The Impact Of Slope And Aspect On Evaporation From Soils In Three Dimensions

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ABSTRACT
The evaporation of soil moisture from sloped surfaces is an important consideration in geotechnical applications such as the design of soil covers for waste disposal sites. The net solar radiation incident on a soil surface is one of the key factors that will determine the total evaporation from that surface. This factor can vary significantly with slope.

A model has been developed to predict net radiation for sloped surfaces, as a function of the net radiation incident on a horizontal surface. This model has been verified, and its use demonstrated in conjunction with a finite element model for the prediction of evaporative flux. Soil and climate data from mine sites in Canada and Australia have been used to illustrate the range of potential impacts by slope on actual and potential evaporation. The predictions made with the evaporation model showed that the difference in potential evaporation between north and south facing slopes could be as great as 100%. Differences in actual evaporation between the slopes were less than differences in potential evaporation, reflecting the impact of moisture availability.

RÉSUMÉ
L'évaporation de l'eau dans les surfaces inclinées revêt une importance considérable dans les applications géotechniques comme la conception des couvertures pour les sites de déposition des rejets miniers. Les radiations solaires incidentes nets sur le sol présentent l'un des facteurs clé qui détermine l'évaporation totale. Pour la plupart des modèles utilisés dans les applications courantes, les radiations solaires totales sont considérées comme uniformes sur un site donné. Bien que cela peut être considéré comme une approximation raisonnable pour certains sites, les radiations solaires incidentes nets sur une surface sont variables en fonction de la direction et de la pente de cette surface.

Un modèle a été développé pour prédire les radiations nets sur les surfaces inclinées, à partir des radiations nets sur des surfaces horizontales. Ce modèle a été vérifié à l'aide des diverses données déjà publiées et à l'aide de mesures sur terrain. Les vérifications sur terrain incluent des tests comparant les radiations nets sur des pentes données par le modèle et celles provenant des mesures effectuées, en 2002 et 2003, sur des surfaces horizontales et inclinées des couvertures placées sur le site Equity Silver au Placer-Dome à la Colombie britannique, Canada. Dans ces vérifications, des modèles d'éléments finis existants ont été utilisés pour calculer les flux d'évaporation. Ceci a permis de prédire l'impact de la pente et de son orientation sur l'évaporation réelle depuis les sols constituant les couvertures. Dans ces prédictions, les données sur le sol et le climat ont été mesurées sur le site de l'Equity Silver. Les calculs effectués à l'aide des modèles d'évaporation ont montré que la différence, au niveau de l'évaporation potentielle, entre les surfaces avec un pendage vers le nord et celles vers le sud sur ce site, peut atteindre les 100 %. Les différences au niveau de l'évaporation réelle ont été inférieures à celles de l'évaporation potentielle, ce qui reflète l'effet de la disponibilité de l'humidité dans les sols. L'effet théorique des pentes sur les flux d'évaporation pour des couvertures dans d'autres endroits et sous d'autres latitudes a été aussi évalué.

1. INTRODUCTION

The importance of evaporation in geotechnical applications has been well established. For the design of soil cover systems at waste disposal sites, tools for the accurate estimation of evaporation are needed to predict the overall water balance through a cover. Evaporation and flux boundary conditions may also be important in areas such as slope stability and earthen dam design when unsaturated soil strength is considered.

Several climate-based models for the prediction of actual evaporation (AE), such as SoilCover (1993), are available and are commonly used. One inherent limitation of all commonly used evaporative models in engineering application is that they have been formulated with the implicit assumption that all processes are taking place on a level, horizontal surface, and that any deviations from this assumption are not significant.

Deviations from the horizontal may affect evaporation in one of two ways. Firstly, when compared to a horizontal surface at a given site, the sloped surface can be expected to receive a different amount of net radiation (Q_{net}) (Oke, 1987). Secondly, the moisture distribution along the length of a sloped soil surface will likely be different than that found along the length of a horizontal site of comparable size. A model has been developed to address the first issue, by providing a simple, robust tool for the prediction of Q_{net} on any given sloped surface, based on the Q_{net} measured at a nearby horizontal surface. This model can be used in conjunction with a model for the prediction of actual evaporation, to provide an estimate of actual evaporation from a sloping cover surface. The model has been formulated for application to a sloped surface with any orientation in three dimensional space.

