MEASUREMENTS AND MODEL PREDICTIONS OF THE RATE OF DRYING WITH TIME AT THE SURFACE OF A WASTE-ROCK PILE AFTER HEAVY RAINFALL EVENTS

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ABSTRACT

Measurements and model predictions of changes of water contents at the surfaces of waste-rock piles are needed in the development of a long-term management plan for waste-rock piles. This study investigated a short-term multi-day [July 28 to August 4, 2002] rate of drying with time at the near-surface of the Deilmann north waste-rock pile (DNWR) at the Key Lake uranium mine, northern Saskatchewan, following the cessation of 75.9 mm rainfall over the initial 48-h period. The water content was determined using the gravimetric method. The initial measured water content profile data were used with SoilCover numerical model to predict changes in water content profiles with time at the near-surface of the DNWR. Results of both the measurements and numerical predictions showed that the impact of heavy rainfall events on waste-rock surface water content at the DNWR is of relatively short duration. The waste-rock surface (0 m) water content was very sensitive to changes in climatic conditions after precipitation, exhibiting a power decrease with time. The drying rates at greater depths (>0.05 m) decreased slowly with time. This behavior was attributed to hydraulic properties of the waste-rock pile. These data can be of value in the long-term development of a plan for mine waste management.

INTRODUCTION

Soil water is an important factor affecting the movement of gases in soils (Edwards 1975; Howard and Howard 1979; Naganawa et al. 1989; Moncrieff and Fan 1999; Davidson and Trumbore 1995; Conen and Smith 2000; and Hutchinson et al. 2000). Fluctuations in water content due to heavy precipitation events or long drying periods greatly affect the water content profile which affects the gas diffusion and redistribution in the unsaturated zones. The water content of soil is dependent on several factors. These include: soil texture, temperature and environmental conditions in adjacent layers. These factors vary in different ecosystems and under different climate conditions. Precipitation can create changes in soil water content profiles within unsaturated zones, the extent of the effect will depend on the intensity and duration of the rainfall (Freeze 1969; Capehart and Carlson 1997). Hydraulic properties of the waste-rock control the storage and release of water from the pile (Barbour 1998). Fine-grained waste-rock is capable of holding larger volume of water even under negative water pressure conditions (Wilson 2000). The larger pores within the coarse fraction, however, create conduits that act as open channels that can transmit water rapidly when it is present under positive pressures. In order to identify characteristic behavior of infiltration that might be expected at a site, Stothoff (1977) examined two idealizations for an effectively semi-infinite column and a two-layer column of alluvium over a fractured impermeable matrix. He reported that between the extreme cases of high and low permeability, there is a zone where decreasing permeability results in decreased infiltration but increased water content, which is explained by the capacity of more permeable media to maintain surface wetness for longer periods of time after precipitation, thus allowing longer periods of evaporation at the potential rate. The purposes of this study are to investigate the effects of heavy rainfall events on the near-surface waste-rock water profile by measurements and simulation predictions using SoilCover. SoilCover is a model developed for the design and analysis of multi-layered soil covers over mine tailings/waste rock/municipal waste facilities. It can be used for any analysis requiring computation of actual surface fluxes based on soil conditions and climatic data (SoilCover, 2000). Numerically simulating the water balance across the air-soil interface is one avenue being considered in order to provide boundary conditions for simulations of deeper flows.

SITE LOCATION AND DESCRIPTION

The Key Lake uranium mine is located at the southern rim of the Athabasca Basin in north-central Saskatchewan, approximately 750 km north of Saskatoon, Canada (57^o 12’ latitude, 105^o 35’ longitude). Basement rock is unconformably overlain by Athabasca Group sandstone. The sandstone is overlain by sandy glacial deposits. Uranium is associated with the unconformity. Predominant uranium-bearing minerals are U_2O_7 and U_3O_9 (Key Lake Mining Corporation 1979). The Deilmann ore body at the Key Lake mine was mined from 1984-1997 (Figure 1). Many of the lakes within a 5 km radius were drained during pit dewatering and a significant portion of the waste-rock piles were placed directly upon dewatered organic-rich lake-bottom sediments (Richards 1997).

