THE WATER BALANCE OF VERMICULITE COVERS ON MINING WASTES IN A SEMI-ARID ENVIRONMENT

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ABSTRACT

Deposition of large quantities of mining waste is an activity that can have a negative impact on surface and ground water resources. These impacts necessitate reclamation and amelioration of the wastes through various measures to reduce these impacts. Specific reclamation measures are therefore needed for mine closure and legal requirements. These requirements include covering the waste with a sustainable cover material which is then vegetated. Covers are mostly designed to restrict the ingress of water into the mine waste, from where water might move pollutants into the environment. Cover designs could also allow for natural attenuation/degradation of pollutants within the waste and often contribute to design stability. To act effectively, the covers need to be constructed of materials matched to the design and task.

The primary task of the cover soil is to hold water for vegetation and and subsequently release it into atmosphere and so contribute to the integrity of the cover. Ideal materials are not always readily available and so some understanding of cover material characteristics are required before effectiveness of the cover's contribution to the site water balance can be evaluated. The interaction of the waste cover with the waste material should also be evaluated for its contribution to sustainability and to the cover's water balance. Knowledge of these interactions will always be beneficial, as the availability of water for the vegetation in the cover stays important for the stability of the cover. This benefit, though, is dependant on the pollution potential of the waste in relation to the cover material.

Through a literature review the studied vermiculite cover design was identified as a type of store and release cover. The study subsequently evaluated the water balance mechanisms of vermiculite covers on mining wastes in its semi-arid environment. The cover material and the waste material's hydraulic properties were evaluated to determine likely flux responses. Soil water volumetric water content status was used to confirm fluxes and water status in cover and waste materials. Surface runoff and lysimeter drainage measurements added information for the assessment of fluxes onto and below the cover material. The HYDRUS unsaturated/saturated soil water physics model was used to model and derive general estimates of the overall waterbalance, having been calibrated with physical results obtained from field observations and material characteristics that were determined in the field.

The study yielded promising results for the use of vermiculite waste as a cover material in that it showed good store and release properties under varying rainfall intensities and should therefore not contribute excessively to ground water pollution under similar circumstances.

TABLE OF CONTENT

List of Tables

List of Figures

Annexures

Abreviations

CSC-	Compacted Soil Cover
ET-	Evapo - Transpiration
PMC-	Palabora Mining Company
PC-	Palabora Copper
TDR-	Time Domain Refractometry
TSF-	Tailings Storage Facility
WRD-	Waste Rock Dump

1. INTRODUCTION

Mines have been a vital component of local and national economy in South Africa. Most of these operations have caused and then often continue to cause a negative impact on the environment. This is due to activities and processes that take place during the life of the mine. Deposition of large quantities of mining waste is an activity that can have a negative impact on the surface and ground water resources. These impacts necessitate reclamation and amelioration of the wastes through various reclamation measures. Measures are needed for mine closure as well as for legal requirements which include a long term and sustainable land use. Covers over the waste are usually provided as one of these measures. Covers usually comprise a soil layer or combination of soils that are often vegetated. The covers are mostly designed to restrict the ingress of water into the mine waste, where it might move pollutants into the environment; they also protect waste materials from water and wind erosion; they may also allow for natural attenuation of pollutants within the waste and often contribute to slope stability (Tanner & Swart, 2007; Patterson, at al., 2006). Covers may also provide storage area for water to ensure a sustainable substrate for vegetation cover. The capping or reclamation covers aim to have a positive influence in minimising or reducing water, air and soil pollution if the cover is in a stable condition. A stable land condition which is productive would then work toward a sustainable land use, after mine closure (Milgrom, 2008).

Vegetation of the cover can contribute to this stability under the correct conditions, as it protects the rehabilitated surface against the negative impacts of precipitation by reducing water runoff and excessive deep percolation. Vegetation also stimulates soil aggregation through root growth and by providing organic material to the cover layer. This may also increase the materials sorption properties (Moreno-de las Heras, et al., 2009). This, then, encourages soil microbial growth which is essential to develop and retain nutrient cycles in the new system; some percolation of nutrient rich leachate is often advantageous for the natural attenuation of possible pollutants (Mitchell & Santamarina, 2005). Reclamation cover characteristics influenced by the water balance mechanisms in vermiculite waste covers may contribute to the colonisation of soil fauna which in turn may contribute to the formation of some nutrient rich leachate in the cover (Andre´s & Mateos, 2006). The water balance is influenced by the interaction between waste material and its soil substrate or cover. This is due the properties or relative characteristics of specific waste material and the cover material. It can either increase water storage in the cover material or induce percolation into the waste material. There can thus be definite advantages of the interaction between waste and cover but this is rarely tested (Yang & Yanful, 2002; Naeth, et al., 2011).

Most mines that have been operating for more than 30 years have a lack of viable soil that is available for reclamation (Dutta, et al., 2003). This is mostly because legislation did not require reclamation of disturbed mine areas, or the conservation of agricultural resources and so, at that time, did not require the stockpiling of topsoil for later rehabilitation or reclamation. Mining companies were and are profit driven and if there was no obligation or business drive to correctly conserve soil resources it would be low on the priority list. This created a deficit of topsoil or viable soil for a rehabilitation cover. Covers designed at operations where topsoil was deficient were usually poor performers regarding vegetation stability, water management and sustainability of the land use as a whole. Such a soil deficit has led to the use of vermiculite waste at an operation as a government approved soil replacement for a cover in the reclamation process. Vermiculite is a mica type mineral that is being used in increasing quantities for horticulture, insulation and composite cements (Van der Nest & Kuit, 1993). No previous studies have been documented, evaluating a vermiculite waste cover as a rehabilitation substrate with its contribution to a facility's water balance, particularly in relation to the underlying wastes.

