WASTE GEO Technics

Net Radiation and the Prediction of Evaporation from Sloped Soil Surfaces

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Figure 1. The main waste rock dump at the site, early morning

The study of soil covers for waste disposal sites has largely become the study of how soils interact with the atmosphere and climatic conditions in the area of the cover. The infiltration of water through a soil cover is a function of both the local climate and soil properties. Earth-atmosphere interactions determine the fate of water added to the cover (precipitation), in terms of how much water evaporates back into the atmosphere, runs off the cover, goes into storage within the soil pore space, or makes it through the cover into the waste below.

In the past fifteen years, huge strides have been made in understanding how water evaporates from soil surfaces, especially as evaporation affects the geotechnical performance of saturated and unsaturated soils. Several computer codes have been introduced to model actual and potential evaporation from soil surfaces, as part of overall water balance simulations. These codes have found application in the design and study of soil covers for waste disposal sites. In these codes, net solar radiation is an important input for calculating evaporation from soil, and is therefore important for calculating the overall water balance. With all soil atmosphere models currently in use for geotechnical applications, there is an implicit assumption that the net radiation received by a soil surface is uniform over the entire site. While this assumption is reasonable as a first approximation, it is a fact that net radiation is strongly affected by both the degree to which a surface slopes, and the direction of its slope (Oke, 1987). Most waste disposal sites are located with large portions above ground, and the surfaces of the site are typically sloped at relatively steep angles. The photograph in Figure 1 shows as an example a section of the main waste rock dump at Placer-Dome's Equity Silver site, located in central British Columbia. As can be seen on the photograph, a large portion of the site is quite steeply sloped. Depending on the orientation of the slopes, certain portions can remain in shadow (receiving less radiation) over more of the day than others. This in turn affects the evaporation from various parts of the dump surface.

Recognizing that the slope and aspect of a soil surface (such as a waste cover) can strongly affect the net radiation received by the surface, and hence the evaporation from it, a research program was undertaken to quantify the variations in net radiation received over the surface of a soil cover. This research resulted in the development of a general model for the prediction of radiation on

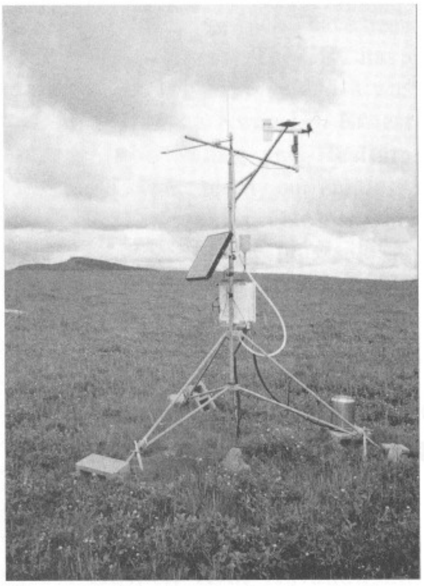


Figure 2. Weather station located in the crest area of the main dump

sloped surfaces that is suitable for application at any latitude.