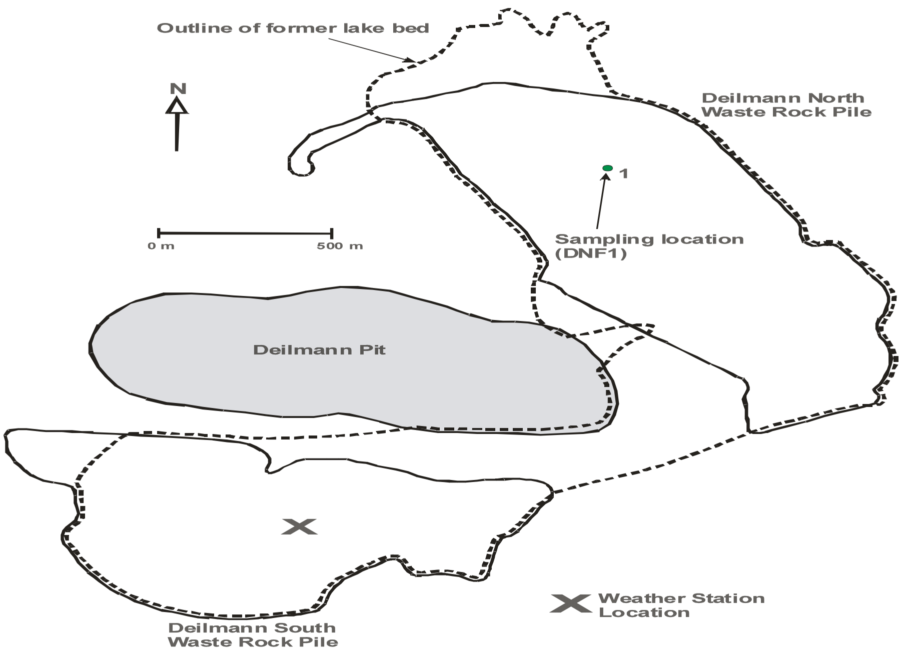

Figure 1. Site plan of the Deilmann north waste-rock (DNWR) and south waste-rock piles (DSWR) and associated Deilmann open pit at Key Lake uranium mine, Saskatchewan, Canada. The dashed lines outline the extent of lakes drained by mine dewatering. Solid circle represents sampling location; X marks the location of the meteorological weather station.

A waste-rock pile, termed the Deilmann north waste-rock pile (DNWR) constructed from overburden sand and gneissic basement rock excavated during open-pit mining of the Deilmann uranium ore body was investigated in this study. The waste-rock pile was constructed in lifts approximately 8 m in height. It has a maximum height of approximately 42 m and a total volume of about 14 million m^3. Haul ramps were used to transport material to each new lift pad where the waste-rock was then dumped and pushed off the edge of the pad to maintain a flat top. The waste-rock pile consists of approximately 18 m of gneissic basement rock (~10% by volume) overlying approximately 24 m of sand/sandstone (~90% by volume) from the overburden (Lee et al. 2003). The basement rock in the DNWR generally had larger particles (gravels, boulders and cobbles) compared to sandy waste-rock material. It should be noted that over the years the exposed rocks have weathered, so that the top surface consists of a silty, sandy soil with a large proportion of rocks below the surface.

MATERIALS AND METHODS

Grain-Size Distribution

The particle-size analysis of the DNWR sample was determined according to ASTM Designation: D 422-63. The distribution of particle sizes larger than 75 µm (retained on the No. 200 sieve) was determined by sieving, while the distribution of particle sizes smaller than 75 µm was determined by a sedimentation process, using a hydrometer.

A 5 kg sample of weathered waste-rock material from surface and near ground surface (0 to 0.15 m) was collected from DNWR at DNF1 (Figure 1). The grain-size distribution for the sample was determined by sieve analysis. Approximately 200 g of waste-rock sample was dried at 105 ^{o}C for 24 h. The oven dried sample was sieved through sieves with mesh sizes of 4, 10, 20, 40, 60, 80, 100, 140, 200 and 270 on a shaker for 10 minutes. The mass and percent of waste-rock retained on each sieve were determined by weighing and plotted against the size of the sieves openings. For the hydrometer analysis, a portion of the material from each sample prepared for the sieve test material was passed through 200 mesh opening sieve. Material not passing the sieve was discarded. The material passing the sieve was then oven dried for 24 hours and the mass was subsequently recorded. A sieve analysis was then performed on the material after the hydrometer analysis was completed.

Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve (SWCC) for the DNWR sample was determined in a Plexiglas Tempe cell apparatus (0.1 m dia. x 0.14 m height) using standard methods (Fredlund and Rahardjo 1993). In this test, approximately 75 percent of the cell volume was filled with the waste-rock sample. The sample was tested using a 1 bar ceramic stone conducted at room temperature of approximately 20 ^{o}C. Atmospheric pressure was maintained at the discharge face of the porous stone. Air did not flow through the cell unless the air pressure exceeded the air entry value of the ceramic disk. Small amounts of the air diffused through the water in the pores of the high air entry disk and were subsequently flushed from the base of the cell. However, the test was not affected as the air pressure in the cell was maintained by the inlet pressure. The high air entry disk at the base of the apparatus was saturated prior to the start of the test. After saturation of the waste-rock specimen, increasing pressures of 0.2, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 50, 80 and 100 kPa were applied to the air phase within the cell. The total mass of the waste-rock filled Tempe cell was continually monitored during the drainage phase of each pressure increment. Equilibrium was achieved when zero discharge (measured as change in mass) was observed over a 24 to 72 hour period. Upon reaching equilibrium at 100 kPa of applied suction, the sample was removed from the Tempe cell. The water content corresponding to the highest matric suction (100 kPa) was measured by oven-drying the waste-rock sample. This water content together with the previous changes in weight were used to back-calculate the water contents corresponding to the other suction values. The matric suctions were then plotted against their corresponding water contents to yield the SWCC. Fredlund and Rahardjo (1993) provide a discussion on the measurement of the matric suction.

Saturated Hydraulic Conductivity (K_{sat})

The saturated hydraulic conductivity (K_{sat}) of the DNWR sample was determined by performing a falling-head hydraulic conductivity test in a stainless steel permeameter cell (0.101 m dia. x 0.116 m height) using an ASTM Standard Test Method, D 5856, 1995. The base and top plates of the permeameter were sealed using rubber O-rings. The top plate was connected to a 100 ml standing pipe burette (0.015 m dia. x 0.70 m height). The base plate was connected to a constant head reservoir. Oven-dried waste-rock samples were uniformly and loosely poured into the cell to approximately 95 percent of the cell volume. The weight of the dry sample was determined by the difference between the weight of the waste-rock-filled cell and the empty cell. The sample was saturated downward with distilled water flowing from the burette through the waste-rock specimen. All air bubbles were removed from the apparatus system by downward flushing of the system with distilled water. Water from the standing pipe burette was allowed to flow through the waste-rock sample using a regulated valve. The time for water to fall between two defined elevations on the standing pipe burette was recorded for each test. The test was repeated until a constant time for water to fall a given height was achieved. The final sample height was then measured before removing the sample from the permeameter cell. The K_{sat} was estimated using an equation described in the ASTM Standard Test Method, D 5856, 1995.

The hydraulic conductivity (K) of an unsaturated soil is a function of the degree of saturation (or the volumetric water content) or soil matric suction (ψ) (Huang et al. 1998). A number of empirical relationships have been proposed to determine K as a function of volumetric water content, or ψ (Richards 1931; Wind 1955; Gardner 1956; Davidson et al. 1969; Philip 1986; and Ahuja et al. 1988). However, the models proposed by Brooks and Corey (1964) and Mualem (1978), appear to be of wider applicability than other models. We used the Brooks and Corey (1964) relation to calculate the unsaturated hydraulic conductivity (K).

Soil Water Content

The water content for all samples obtained in the field was determined using the gravimetric method. Waste-rock samples were collected at different depths (0, 0.05, 0.10, and 0.15 m) in triplicates of about 100 g each at three different locations around DNF1 (Figure 1). The samples were placed in zippered air tight plastic bags. Gravimetric water contents were determined in the laboratory at the Key Lake mine by oven-drying the waste-rock sample within 24 h. The replicate measurements were combined to yield a mean water content value for each depth. The gravimetric water contents were converted to volumetric water contents using data from the sample SWCC and specific gravity. The waste-rock samples were collected daily during the test period (August 1 to August 6, 2002).

