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Two New Models to Predict Rainfall-Runoff in Soil Cover Systems

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ABSTRACT

Solving the water balance equation is a prerequisite for many geoenvironmental engineering problems especially these centred around mine operation and closure. The water balance equation represents the difference between water inflow and water losses. Despite the mathematical simplicity, the equation remains indeterminate so long as the rainfall runoff is not measured. This paper puts forth two new models to predict rainfall runoff fluxes using analytical and empirical approaches that can improve design and assessment of structures involving water balance including soil cover systems. The first approach is deterministic and depends on readily measured soil properties and accessible meteoric data. The second technique is parametric and relies on empirical correlations obtained during physical laboratory simulation of rainfall. Both proposed solutions require only minimal input and predict runoff fluxes within 15% accuracy for average rainfall events. Both methods are suitable as a first estimate to facilitate calibration of detailed numerical models. The analytical model is limited in accuracy to predict runoff resulting from extreme rainfall storms exceeding 90mm/hr.

RÉSUMÉ

La résolution de l'équation d'équilibre de l'eau est une condition préalable à de nombreux problèmes d'ingénierie géoenvironnementale, en particulier ceux liés au fonctionnement et à la fermeture de la mine. L'équation du bilan hydrique représente la différence entre l'apport d'eau et les pertes d'eau. Malgré la simplicité mathématique, l'équation reste indéterminée tant que l'écoulement des précipitations n'est pas mesuré. Cet article présente deux nouveaux modèles pour prédire les flux de ruissellement des pluies en utilisant des approches analytiques et empiriques qui peuvent améliorer la conception et l'évaluation des systèmes de couverture du sol. La première approche est déterministe et dépend des propriétés du sol facilement mesurées et des données météorologiques accessibles. La seconde technique est paramétrique et repose sur des corrélations empiriques obtenues lors de la simulation physique en laboratoire des précipitations. Les deux solutions proposées ne nécessitent qu'un apport minimal et permettent de prédire les flux de ruissellement avec une précision de 10% pour les indices de précipitations moyennes. Les deux méthodes conviennent comme première estimation pour faciliter l'étalonnage de modèles numériques détaillés. Les modèles sont limités en précision pour prédire le ruissellement résultant des tempêtes de pluie extrêmes à l'exclusion de 90mm/hr.

1 INTRODUCTION

Many enigmas facing geotechnical and geoenvironmental engineers revolve around water flow and water balance. Water balance is not only a subtle art in both practices, but also constitutes a fundamental design tenet for many geostructures. For example, the design of earth-fill dams, landfills, and slope stability, and the like, require a profound understanding of water flow at the soil-atmosphere interface. Quantifying the inflow and outflow of water is indispensable in mine waste containment structures such as soil covers.

Soil covers are a preferred reclamation option for both waste rock and tailings. The reason is simple, from a geotechnical perspective dry stable covers appeal as a reliable option to transform mined landscapes into the wilderness they should become. Soil covers are synonymous with engineered barriers over hazardous wastes. Conceptually, the containment aims to provide control of oxygen diffusion and water percolation into the underlying waste to eliminate leaching. Mine waste storage facility can be contained using several types of covers O'Kane and Ayres (2012). These include, conventional low permeability covers synthetic covers, which are used to cut off water flow into underlying waste incorporating synthetic geomembrane (Benson 2014). The alternative approach is water balance covers, also referred to as store and release covers. These covers rely on unsaturated soil behaviour to control hydrology. This involves allowing natural storage within the soil layer with minimum drainage during wet periods then allowing energy from the sun to release that water.

The design of water balance covers entails a detailed assessment of water fluxes at the soil-atmosphere interface. The central idea is theoretically simple; the minimum thickness of the soil cover is calculated based on sufficient storage capacity to retain water that accumulates during precipitation periods with limited percolation until the energy needed to remove water by either evaporation, transpiration, or evapotranspiration is reached (Benson et al. 2007).