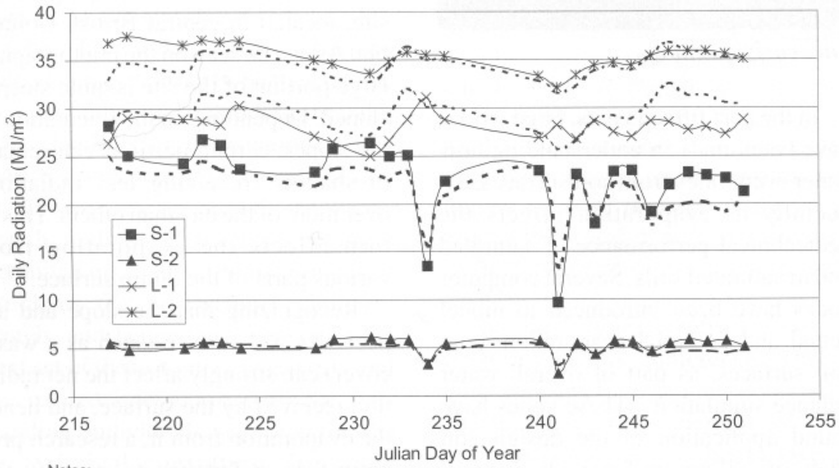
Background

The importance of evaporation for the water balance on soil covers has been well documented, especially for sites located in arid or semi-arid climates. As an example, Nyhan et al (1997) found that 86% or more of the precipitation loss they observed on soil covers was due to evaporation, with only 2-3% of precipitation loss due to runoff. This study was conducted on east-facing, sloped soil covers in a semi-arid climate. Under such conditions, variations in evaporation over a site become of greater interest than variations in runoff (at more humid sites, the importance of runoff may become greater). For the site studied by Nyhan et al (1997) it was also observed that variations in slope did not greatly affect runoff, while steeper slopes did have greater evaporation, correlating to increased exposure to sunlight. Blight (2002) has published data showing how solar radiation varied with slopes of different orientation on tailings dams, and illustrated how these variations could result in different evaporations from different slopes.

Net radiation is typically measured with a net radiometer, a relatively simple device that when oriented parallel with the ground surface gives an indication of the difference between the total radiation incident on the ground surface, and that which is reflected back into the atmosphere. The instantaneous measurement of radiation (typically reported in W/m^2) is a single value that is made up of the net amounts of shortwave and longwave radiation. Values of net radiation measured over the course of the day with a net radiometer can be integrated to determine the total energy received over the day (typically in MJ/m^2). Net radiometers are commonly used in weather stations, such as the one at the Equity site shown in Figure 2.

Net radiation can be subdivided into three main components: longwave radiation, shortwave (beam) radiation, and shortwave (diffuse) radiation. These components are of concern since each component is affected to a different degree by the slope and aspect of a surface. For instance, a slope facing away from the direct sunlight will receive considerably less shortwave (beam) radiation than a slope facing towards the sun. The amount of shortwave (diffuse) and longwave radiation received by the far slope will also be less, but not to the same degree. This factor complicates modeling of the net radiation data for slopes.

For the study of net radiation on slopes, Placer-Dome's Equity mine site in the central interior British Columbia was selected as a research site. The waste rock dump at this site has been protected with a soil cover, designed to maintain saturation (so as to act as an oxygen barrier) and minimize infiltration to the waste rock. The site has been heavily instrumented, with over ten years of soil moisture and weather data available for evaluation. The surface of the site's soil cover provided an opportunity to measure solar radiation under a variety of conditions, with side slopes as steep as 2.5H:1V, and a near-horizontal crest area (where the weather station has been placed).



Notes:
Dashed lines indicate radiation component as estimated from Net Radiation on the Horizontal Surface, using SunModel program
S - Indicates Shortwave Radiation
L - Indicates Longwave Radiation
1 - Indicates incident radiation
2 - Indicates reflected radiation

Figure 3. Comparison of measured and predicted components of net radiation

Predictive Model

To help evaluate the importance of slope and aspect for evaporation, a predictive model (called SunModel) was developed. This model was designed to estimate the net radiation on a given slope, based on the net radiation measured at a horizontal surface in the same general area. A brief overview of the model is presented here, with a more detailed description available in Weeks and Wilson (2003).

To estimate the net radiation on a slope, based on measured net radiation from a horizontal area, the measured net radiation needs to be broken down into its constitutive parts. This is necessary as the different components that make up net radiation as measured with a radiometer have differing sensitivities to slope and aspect. A series of well-established empirical and analytical methods were linked in the model to accomplish this. In the model, the longwave component of net radiation is estimated largely as a function of the surface and air temperatures at the site. The shortwave components are estimated based on the relations between the radiation that is actually measured at the ground surface at a given time, and the radiation that theoretically could be received at that time. The calculation of the radiation that theoretically could be received at a given time is based on the physical relationship between the sun and the geographical location under consideration at that particular time.