SoilCover

SoilCover is probably the most widely used code for the design of soil covers for waste-rock dumps and tailings impoundments worldwide (Noel and Rykaart, 2003). SoilCover is a one dimensional finite element package that models transient conditions. The model uses a physically based method for predicting the exchange of water and energy between the atmosphere and a soil surface. SoilCover model calculate actual evaporation from a soil profile based on coupled heat and mass flow as governed by the meteoric and soil condition. The theory of SoilCover is based on the well known principles of Darcy’s and Fick’s Laws which describe the flow of liquid water and water vapour, and Fourier’s Law to describe conductive heat flow in the soil profile below the soil/atmosphere boundary. SoilCover predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of atmospheric conditions, vegetation cover, and soil properties. A modified Penman formulation is used to compute the actual rate of evaporation from the soil/atmosphere boundary. The input requirements for SoilCover are categorized into soil type, climate parameters, vegetation parameters, boundary conditions, initial conditions, and modeling details. The climatic parameters for detailed or reduced weather data used in this study were collected from a weather station at the mine site.

Meteorological Weather Station

A meteorological weather station (Campbell Scientific, Inc.) was installed on Deilmann south waste-rock pile (DSWR) (Figure 1) approximately 2 km from DNWR on April 28, 2000. The meteorological station sensors and data acquisition systems (DAS) were installed on a tripod. The wind monitor and net radiometer were mounted on a steel cross-arm at a height of approximately 3 m above the ground surface. The air temperature and relative humidity probe was housed in a radiation shield (approximately 1.8 m above the ground surface) to minimize the effects of solar radiation. The tipping bucket rain gauge was installed on a wooden plank near the tripod (approximately 1 m above the ground surface). The DAS consisted of a CR10 data-logger (Campbell Scientific Inc.), a storage module and a solar panel with 12 volt battery system. The station collected hourly average air temperatures.

RESULTS AND DISCUSSION

Laboratory Test Results

Grain-size distribution

The grain-size distribution for the near-surface sample collected from DNWR (Figure 2, curve with symbols) indicated that 83% of the material was sand size with 17% silt and clay size particles. The sand sizes ranged from coarse (16%), medium (42%), and fine (25%). The uniformity coefficient of the sample (C_u) was found to be about 6.3. A sample with a C_u >6 is considered poorly sorted (Keen 1931). The mean ± one standard deviation of 26 grain-size distributions obtained from core samples from DNWR (Birkham 2002) are also presented in Figure 2 (curves with solid lines). The grain-size distribution curve measured in this study was outside the mean ± one standard deviation envelope for the basement rock core samples. The C_u of the mean grain-size distributions (not shown) for the basement rock was determined to be about 30. Birkham (2002) found that 40% of DNWR basement rock bulk sample was cobble-sized. This was consistent with the visual observation that basement rock in the DNWR generally had larger particles compared to sand/sandstone material. The grain-size distribution of the sample could not be considered representative of the entire DNWR pile because boulder-sized particles were excluded from the analysis (Birkham 2002). It is documented that fine-grained waste-rock is capable of holding larger volumes of water even under negative water pressure (suction) conditions (Wilson 2000). The larger pores within the coarse fraction, however, create conduits that act as open channels that can transmit water rapidly when it is present under positive pressures.

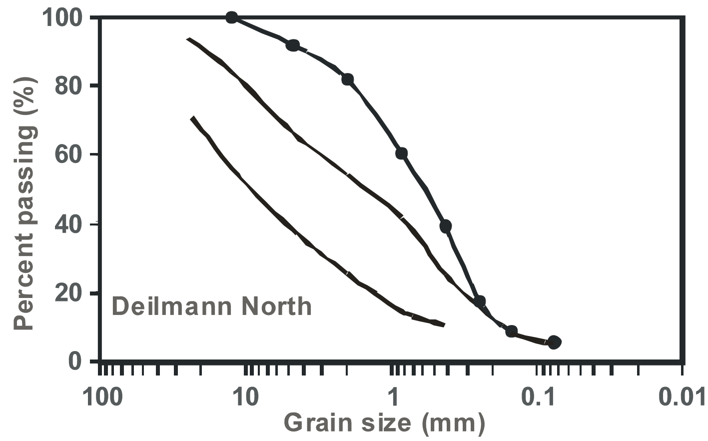

Figure 2. Particle size distribution curves for the samples of waste-rock from the Deilmann north waste-rock pile (DNWR) for surface sand (curve with symbols) and core basement rock (curves with solid lines). Symbols represent the measured data from this study. The full lines show the one standard deviation range of grain size data obtained by Birkman et al. (2002).