The design core of soil cover systems is water balance calculations. The water balance relies on the principle of conservation of mass. The continuity equation states that during any period, the difference between total input and output of water is balanced by the change of water storage within the system as described in Equation 1.

$$P - R - E - \Delta S = NP \qquad [1]$$

where:
P = precipitation received at the ground surface
R = surface runoff
E = evapotranspiration
ΔS = change in water storage
NP= net percolation

It is essential to measure or compute all the balance elements, using independent methods whenever possible to close the water balance equation. The water balance equation therefore usually does not balance unless the surface runoff is measured.

Therefore, surficial runoff waters have a significant impact on the performance of the cover system affecting water flow, yet runoff is rarely measured (Jubinville 2013). This shortcoming means it would not be possible to directly verify the predicted in-field fluxes without an accurate estimate of surface runoff.

Abdulnabi 2015 summarizes the evolution of rainfall runoff prediction models indicating that available models are either at the point scale or the watershed scale. Both of which may not accurately reflect what to expect on the field scale, which is the appropriate scale for soil cover systems.

Rainfall runoff and infiltration have a unique interdependency. The relationship has been theorized in classic literature (Horton 1933), where the infiltration capacity was first introduced. The concept considers the soil as a separating facade that distributes rainfall water into two portions. A portion is initially absorbed by the soil (infiltration) and then percolates into groundwater. The remainder does not infiltrate into the soil but runs off in the form of surface runoff (also referred to as rainfall excess runoff). However, the infiltration portion of this partition is abundantly addressed in the literature (Green and Ampt 1911; Horton 1939; Philip 1957; Mein and Larsen 1978). The same cannot be said about the portion that constitutes runoff.

One cannot design a soil cover system that relies on water balance without confidently evaluating rainfall-runoff fluxes. Thus far, there is no conclusive model to predict runoff fluxes at the field scale satisfactory to be used in practical scenarios. The present paper offers two new methods to alleviate the effects of this shortcoming.

2 THEORETICAL PROLOGUE

A succinct theoretical foreword is paramount to contextualize the proposed models and highlight their value. Conceptually, the laws of water flow thru soil are simple. The driving potential for water flow through saturated and unsaturated soils is the hydraulic head. The hydraulic head can be understood in terms of energy. The total head is the summation of elevation and pressure heads which can be written as follows:

$$h_w = y + \frac{u_w}{\gamma_w\, g} \qquad [2]$$

where:
h_w = total hydraulic head [L]
y = elevation head [L]
u_w = pore-water pressure [ML-2]
γ_w = unit weight of water [ML-3]
g = gravitational acceleration [LT-2]

In saturated soils under steady-state flow, Darcy's law adequately describes the flow of water through the soil matrix. Darcy's law postulates that the rate of water flow through a porous medium is directly proportional to the hydraulic gradient and coefficient of permeability.

By representing the change in volume of water in terms of change in volumetric water content, and then substituting Darcy's law into the equation, the following basic equation for water flow in the soil can be written:

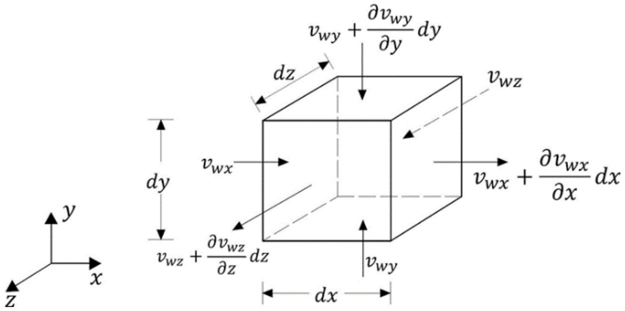

Figure 1 Water flow through a referential element in unsaturated soil.

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial x}\left(-k_{wx}\,\frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_{wy}\,\frac{\partial h_w}{\partial y}\right) + \frac{\partial}{\partial z}\left(-k_{wz}\,\frac{\partial h_w}{\partial z}\right) \qquad [3]$$

$\frac{\partial \theta_w}{\partial t}$ = net flux of water per unit volume of the REV soil
k_{wi} = coefficient of permeability in the i-direction
h_w = hydraulic head

Therefore, as Equation 5 demonstrates, the governing equations of water flow through unsaturated soils are second-degree partial differential equations (PDE) that are highly non-linear given that coefficient of permeability is dependent upon soil suction. The most appropriate means of solving Equation 5 is numerically using finite element or finite difference methods.