Conceptually, the operation of the predictive model is relatively simple. For a given measurement of net radiation, each subcomponent is estimated. Each sub-component of the radiation measured is then modified as appropriate for the slope under consideration. The modified components are summed, with the new total giving the estimated net radiation for the slope under consideration. Once this basic algorithm was shown to represent field conditions with reasonable accuracy, the model was extended to link with geographical site data. A TIN (triangulated irregular network) surface that represents the site can be interpolated based on geographical data. Net radiation on each triangle that makes up the surface can be calculated, based on the slope and azimuth calculated for each triangle of the TIN.

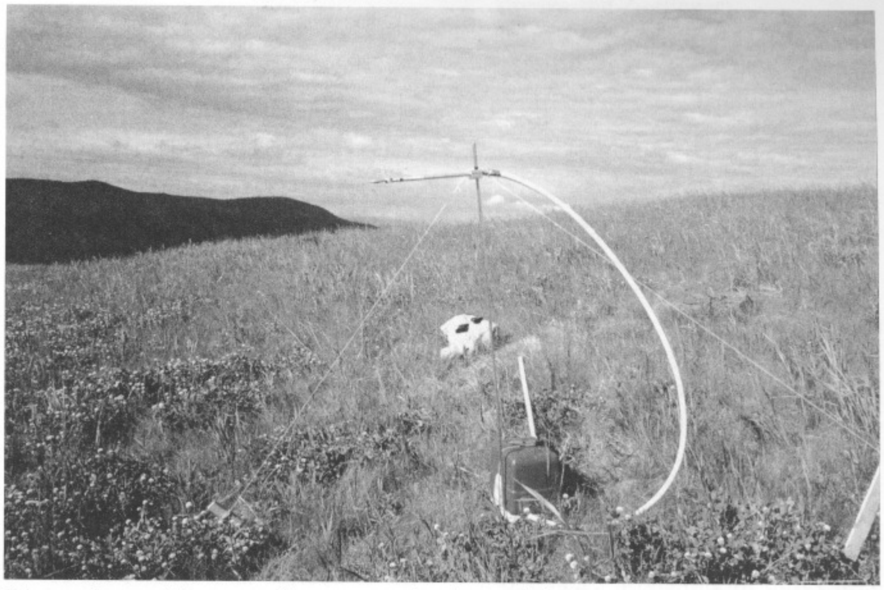


Figure 4. portable net radiometer on the slope of the cover.

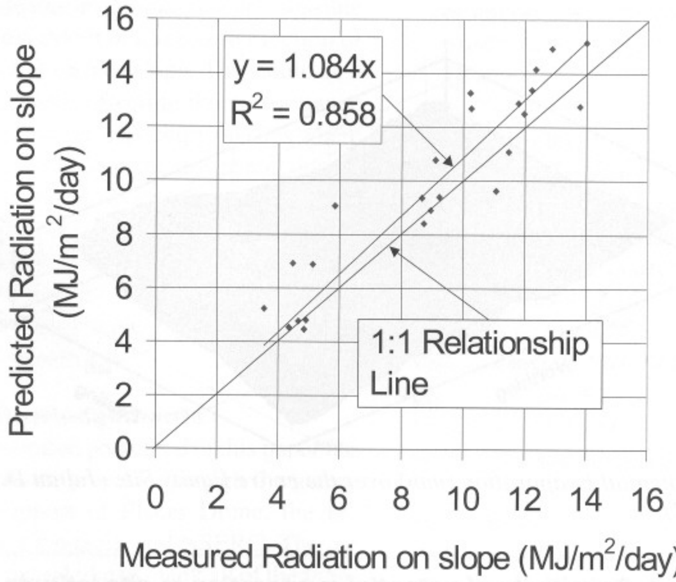


Figure 5. Comparison of measured data on slope to the SunModel predicted values data for Equity site.

Testing of Model

The first step in testing the predictive model was to evaluate the algorithms developed for splitting net radiation into its various components against data that has been presented in the literature. Figure 3 shows components of short and long wave radiation as measured in the field by Weiss (1982), and compares them to the same components as would be predicted for that site by SunModel. As can be seen in Figure 3, a close agreement was reached between the field measurements of Weiss and the values predicted in the model.