Soil water characteristic curve

Figure 3(A) shows the soil-water characteristic curve (SWCC) for the sample from DNWR. The SWCC provides useful information on the water retention and water transmission behavior of piles and helps to describe the effects of waste-rock texture and void ratio on the distribution of the water phase in the waste-rock pile (Barbour 1998). From the SWCC (Figure 3) the soil sample is close to saturation only up to 1 kPa suction which is the air entry value (AEV). The SWCC shows the sample drains rapidly between values of matric suctions of 1 and 10 kPa. At 10 kPa suction, the sample retained about 20% water. This behavior is characteristic of sand and sand/silt materials (see grain-size distribution above) and has been also described by others (Wilson et al. 1993; Barbour 1998).

Hydraulic conductivity

The falling-head hydraulic conductivity test yielded a value of $K_{sat} = 1.20 \times 10^{-6}$ m s^{-1} for the surface sample of waste-rock from the DNWR. This value is characteristic of sand and sand/silt materials. Wilson et al. (1993) obtained similar results in a previous study conducted on beaver Creed sand. The relation between the unsaturated hydraulic conductivity (K) and suction (ψ) derived from the Brooks and Corey (1964) model for the sample is shown in Figure 3(B). The K of the sample decreased rapidly with increasing ψ past the AEV at about 1 kPa suction. As suction was increased by two orders of magnitude, the K is predicted to decrease by more than 10 orders of magnitude. At ψ=100 kPa, the K value decreased to $<10^{-15}$ m/s.

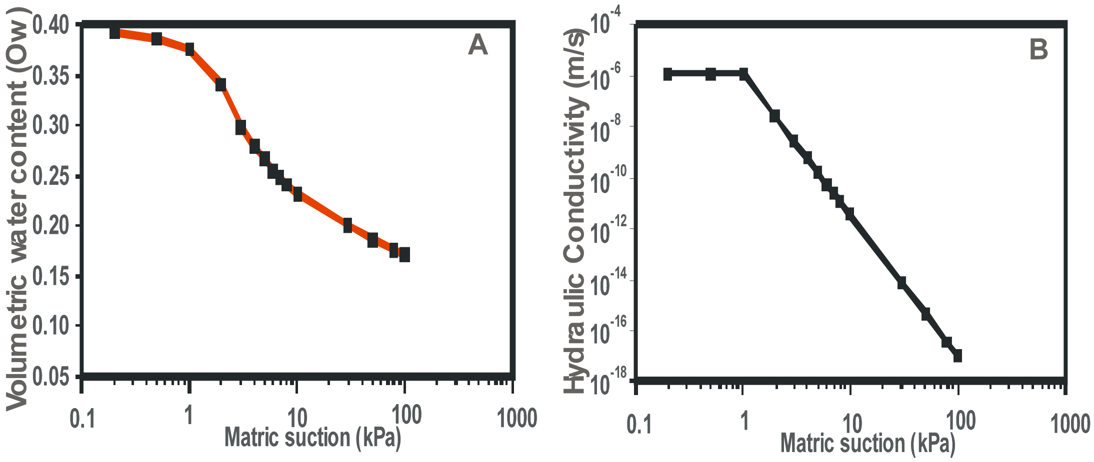

Figure 3. (A) soil water characteristic curve (SWCC) of the sample of waste-rock from the Deilmann north waste-rock pile (DNWR) (symbols represent the measured data) and (B) the unsaturated hydraulic conductivity curve (K) of the sample of waste-rock from the Deilmann north waste-rock pile (DNWR) derived from the Brooks and Corey model (1964).