Although numerical models constitute a compelling tool to provide a rigorous solution for equation 6, there is a paradox. Practitioners face a sort of 'the chicken or the egg' causality predicament. One needs runoff fluxes for a determinate water balance equation. Numerical models help solve the highly non-linear equations that control water flow through soils discussed above. To get accurate predictions, one must have a notion of how much runoff to expect (Jubinville 2013 and Abdulnabi et al. 2016). Numerical predictions only work when the engineer calibrates input parameters appropriately to ensure that physical processes in the model are correctly simulated.

Numerical simulation of water flow is extremely sensitive to input parameters such as surface hydraulic conductivity (Scanlon et al. 2002 and Bohnhoff et al. 2009). Besides, numerical runoff predictions have also proven sensitive to rainfall resolution (Jubinville 2013 and Abdulnabi et al. 2016).

Abdulnabi (2015) discuss the numerous studies that have attempted to replicate field measurements of water balance parameters in soil cover systems utilizing different commercial numerical models available in the industry. The unanimous conclusion of all investigated studies was that numerical models must be calibrated to yield accurate results. Scanlon et al. (2002), Swanson et al. (2003), and Abdulnabi and Wilson (2017) systematically illustrate the significance of model calibration when utilizing numerical models to predict water balance components.

A perception of the expected answer must be available at the time of simulation to calibrate input parameters. The present paper offers two techniques to formulate this first estimate required to optimize numerical prediction of rainfall runoff in soil covers systems. The reader may wish to refer to Abdulnabi and Wilson (2015) for a background on the laboratory program leading to the work presented in this paper.

3 METHODS

The chief purpose of this paper is to develop a method suitable as a first estimate to enhance numerical models prediction involving rainfall-runoff. To do that, one must understand the primary mechanisms that rule runoff onset. Much of the literature on that is multi-disciplinary. However, the underlying processes to generate surface runoff depend on the conditions of the soil surface. Schmocker-Fackel et al. 2007 summarise the several mechanisms of rainfall runoff generation as illustrated in Figure 2. In the context of soil cover systems, the soil top surface is designed to inhibit infiltration. Therefore, one could argue that following a rainfall event, runoff on the cover system would most likely the be a Hortonian flow.

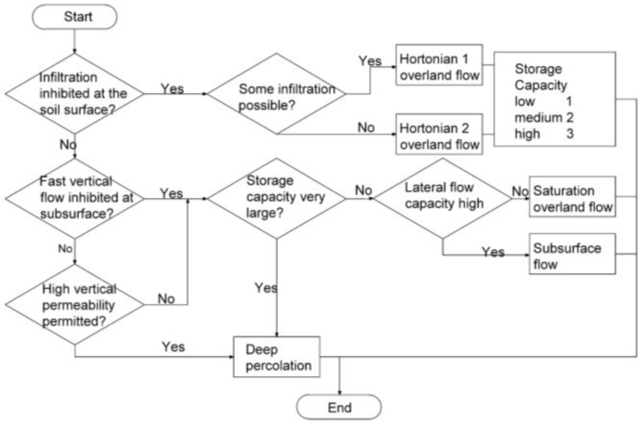

Figure 2 Selection of the dominant runoff mechanism (after Schmocker-Fackel et al. 2007).