The second step in the evaluation of the predictive model was to compare measured values of net radiation on a sloped surface to those that would be predicted for a sloped surface by the model. The predicted values are estimated based on measurements collected on a horizontal surface. The data was collected at the Equity site, using the net radiometer at the weather station (Figure 2) and a portable net radiometer with data logger (Figure 4) that was moved around to various slopes at the site. Data was collected on East, West and South facing areas that sloped at angles between 11° and 25°. Figure 5 shows a comparison between the data collected on the sloped surfaces, and the net radiation values for those surfaces

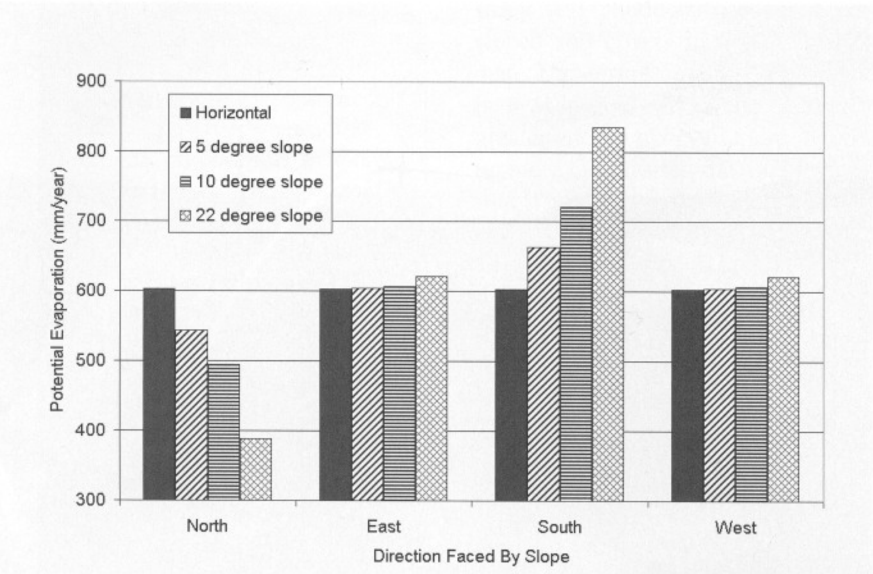


Figure 6. Effect of Cover Slope and Direction on Potential Evaporation at Equity Site (Based on 1998 Climate Data for Horizontal surface, and predicted net radiation on slope)

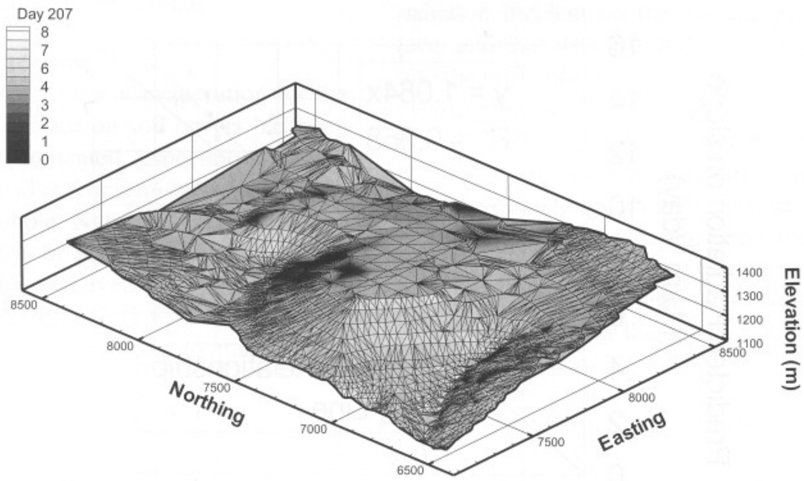


Figure 7. Potential Evaporation (mm) over the entire Equity Site (Julian Day 207, July 27).