2. BACKGROUND

The following sections provide background information relevant to the model on the role of Q_{net} for evaporation, and on the two field sites used in this research.

2.1 Evaporation and Net Radiation

At arid and semi-arid sites, evaporation is often the dominant removal mechanism for precipitation over a site. For example, Nyhan et al. (1997) studied the water balance for a cover system in a semi-arid climate, and found that evaporation dominated the water balance, accounting for over 86% of the precipitation, with runoff accounting for only 2-3%. Further, they observed that evaporation varied with the degree of cover slope, but that runoff remained relatively constant. Blight (2002) has published data showing how solar radiation varied with slope for tailings dams, and indicated that these variations affect evaporation.

The form of the widely used Penman equation (Penman 1948) for potential evaporation (PE) shows clearly that Q_{net} can be a major contributor to PE.

$$PE = \frac{\Gamma Q_{net} + \nu E_a}{\Gamma + \nu} \qquad [1]$$

Where:

Γ = slope of the saturation versus vapour pressure curve at the mean air temperature
Q_{net} = Net solar radiation
ν = psychrometric constant
E_a = $f(u)(e_{sa}-e_a)$
f(u) = a wind mixing function
e_{sa} = saturation vapour pressure of the air at mean air temperature
e_a = vapour pressure of the air above the evaporating surface

The modified Penman equation of Wilson (1990) has a similar form, and illustrates that Q_{net} can also affect AE.

$$AE = \frac{\Gamma Q_{net} + \nu E_a}{\Gamma + A\nu} \qquad [2]$$

Where:

E_a = $f(u)e_a(B-A)$
B = inverse of air relative humidity
A = inverse of relative humidity at soil surface

A climate-based solution for the modified Penman equation [2] (coupled with solution of heat an mass transfer equations) forms the basis of the evaporative model SoilCover, used in this research. SoilCover is a well-established and verified model for actual evaporation (Scanlon 2002). Numerical solutions of the modified Penman equation have also been developed for two other software packages, Vadose/W (2003) and SVFlux (2004).

The value of a single Q_{net} measurement represents an aggregate of several radiative inputs. The net radiation represents the total incoming radiation (both shortwave and longwave), less the outgoing. This can be represented as:

$$Q_{net} = L_{\downarrow} - L_{\uparrow} + S_{\downarrow} - S_{\uparrow} \qquad [3]$$

Where:

$L_{\downarrow}$ = the longwave radiation incident on the surface,
$L_{\uparrow}$ = the longwave radiation emitted and relflected by the surface,
$S_{\downarrow}$ = the shortwave radiation incident on the surface, and
$S_{\uparrow}$ = the shortwave radiation reflected by the surface.

The shortwave radiation is further subdivided into beam (S_b) and diffuse (S_d) components, where the beam component is the radiation from the sun that arrives directly at the surface, and the diffuse component is that part of the solar radiation that first has been scattered in the atmosphere. These distinctions are important when trying to predict the Q_{net} value on a sloped surface, as each component is affected by slope to a different degree, or in a different manner.

2.2 Research Sites

Research for this project has focused on two main sites – the Placer-Dome Equity Mine, located in North-Central British Columbia, and the Placer-Dome Kidston Mine, located in North Queensland, Australia. Both mine sites were at or near closure, and featured extensive soil cover systems and instrumentation. The sites also provided sharply contrasting environments for the testing and application of the evaporative model. The Equity site is located in a humid alpine environment, at a relatively high northern latitude of 54°. The Kidston site is located at a low southern latitude of 19° in a semi-arid climate with pronounced wet and dry seasons. Further, significant evaporation from the soil at Equity only takes place when there is no snow-cover on the ground (typically 200 days per year), while evaporation from the soil may occur year-round at Kidston.