3.1 Analytical Approach

Jubinville (2013) proposed a simple analytical solution for single layer saturated soil covers based on Dunne and Black (1970) and Wilson (2006). Figure 3 illustrates the general premise of the method summarized as follows: when the rainfall intensity does not exceed the saturated hydraulic conductivity of the profile K_{sat}, then no runoff is generated, and rainfall infiltrates the soil profile at the rate of K_{sat} or rainfall intensity, whichever is smaller. When the rainfall intensity exceeds K_{sat}, then runoff rate can be calculated as the arithmetic difference between the rainfall intensity and the material saturated hydraulic conductivity K_{sat}. Rainfall intensity function can take on any shape, the normal distribution in Figure 3 is for illustration only. Runoff volumes could be predicted using simple 1D arithmetic for the profile as follows:

$$R = (I - k_{sat})\ t\ A \qquad [4]$$

where:

R = runoff volume [L^3]
I = rainfall intensity [L/T]
k_{sat} = saturated hydraulic conductivity of the soil [L/T]
t = duration of rainfall
A = profile area [L^2]

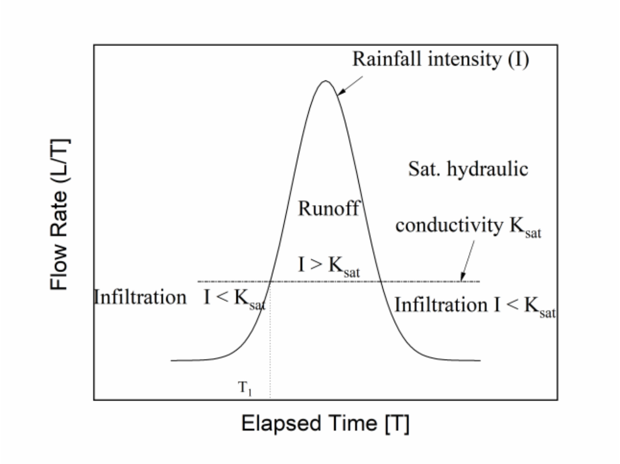

Figure 3 A simplified schematic representation of the parameters controlling runoff generation in saturated soils (after Wilson, 2006: and Jubinville, 2013).

Using K_{sat} to estimate runoff in unsaturated profiles with the assumption that the immediate soil surface should be saturated for runoff to occur (Smith 2002), is fundamentally flawed. There can be a significant amount of runoff across the ground surface even when the profile is unsaturated as demonstrated in Abdulnabi and Wilson (2015). Failure to include the substantial runoff that can occur in the unsaturated zone may lead to unrealistic predictions.

So, the question becomes: how can we predict rainfall runoff without overlooking the period when the profile is unsaturated? What is the equivalent unsaturated soil property that can characterize rainfall runoff and can be easily measured? The answer is quite simple: it is the infiltration capacity function. The infiltration capacity function can be considered the most straightforward controlling parameter to quantify water seepage into unsaturated soils. The surface runoff would be a function of both the applied rainfall intensity and the soil infiltration capacity function as shown in the laboratory experiments on the unsaturated profiles (Abdulnabi and Wilson 2015).

Infiltration capacity functions can be obtained using a field infiltrometer or a column test in the laboratory.

The idea of the proposed technique to calculate runoff in unsaturated profiles relies on the infiltration capacity (Ic) functions and follows the logic illustrated in Figure 4. In short, when the rainfall intensity does not exceed the infiltration capacity of the profile, then no runoff is generated, and rainfall infiltrates the soil profile at the rate of Ic or rainfall intensity, whichever is smaller. When the rainfall intensity exceeds the Ic, then runoff rate can be calculated as the integration of the arithmetic difference between the rainfall intensity and the infiltration capacity function. Using the laboratory data presented in Abdulnabi and Wilson (2015), runoff volumes were predicted for each profile using Equations 8 and 9. Statistical comparisons between measured and predicted values are presented in Section 4.

$$R = \int_0^t (I - I_c)\ t\ A \qquad [5]$$

where:

R = runoff volume [L3]

I = rainfall intensity [L/T]

I_c = infiltration capacity of the soil [L/T]

t = duration of rainfall

A = profile area [L2]