<u>Field Test</u>

<u>Effects of heavy rainfall events on the near-surface waste-rock water content at DNWR</u>

Figure 4 (open circles) shows the changes of measured water contents at ground surface with time at DNWR following the cessation of 75.9 mm rainfall over the initial 48-h period [July 28 (day 1) to July 29 (day 2)] and the gradual decrease in rainfall from July 30 (day 3) to August 4 (day 8). The ground surface of the pile dried rapidly (Figure 4 open circles) while the drying rates at greater depths (0.05 m and below) decreased slowly with time (see Figure 5(A)). For example, on day 3 (July 30, 2002) the ground surface water content at DNWR was about 0.20 which is about 60% saturation (see SWCC, Figure 3). The ground surface continued to dry rapidly with time to a water content value of about 0.010 (day 8). The drying rate eventually diminished with time, although at greater depths (0.05 m and below) (Figure 5(A)), water contents remained elevated at the end of the test period (day 8). Capehart and Carlson (1997) pointed out that when this divergence between the drying rates at the surface and greater depths occurs, the waste-rock water profile at the surface and at greater depths (0.05 m and below) have become "decoupled" because the drying rates at the surface and at the greater depths cease to be linearly correlated. This behavior is caused by the reduction of the K due to the decrease in surface water content as evaporation continues (Shuttleworth 1993; Capehart and Carlson 1994; Ek and Cuenca 1994; Capehart and Carlson 1997). Edwards (1975) also noted that in mixed deciduous forest floor, with high precipitation and a well drained soil, the effect of water appear to be of relatively short duration, usually just after a heavy rain or during extremely dry periods. The rate of the decrease of surface water content ($d\theta_w/dt$) can be described by (Gray 1995):

$$-\frac{d\theta_w}{dt} = a * t^{-b} \qquad [6]$$

where θ_w is the volumetric water content $\left(m_w^3 m_{air}^{-3}\right)$, *t* the time, and *a* and *b* constants related to the boundary conditions and conductance properties of the soil. The exponent *b*, which is related to soil diffusivity, is obviously most important, and the greater its value, the greater the decrease in water content. The use of this model to develop prediction equation for the rate of drying of ground surface at the DNWR:

$$(-\frac{d\theta_w}{dt} = 7.19 * t^{-3.30}, \; R^2 = 0.826) \qquad [7]$$

yielded a high correlation coefficient. Gray (1995) pointed out that, if the drying rate was limited only by a diffusion-limited process (i.e. vapor diffusion across the drying zone) the exponent in the drying rate function would be 0.5. However, during drying, the water is simultaneously redistributing away from the waste-rock ground surface because of the capillary forces and gravity, thereby speeding decay of the drying rates. The time-variable rate of redistribution depends not only on the hydraulic properties of the waste-rock, but also on the initial wetting depth, as well as on the relative dryness of the bottom layers (Hillel 1980).

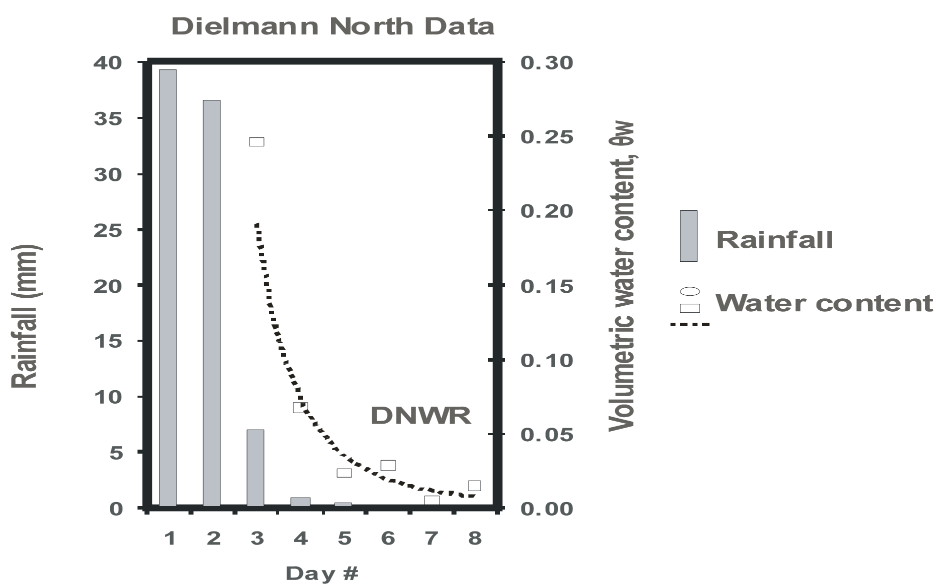

Figure 4. Rainfall and water content measured at DNF1 over an 8-day test period [July 28 (day 1) to August 4 (day 8), 2002] at the Deilmann north waste-rock pile (DNWR).