Waste rock covers are in place at both sites. At the equity site, the cover consists of a 0.5 m thick layer of compacted till, overlain by a 0.3 m thick layer of loosely placed till. A summary of the cover material properties (as used in the evaporative model discussed in Section 5) is presented in Table 1. A more detailed description of the cover design and soils at this site can be found in O'Kane et al. (1998) and O'Kane (1995).

Table 1: Characteristics of Till Cover Soils at Equity

Properties	Uncompacted	Compacted
K_{sat} (m/sec)	3 x 10^{-8}	5 x 10^{-10}
Porosity	0.33	0.31
Sg	2.77	2.77
Air Entry Value (kPa)	100	1000
Classification	SC-CL	SC-CL

The cover at the Kidston site consists of an oxidized waste rock. Several different cover configurations were used at the site. For this study, we focused on what was considered the optimum cover, which consisted of a 0.5 m thick layer of compacted oxidized waste rock, overlain by approximately 1.5 m of loosely placed oxidized waste rock. Key material properties for the cover as used in the evaporative model are summarized in Table 2, with further details available in Durham et al. (2000).

Table 2: Characteristics of Oxidized Waste Rock Cover at Kidston Mine

Properties	Uncompacted	Compacted
K_{sat} (m/sec)	1 x 10^{-6}	3.8 x 10^{-9}
Porosity	0.2	0.16
Sg	2.72	2.72
Air Entry Value (kPa)	10	10
Classification	SW-SC	SW-SC

3. PREDICTIVE MODEL FOR ENERGY ON SLOPES

The predictive model for Q_{net} on slopes was developed to allow the estimation of the daily total Q_{net} on a slope of any orientation and at any latitude, based on readily available climatic data. In formulating the model, the authors wanted to develop a simple tool that would allow historic data from existing sites to be used. A brief overview of the model is provided here, with more detail available in Weeks and Wilson (2003).

In application, the model takes daily data for Q_{net}, temperature and (if available) vapour pressure, and uses this data to estimate the Q_{net} that would be expected on a given slope in the same general area. In addition to the angle and direction of the slope under the consideration, the site latitude is required, as well as measured or estimated values of ground surface albedo and emissivity.

To calculate net radiation on a slope from that measured on the horizontal, it is necessary to estimate each of the components that make up Q_{net} (the various parts of short and longwave radiation). This can be done with an iterative solution. Once the individual radiative components are estimated, the appropriate calculations can be performed on each component to estimate the component on a sloped surface. The transformed components are then summed to give an estimate of Q_{net} on the slope.

The longwave component of Q_{net} is estimated on the basis of daily average temperatures and estimated cloud cover. Outgoing longwave radiation is estimated using the formulation of Nunez (1980). The incoming net radiation is estimated using the relatively simple method of Swinbank (1963). If daily average vapour pressure is available, the method of Brutsaert (1975) can be used.

Once the longwave radiation has been estimated, the remaining shortwave is separated into its beam and diffuse components using the well-established and robust method of Bristow and Campbell (1985). This method provides an indirect estimate of daily cloud cover (the ratio of shortwave radiation actually received to that theoretically possible), which is used to refine the estimate of longwave radiation. The shortwave radiation is then re-estimated, and the process iterated until there are no significant changes in the values of the components. Convergence is normally very quick (less than ten iterations with a tolerance of 0.01 MJ/m^2/day).

Once the components are estimated, the site geometry and daily calculated sun-earth geometry relations for the site are used to estimate changes in each of the radiation components, as a function of the specified slope under consideration. The modified components are then summed to provide the estimate of Q_{net} for the slope.

4. VERIFICATION OF PREDICTIVE MODEL

Verification of the predictive model for Q_{net} on slopes has been conducted at sites in Canada (Equity and Vancouver), and in Australia (Kidston). Components of the model have also been verified against data published in the literature (see Weeks and Wilson, 2003). The most extensive verification of the model was conducted through a series of field experiments conducted at Equity in 2002 and 2003. Details of this verification are presented below.