Table 1. Sensitivity of potential evaporation to site latitude for a 22° slope

Site Latitude	Potential Evaporation (mm/year)	
	North Face	South Face
54° N	389	834
45° N	439	698
30° N	533	581

that would be predicted based on the model. Data points that plot on the 1:1 line indicate full correlation between prediction and field observation. The best-fit straight-line regression for the data is also plotted on the graph for comparison. It can be seen on the graph that the model provides a reasonably close approximation of the actual data, but is not a perfect match. Review of the data shows that for 58% of the days measured, the difference between the measured and predicted net radiation values on the slopes was less than 10%, with the difference less than 5% on 29% of the days. More data is being collected, to further verify and refine the model.

Application

Using SunModel to calculate the net radiation, it is possible to evaluate the effect that slope and aspect variations may have on potential and actual evaporation values for differently oriented surfaces. To illustrate this, the model has been used for the calculation of potential evaporation from the slopes of the Equity site. The initial calculation of potential evaporation over the site was made using weather data collected at the site (net radiation on the horizontal surface, wind speed, temperature, humidity, and other parameters) for a typical 200-day period during the non-freezing months of the year. Based on this data, the potential evaporation for the year was calculated to be approximately 600 mm, using the Penman method (Penman, 1948).

To evaluate the sensitivity of potential evaporation to slope and aspect, the net radiation values from this data set were used to calculate the equivalent net radiation values that would be expected on variously sloped surfaces at the same site. Net radiation values were calculated for slopes facing each of the cardinal compass directions (North, South, East and West), at slopes of 5°, 10°, and 22°. The net radiation values for these slopes were then used to calculate the corresponding potential evaporation for the year. The results are summarized on Figure 6. It can be seen in the figure that the steepness of the slope and the direction that the slope faces both strongly affect potential evaporation. On slopes that face to the south, there is a significant increase in potential evaporation with slope steepness. On the north-facing slopes, the trend is reversed, with less evaporation as the slope increased in steepness. This matches what one would expect for slopes in the northern hemisphere, where it is well known that south-facing slopes receive more sunlight year-round than north-facing ones. For the steepest slopes considered, there is a difference of more than 100% between the potential evaporation on the south facing slope (835 mm) and the evaporation on the north-facing slope (390 mm). On the eastern and western slopes, the impact of slope angle is much less dramatic.

Figure 7 shows the application of the SunModel to potential evaporation predictions over the entire Equity site. The TIN surface shown represents the cover on the waste rock disposal site, and the immediately adjacent area. Potential evaporation for a single day is illustrated on this figure (July 26, or Julian day 207). As can be seen by the grey scale on the figure, the slopes with a more southerly exposure have the greatest potential evaporation, and those facing the north have a lesser potential.

The Equity site is located relatively far north, at an approximate latitude of 54°N. In general, the further north a site is, the greater the difference between the solar energy received by north and south facing slopes over the course of the year. At extreme latitudes (either to the north or the south) the sun is relatively lower in the sky, and the far slope will be shaded for a correspondingly greater portion of the day. The impact of latitude on the relationship between slope direction and potential evaporation is illustrated on Table 1. The data in the table is based on potential evaporation values for slopes of 22°, with net radiation on the slope calculated using the appropriate latitude, while the remainder of the 200 day weather data set was unchanged. As shown on the table, the differences between potential evaporation on the north slope and on the south slope diminished with decreasing latitude. This indicated that the impact of slope direction and angle on evaporation should be increasingly important at sites in the far north or the far south.

Conclusion

In the design of soil covers for waste disposal sites, evaporation is an important factor affecting the overall water balance for the cover. The net radiation incident on a soil surface is a major factor driving evaporation from that surface. It is therefore potentially important to quantify variations in net radiation that may occur due to differences in the orientation of the soil surface.

To help quantify the effects of slope and direction of exposure on net radiation, a numerical model (SunModel) has been developed to estimate the net radiation on sloped surfaces at any given site, based on the net radiation received on a horizontal surface at the same site. Preliminary verification of the model has shown that it can provide a reasonable representation of field conditions. Application of the model to a test site illustrated that large variations in potential evaporation were possible over the extent of a site, as a function of the cover surface slope. This could be a major factor affecting the performance of a soil cover, especially on sites where large portions of the cover are sloped. This is especially true at more extreme latitudes (far south or far north) where the differences between the radiation received by south-facing and north-facing have been shown to be quite significant.

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