Simulated soil water content profiles using SoilCover

The SoilCover model was used to simulate water content profiles at the near-surface of the DNWR following the cessation of a 75.9 mm heavy rainfall events as described above (Figure 4). SoilCover predicts the evaporative flux from an unsaturated soil surface on the basis of atmospheric conditions and soil properties. The measured water content profile on day 3 was used as the initial condition. The measured waste-rock properties (e.g., soil porosity, specific gravity, SWCC and hydraulic conductivity) and the climatic parameters at the mine site (e.g., precipitation, net radiation, air temperature, relative humidity, windspeed, etc…) were used as input requirements for the model simulations. Figure 5(B) exhibits the numerical model (SoilCover) results for water content profiles from day 3 to day 8. The model simulations exhibit the water content profiles comparable to those obtained from the measurements (Figure 5(A)). For example, the model also predicts rapid drying rates at ground surface of the pile and slow decrease in drying rates at greater depths (0.05 m and below). However, the model slightly overestimated the water content profiles.

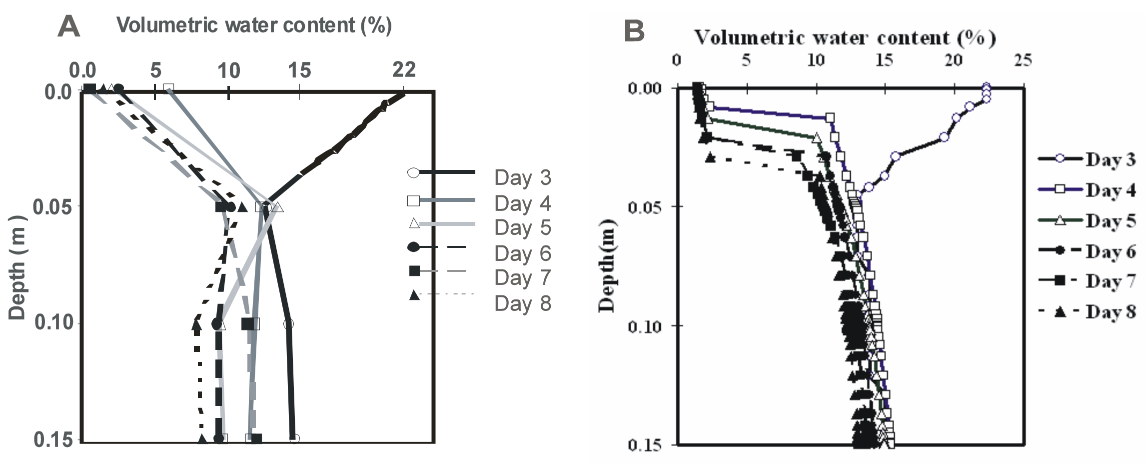

Figure 5. Comparison of (A) measured volumetric water content profiles and (B) simulated volumetric water content profiles data using SoilCover numerical model for a 6-day test period [July 30 (day 3) to August 4 (day 8), 2002] at the Deilmann north waste-rock pile (DNWR).

CONCLUSIONS

Results showed that the impact of heavy rainfall events on waste-rock surface water content at the DNWR is of relatively short duration. The surface water content returned to its initial value after five to six days. This behavior was attributed to the sandy texture of the waste-rock and its associated high saturated hydraulic conductivity (1.20 x 10^{-6} m/s). The rate of decrease of water content at the waste-rock surface at the DNWR can be predicted by the equation $-\frac{d\theta_W}{dt} = 7.19 * t^{-3.30}$. Results also showed that the SoilCover model can be a useful tool in predicting fluctuations in waste-rock water contents due long drying periods and heavy precipitation events. This study should be of value in the development of a long-term management plan for waste-rock piles.

Acknowledgements

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