, indicates the critical role climate variability plays for the performance of soil cover systems, and the need to implement a similar approach into post-mining planning schemes (Audet et al., 2013). Based on our approach (Fig. 1), the strategy of: (i) using historical rainfall and evaporation data to generate statistically identical weather time-series, and

(ii) assess soil cover designs regarding seepage patterns when being forced to climate variability could be readily applied to other locations that are similarly affected by variable/erratic rainfall events and used to guide initial cover design planning.

ACKNOWLEDGEMENTS

This work was kindly supported by the Early Career Research Grant of The University of Queensland to Sven Arnold.

NOMENCLATURE

${E^{corr}}_i$	corrected evaporation used for further simulations (mm day^{-1})
${E^{g}}_i$	evaporation values generated by LARS-WG (mm day^{-1})

APPENDIX A

Table A1 Statistics of the generated rainfall time-series. The t-test compares the mean values and the associated p-values indicate the probability that the observed and generated mean values are derived from the same population. Likewise, the F-test tests whether the observed and generated rainfall are from normal distributions with the same variance.

Test	Average monthly p-value											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
t-test	0.620	0.515	0.628	0.357	0.587	0.664	0.607	0.572	0.546	0.616	0.573	0.418
F-test	0.063	0.448	0.242	0.366	0.199	0.230	0.225	0.206	0.264	0.499	0.332	0.553

APPENDIX B

Table B1 Configuration of the Hydrus-1D model for all selected soils.

Attribute	Value
Soil profile	
Depth (cm)	200
No. of layers	1
No. of nodes	300
Nodal density	200 (upper), 1 (lower)
Hydraulic model and boundary condions	
Single porosity model (silt)	van Genuchten-Mualem
Dual porosity model (waste rock)	Durner, dual van Genuchten-Mualem
Hysteresis	N/A
Upper boundary	Atmospheric (rainfall and evaporation data) with surface runoff
Lower boundary	Free drainage
Iteration criteria and time information	
Maximum No. of iterations	10
Water content tolerance	0.001
Pressure head tolerance (cm)	1
Lower [upper] optimal iteration range	3 [7]

Lower [upper] time step multiplication factor	1.3 [0.7]
Lower [upper] limit of the tension interval (cm)	10^{-6} [10^{4}]
Initial [final] time (day)	1 [36500]
Initial time step (day)	0.001
Minimum [maximum] time step (day)	10^{-8} [1]

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