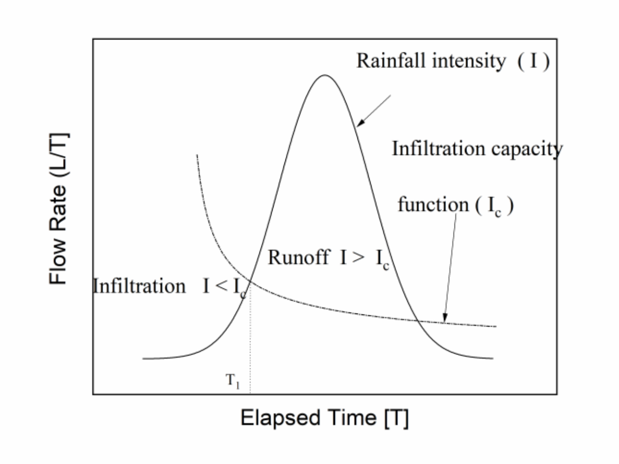

Figure 4 A simplified schematic representation of the parameters controlling runoff generation in unsaturated soils (after Mein and Larson 1973).

The Infiltration capacity function captures the upper bound of change in infiltration rate with time. This function is known to start at a maximum rate and then decrease nonlinearly with time down to a minimum value related to the saturated hydraulic conductivity of the soil (Horton 1939, Mein and Larson, and Beven 2002). The infiltration capacity functions are easy to determine through simple time- and cost-effective tests.

There is no standard test method to determine the infiltration capacity function of soil. Nevertheless, the standard test method for infiltration rate of soils in the field using double-ring infiltrometer (ASTM D3385 2009) was implemented with adjustments. The test was converted into a column test subjected to a sufficient ponding depth to generate the maximum infiltration rate. The column boundary conditions mirrored those of the laboratory flume. For each soil type, four samples were prepared at four dry densities ranging from 1.46 g/cm^3 to 1.60 g/cm^3. The samples were tested inside transparent plexiglass cylinders to observe the wetting front propagation with time. Table 1 provides detailed information about the density, dimensions, and the ponding depth corresponding to each sample.

Each experiment started at a known ponding depth. While the time was being recorded, each column was manually refilled with water to keep the ponding depth constant. The volume of water needed to maintain a constant ponding depth and elapsed time were recorded. The volume of water added during each time interval was converted to water depth, and incremental infiltration rate was calculated and then plotted with time. During each test, photographs were taken at a constant interval to observe the change in wetting front propagation. It is important to point out that air pressure freely dissipated through the bottom valve of each column to atmospheric pressure.

Table 1 Infiltration capacity tests details.

Sample	Dry Density (g/cm^3)	Cell Diameter (mm)	Depth of soil (mm)	Ponding depth (mm)
S1	1.60	100	188	59
S2	1.54	126	272	64
S3	1.50	100	189	66
S4	1.46	130	279	105

3.2 Empirical Approach

A positive linear correlation between the applied rainfall volumes and the subsequent runoff volumes was evident in both types of profiles regardless of initial saturation as reported in Abdulnabi and Wilson (2015). The direct increase in the volume of applied rainfall-induced a proportional increase in the volume of subsequent runoff irrespective of the applied rainfall intensity for both types of soil profiles. An in-depth development of the correlation of the concatenated data for each profile can be expressed as follows:

$$R = a.\ P + b \qquad [6]$$

where:

R = cumulative volume of runoff

P = cumulative volume of rainfall

a = empirical coefficient function of the type of profile

b = empirical coefficient function of the data-fitting technique

Parameters a, and b represent the slope and intercept of the correlation function. The coefficient of determination for linear regression R^2 exhibits a near 100% match. This statistical measure indicates how close the laboratory data are to the fitted regression line. The empirical method developed in this paper is built upon previous work by the authors. The readers may choose to refer to Abdulnabi and Wilson (2015) for an in-depth review of the laboratory work leading to the empirical correlation.

4 RESULTS

4.1 Analytical Solution

Measured infiltration capacity functions with time for both Devon silt and tailings beach sand exhibited a nonlinear decrease of infiltration rate with time following the theoretical assumption. The rate changed more rapidly reaching constant values in the sand specimens relative to the silt specimens. A representative illustration of the measured infiltration capacity functions for sand and silt is presented in Figure 5.