To evaluate the performance of the model, net radiation measurements were collected simultaneously on a level surface at the Equity site, and on sloped surfaces. The measured daily net radiation values from the level surface were used to predict the net radiation on the sloped surfaces, and the predicted values compared to those that were actually measured.

Measurements for the level surface were collected at the weather station located on the main waste rock dump cover at the Equity site. Temperature data collected at the weather station was integrated to provide values for daily average temperature. Due to malfunctions in the humidity probe, daily vapour pressure data was not available for the full data set, and all estimates of outgoing radiation were made using the basic method of Swinbank (1963).

Measurements of net radiation on the sloped surfaces of the cover were taken using a net radiometer fitted with a portable data logger. The net radiometer was of an identical type to that used on the weather station (a Kipp & Zonnen NR-LITE with a spectral response range of 0-100 µm). The portable set-up was moved around the site, with net radiation measured on slopes facing approximately to each of the cardinal compass directions (north, south, east and west), and on slopes of different steepness. Measurement locations are summarized on Table 4, with the exact slope direction for each measurement location indicated by the compass bearing of the down-slope direction. Measurements were made in 2002 and 2003.

Table 4: Measurement Location Summary

Location	Year	Slope	Slope Bearing	Days Measured
North	2003	19°	320°	Aug 6-10; Sept 11-Oct 14
South	2002	22°	183°	Aug 13-23
	2003	18°	175°	Aug 15-Sept 10
East	2002	11°	113°	Aug 4-11
West	2002	25°	239°	Aug 25-29
	2003	16°	276°	Aug 11-14

The results of the verification work at Equity are summarized as shown on Figure 1. The Q_{net} values predicted on the slope are shown as a function of the Q_{net} measured on the slope. For a perfect model, all of the predicted data points would plot along the 1:1 line. For these 90 data points, the model correlation is very good, with an R^2 value of 0.95. To determine if the model fits the data well, it is also necessary to evaluate the residuals (the difference for each prediction between the predicted value and the actual value). The normal distribution plot of the calculated residuals (Figure 2) shows that the residuals can be reasonably described with a normal distribution (i.e. straight line) on the plot. The R^2 value for the shown best-fit straight line to this normal distribution plot is 0.81. The normally-distributed random behaviour of residuals, considered with the strong graphical correlation shown in Figure 1 suggests that this model fits the data.

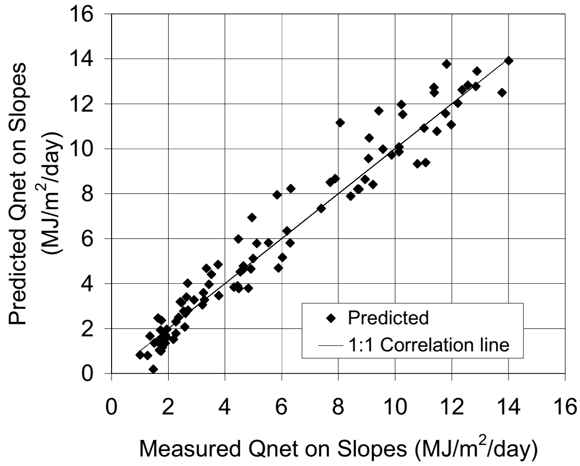

Figure 1: Correlation of measured and predicted net radiation on slopes

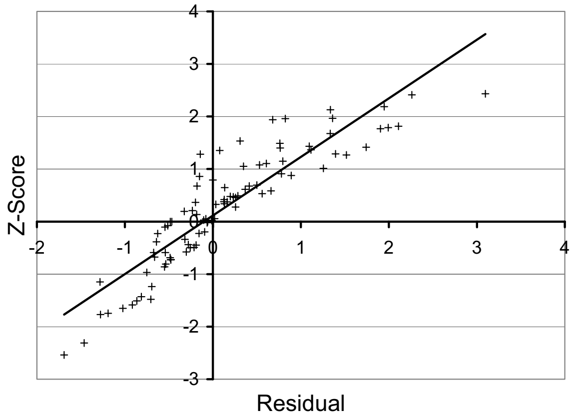

Figure 2: Normal distribution plot for residual values

Based on these plots it appears that the model can be used to provide a reasonable estimate of the net radiation expected on a sloped surface, using the net radiation and temperature measured on a horizontal surface.