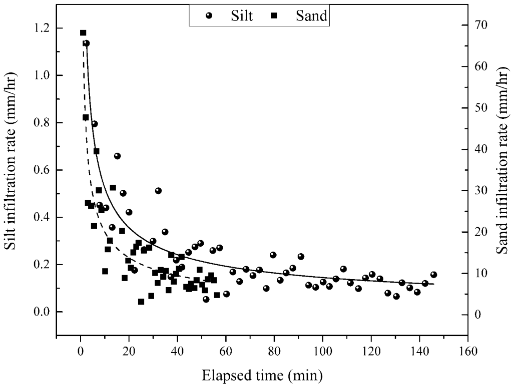

Figure 5 Typical measured infiltration capacity functions of tested soils.

During infiltration capacity tests, the wetting fronts' propagation was observed and recorded using time-lapse photography. A typical wetting front propagation for Devon silt and tailings beach sand samples is illustrated in Figure 6. The depicted column is 100 mm in diameter and 500 mm in height. Soil height in the column is 270 mm.

The depth of the wetting front is noted in the photo along with the corresponding point in time. The results of the wetting fronts' propagation suggest that the infiltration rate is decreasing with time, as has been established from measured data. For Devon silt, the rate decreases about an order of magnitude within an hour. The theoretical explanation is that dry soil is a two-phase matrix, and water readily displaces air at the beginning. As time progresses, more pores are filled with water and soil becomes a three-phase system. Water can only flow through pores that are filled with water. Therefore, lower flow rates ensue.

Results of wetting front propagation suggest that the infiltration rate trend is comparable to the pattern observed in the silt specimen. The only distinction was that the rate change occurred faster than what had been observed in the Devon silt specimen. The wetting front propagated through the entire depth of soil within ten minutes of testing. More frequent readings had to be taken during the infiltration capacity tests, and higher interval in time-lapse photography had to be implemented to capture the quick change in rate in tailings beach sand specimens. Inability to do so may result in a misrepresentation of the infiltration capacity function as a linear function.

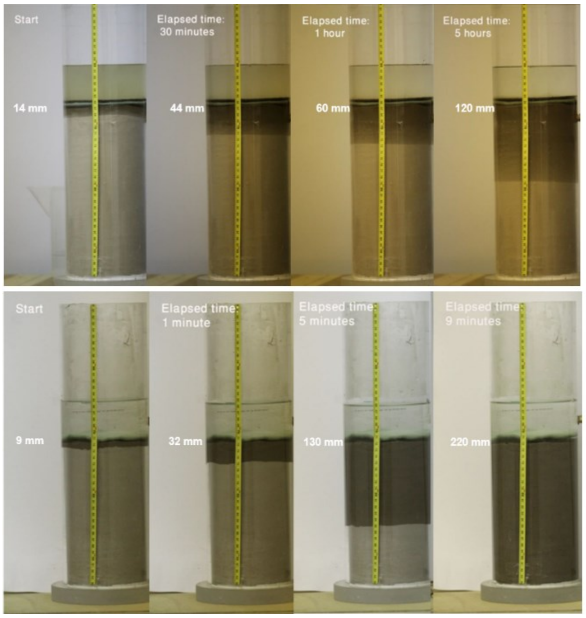

Figure 6 Typical stages of infiltration capacity test along with the wetting front propagation with time in the silt samples (top) and sand samples (bottom).

Volumes of runoff were predicted for saturated and unsaturated initial states using Equations 8 and 9, respectively. Figure 7 illustrates a schematic synopsis of the calculation of runoff in unsaturated profiles. The analytical solutions were then compared to the measured laboratory values. For more details on the laboratory measurements, the reader can refer to Abdulnabi and Wilson 2015. In this study previously conducted by the authors, rainfall-runoff responses in low permeability and capillary barrier profiles were investigated in a flume scale study in a controlled environment.