5. APPLICATION OF THE MODEL

To illustrate application of the verified model, climatic and soils data from the two research sites (Equity and Kidston) are used. The solar model and climate data have been used to illustrate the impact of slope on annual net radiation values for both sites. These net radiation values were then used as inputs to SoilCover (along with soils data), to illustrate the possible impacts on both potential and actual evaporation.

5.1 Prediction of Net Radiation on Slopes

Figure 3 shows the effect of slope on predicted net radiation for the Equity site over the course of a full year.

The data shown is calculated based on summation of daily values estimated in the model, for weather data measured in 1998. Note that in the context of evaporation from soils at Equity, a "full year" refers to the period of time in which there is not snow on the ground. For 1998, this is from approximately Julian day 108 to 306. Any slope in three-dimensional space could be evaluated. The slopes shown in Figure 3 (and subsequent figures) are taken along a north-south axis, to illustrate the most extreme effects of changes in slope.

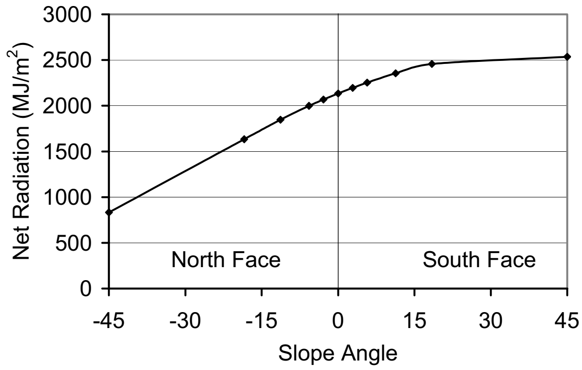

Figure 3: Variation in annual net radiation at Equity as a function of slope

Figure 4 shows the effect of slope on the predicted net radiation for the Kidston site, also over the course of a full year (365 days in the case of Kidston). Note that at Equity, the peak net radiation occurs on the south facing slopes, as would be expected for a site in the northern hemisphere, whereas at Kidston, the peak net radiation occurs on a north facing slope.

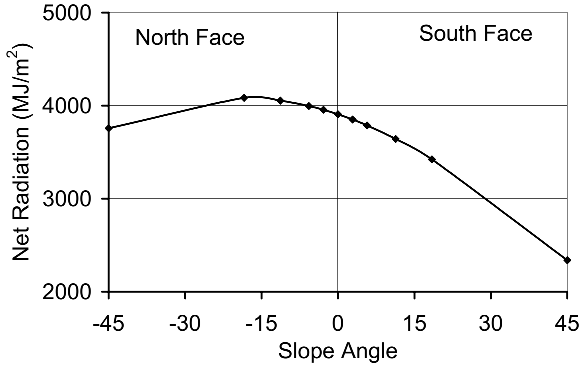

Figure 4: Variation in annual net radiation at Kidston as a function of slope

For both sites, the curve created by the net radiation/slope relationship is asymmetrical. Increases of slope on the sunward side of the site have a less dramatic effect on the net radiation than increases of slope on the shaded side. Also note that for the site at a higher latitude (Equity) the impact of slope on the daily net radiation is generally greater than that found on radiation at a more moderate latitude (Kidston). For the Kidston site, there is a point where increases in slope to the north (within the range of slopes evaluated) actually begin to diminish the Q_{net} received.

5.2 Prediction of PE and AE on slopes

To predict the impact of slope angle on potential and actual evaporation from slopes, daily weather data collected at the two sites were used in conjunction with the soils data for the two sites (Table 1 and Table 2). For each combination of site location and slope angle, a data file was prepared for analysis in SoilCover, using the actual weather data, modified with daily Q_{net} values as predicted with the solar radiation model. The predicted total PE and AE values for each location are summarized on Figure 5 (Equity) and Figure 6 (Kidston).