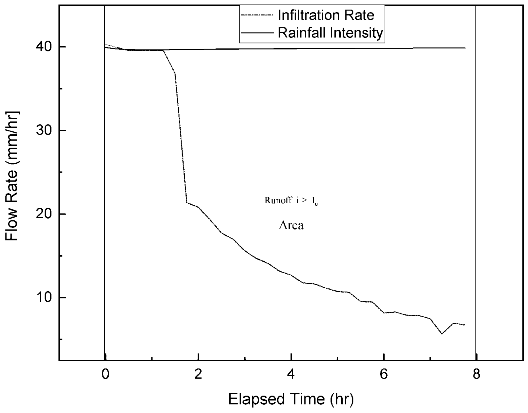

Figure 7 Typical calculation of runoff for unsaturated profiles using infiltration rate of each profile – the applied rainfall intensity is 40 mm/hr.

Table 2 summarizes the percent difference between analytically-predicted and laboratory-measured runoff volumes. Furthermore, Figure 8 illustrates a histogram summary of that percentage of final cumulative runoff volumes denoted by profile type and the applied rainfall intensity.

Table 2 Comparison between measured and predicted runoff values using the saturated hydraulic conductivity and infiltration capacity function in the saturated and unsaturated profiles.

Rainfall intensity (mm/hr)	Percent difference between measured and calculated volumes (%)					
	40	55	90	140	190	260
Saturated silt	-2[1]	0	-1	-8	-8	-21
Unsaturated silt	4	-13	-10	-30	-40	-5
Saturated CB	1	-1	-4	-28	-67	1
Unsaturated CB	-12	-16	-15	-28	-36	-69

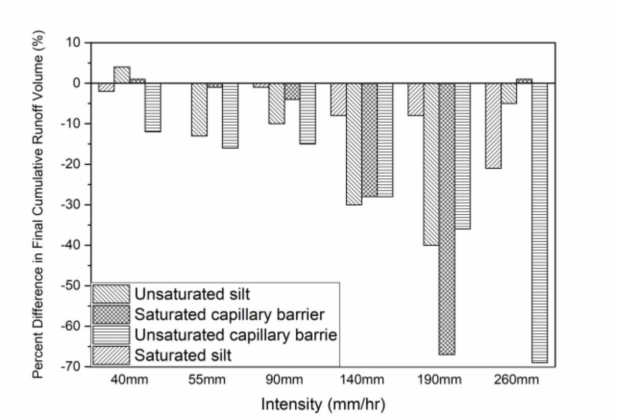

Figure 8 Percentage difference between the laboratory-measured and analytical prediction of final cumulative runoff volumes denoted by profile type and the applied rainfall intensity.

Results indicate that the accuracy of the proposed analytical predictions in rainfall events not exceeding 90mm/hr in intensity was within 16%. Predictions' uncertainty increases in extreme rainfall events, exceeding 90mm/hr. The analytical prediction overpredicted the runoff volumes in most cases.

On the whole, the proposed analytical technique is a valuable cursor to anticipate runoff volumes. This model does not eliminate the need for detailed numerical simulation but is instead a complementary tool to calibrate advanced numerical simulations when runoff measurements are not available. This simple solution helps select the proper prediction since numerical prediction can be extremely sensitive to input parameters as discussed in Section 1 of this paper.

4.2 Empirical Approach

Abdulnabi and Wilson 2015 presented a preliminary linear correlation between the applied rainfall volumes and the resultant runoff volumes from controlled laboratory experiments. Table 1 summarizes the empirical correlation parameters developed for each type of profile under saturated and unsaturated conditions. This empirical correlation can be used for covers of comparable materials when rainfall volumes, or rainfall intensity and storm duration, are available.

From Equation 10, parameter a, indicative of the type of profile, is represented by the slope of the correlation function. For single layer profiles, a slope of 0.9 for both saturated and unsaturated profiles was observed. For capillary barrier profiles, the slope was around 0.8. Parameter b represents the intercept of the correlation function. The intercept has no physical or intrinsic denotation, it purely eliminates bias in the linear regression residuals, and is, therefore an artifact of the data-fitting scheme.