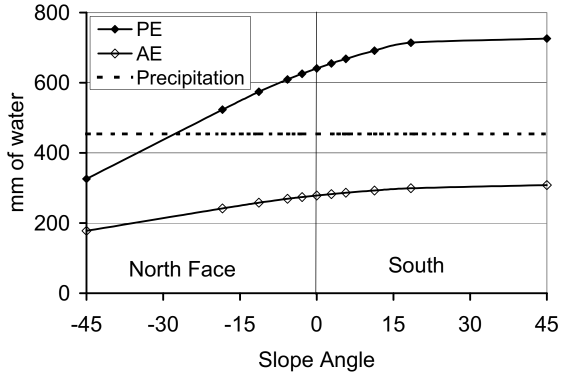

Figure 5: Effect of slope on calculated evaporation at Equity

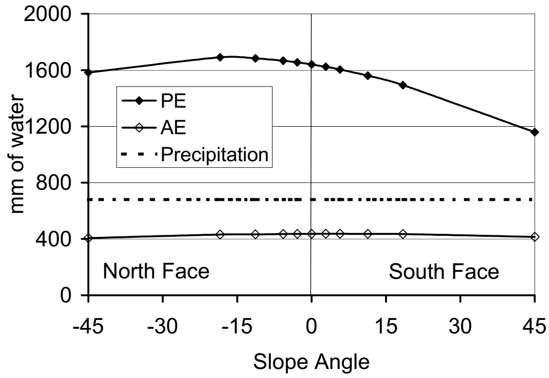

Figure 6: Effect of slope on calculated evaporation at Kidston

The lines illustrating PE on both Figure 5 and Figure 6 clearly show that PE can vary quite significantly as a function of slope at both sites. At Equity, the PE more than doubles between the extreme (45 degree, or 1H:1V) north-facing slope and the extreme south-facing slope. Even the more moderate slopes (18 degree, or 3H:1V) show over a 30% difference in PE between the north and south-facing slopes. At Kidston, the difference is less dramatic (as expected for a site at a more moderate latitude), but it is still clearly evident as shown on the figures.

For both sites, the annual actual evaporation is considerably less than the potential. This is expected, as limited moisture availability in the soils typically results in AE that is less than PE. At the Equity site, there is still clearly an impact of slope on AE. For the extreme (1H:1V) slopes, AE on the south facing slope is more than 75% greater than evaporation on the north facing slope.

At Kidston, there is almost no impact of slope on AE. This is attributed to the fact that site is located in an extremely arid region, where on an annual basis, the potential evaporation greatly exceeds the moisture availability. As a result, surface soils spend much of the year at dry moisture conditions. In such conditions, there is relatively little moisture for the soil to give up to the atmosphere, and small variations in the moisture demand (represented by variations in Q_{net} or in the potential evaporation) have little impact on the limited amount of moisture that is available for evaporation. This suggests that at arid sites, variations in Q_{net} with slope may be less important on an annual basis than at more humid sites.

6. CONCLUSIONS

The research presented illustrates that it is possible to estimate net radiation on a sloped surface, based on limited climatic data from the region. A simple, robust model has been developed to do this for engineering applications. Net radiation predicted with this model for a sloped surface can be used as an input to a flux boundary model, to estimate the evaporation that might be expected on a sloped surface.

Using the model with climate data from research sites illustrates that net radiation can vary significantly as a function of slope. In the northern hemisphere, steeper north facing slopes receive less radiation than the less steep slopes, while south-facing slopes receive more energy, to a limit. This is in keeping with well-established principles of solar energy and boundary layer climates.

The work conducted to date suggests that the importance of slope for actual evaporation in an engineering application is at least partly climate dependant. In humid climates, where there is a great deal of moisture available in the soil, changes in net radiation can result in large changes in both potential and actual evaporation. In dry climates where potential evaporation greatly exceeds the moisture availability, the variations in net radiation caused by changes in slope will affect potential evaporation, but ultimately may not have much of an effect on actual evaporation.

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