Predictions for runoff volumes were obtained using Equation 10 and the empirical coefficients listed in Table 4.

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[1] The negative sign indicates that the predicted values are higher than laboratory measured ones.

The empirically-predicted runoff volumes were then compared to those measured in the laboratory. Table 5 lists the percent difference between laboratory-measured and empirically-predicted quantities. Moreover, Figure 10 illustrates a histogram of prediction uncertainty categorized by rainfall intensity.

Empirical results indicate that predictions were within 7% accuracy regardless of profile type and rainfall intensity, with one exception. One unsaturated silt profile at 40mm/hr resulted in 26% difference. The reader may refer to Abdulnabi and Wilson 2015 for more details. Profiles of comparable hydraulic properties can utilize this method.

This empirical approach method is suitable as an initial estimate for potential volumes of runoff. The availability of this correlation can serve as a calibration basis for numerical prediction. Typical caveats associated with empirical methods are appropriate here: The empirical relationship may only be suitable to implement in a comparable soil at a similar slope. The flume at the laboratory study had a gentle slope of 1%.

Table 3 Summary of empirical correlation parameters obtained for each type of profile.

Parameter	a	b	[2]R^2
Saturated silt profiles	0.942	4.278	0.999
Unsaturated silt profiles	0.900	-14.527	0.997
Saturated capillary barrier	0.841	10.154	0.997
Unsaturated capillary barrier	0.839	-4.192	0.999

Table 4 Comparison between measured and predicted runoff values using the saturated hydraulic conductivity and infiltration capacity function in the saturated and unsaturated profiles.

Rainfall intensity (mm/hr)	Percent difference between measured and calculated volumes (%)					
	40	55	90	140	190	260
Saturated silt	-1	0	2	2	0	-2
Unsaturated silt	-26	-5	6	-4	-1	-1
Saturated CB	0	2	4	-7	-2	-1
Unsaturated CB	-9	-6	-1	0	-1	-2

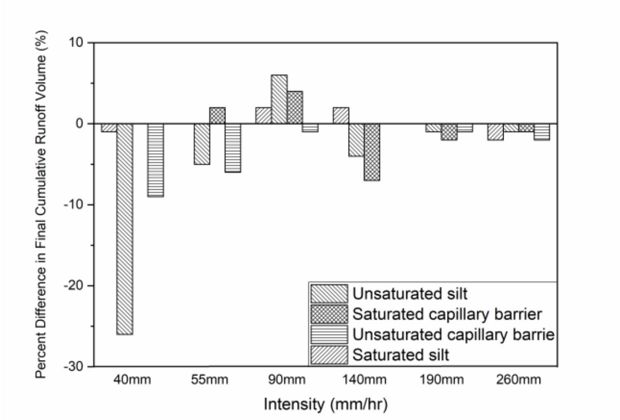

Figure 9 Percentage difference between the laboratory-measured and empirical prediction of final cumulative runoff volumes denoted by profile type and the applied rainfall intensity.

5 SUMMARY AND CONCLUSIONS

Cover systems are a tool for meeting mine closure goals that can serve different functions. The water balance equation is a prerequisite for the design of cover systems that remains indeterminate so long as the rainfall runoff is not available. The paper presents two new methods to predict rainfall runoff in soil covers systems. Both approaches are intended as a first estimate to optimize and calibrate numerical simulation predictions. The first approach is an analytical solution for both saturated and unsaturated conditions. The proposed analytical method requires only minimal input comprising simple, measurable soil properties and rainfall intensity. The equations to be used in predictions are easy to use. Results indicate that simple arithmetic is capable of predicting runoff within 8% and 15% accuracy in saturated and unsaturated profiles, respectively for average rainfall events regardless of the profile type. In an extreme rainfall event, the prediction accuracy of the suggested method is limited.

The second method presents a linear empirical correlation between the applied rainfall and the measured runoff. The paper develops empirical parameters based on a precious laboratory study conducted by the authors. The suggested empirical equation is appropriate for profiles of comparable hydraulic and physical properties.

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[2] R^2 is the coefficient of determination for linear regression

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