The current general proposed best practice for topsoil or soil cover replacement on mine waste material, is the placement of 500 mm of subsoil followed by an uncompacted layer of 300 mm topsoil. A soil amelioration process is then usually followed to prepare the area for revegetation (Dunger & Wanner, 2001). After the soil cover placement and amelioration, the reclamation area will be revegetated with a mixture of indigenous grass species. Research on the cover material of reclaimed or anthropologically disturbed land has been considerable and can be considered well researched (Wanner & Dunger, 2002). However, the inclusion of the waste material, especially in the water balance is often overlooked, even though these wastes can be of considerable influence in water retention and supply of water to the vegetation cover of the reclaimed or rehabilitated area. Effectiveness of the cover, to include the influence of the waste covered on overall performance, is rarely tested (DehghaniSanij et al., 2004). In particular water retention, release and loss mechanisms of the cover/waste interactive systems in determining the water balance of a specific cover, is similarly rarely tested (Vermaak et al., 2002).

Some specific cover materials such as vermiculite waste have also not been adequately evaluated. Although previous studies have studied certain aspects of vermiculite, such as the study of Van der Nest & Kuit 1993, that evaluated the addition or mixing of exfoliated vermiculite to gold tailings as a growth medium, no studies exist on the use of unexfoliated vermiculite as a cover material. The Van der Nest & Kuit study was done to improve vegetation growth and amelioration of a specific tailings facility. The trial performed in the mentioned study entailed different amounts of exfoliated vermiculite being mixed into gold tailings or slimes which consisted of 95% silica and almost no clay minerals, where after the biomass, due to vegetation growth, at different vermiculite application levels was evaluated.

The aim of this study on vermiculite waste as a specific cover material, in relation to the cover material's contribution to the tailings facility's water water balance, would be to:

- evaluate and quantify the water balance mechanisms of the cover and
- asses the cover interaction with the underlying waste in relation to the water balance,

in order to determine the adequacy or effectiveness of the specific cover material to limit the ingress of water through to the waste and thus prevent seepage effluent migrating into the surface and groudwater regime.

In order to achieve an understanding of the effectiveness of the vermiculite waste cover in relation to the cover contribution to the mine waste facilities water balance, a combination of the following objectives are proposed to assess the water balance:

- Evaluate the material hydraulic properties (Sec 3.2) to determine the likely flux responses form the cover and waste materials;
- Measure and assess the soil volumetric water content status (Sec 3.3) over a time series of at least one wet and one dry season to confirm the fluxes and water status in the cover and waste materials;

- Measure and assess surface runoff in the talings and waste rock and lysimeter drainage in the waste rock (Sec 3.4) to further add to the assessment of the fluxes into and below the cover material;
- Use the observed fluxes and soil water status, together with a simple simulation of the soil water fate using the HYDRUS unsaturated/saturated soil water physics model, to derive general estimates of the overall water balance (Sec 4.5.1).

Water balance modelling of soil covers for waste materials through simulation of the near surface water balance is critical to make final cover implementation decisions and to predict future mass loading of solutes into aquifers underlying the covers. It is therefore necessary to review these designs used, along with identification of cover properties and integrity, in order to evaluate water balance mechanisms (Fredlund, et al., 2003).

Vermiculite waste has been used as a cover material for a tailings storage facility at a mine in the Limpopo Province. The design specification to use this type of cover as a mine waste cover was not investigated or specified prior to implementation. Currently the general practice recommended by the Chamber of Mines for coal mine rehabilitation has been used as a criteria guide for the design. This cover has also not been evaluated in regard to its water balance mechanisms that will have an effect on the water balance of these facilities. It has been shown that the exfoliated vermiculite mixed with tailings does have some water retention capabilities and could serve as a good growth medium but the effectiveness of vermiculite waste that has not been expressly exfoliated and used a a cover material, still needs to be assessed (Van der Nest & Kuit, 1993).

This study comprises of:

- A review of the literature (Sec. 2), specifically on the types and efficiency of cover materials;
- A detailed methodology (Sec. 3) description for this seven (7) sampling sites used to acquire evaluation data for water balance mechanisms;
- An assessment of the results of the hydraulic characteristics (Sec. 4), soil water status observations, runoff observations and lysimeter drainage observations;

- A compilation of the long term water balance fluxes based on the assessments and a simple soil water model (Sec. 4.5);
- A discussion, conclusions and recommendations (Sec. 5) on the effectiveness of the vermiculite covers on tailings and waste rock.

2. LITERATURE REVIEW

2.1 COVER TYPES

The performance of soil or reclamation covers used in the mine industry for the reduction of water and oxygen ingress into mine wastes is of great importance for reducing ground and surface water pollution. Although there may be problems with existing covers, the following cover types have been used for the amelioration and stabilisation of waste materials that will affect the water balance and water pollution and which will be looked at in this review. These are store and release, shedding, capillary barrier, rock armouring, composite, wet cover systems and reactive barrier covers. Predominantly used systems are capillary barrier as well as store and release covers. Covers may also be used in combination to increase effectiveness (Dye, et al., 2008; Vermaak, et al., 2002; Wates, et al., 2006). A review of these covers' water balance mechanisms can be used as part of the evaluation of vermiculite water balance mechanisms as vermiculite covers has not previously been investigated as a mine waste cover.

2.1.1 Store and release covers

Store and release covers are designed to store moisture during precipitation events and allow evaporation and evapo-transpiration of stored moisture during dry periods. These covers may consist of either mono or dual soil covers. Mono-covers usually comprise a single layer of soil with the thickness of the cover depending on the design, dual or multiple layer covers may also be used where the top layer is used in conjunction with a sub-layer that is directly in contact with the waste material.

This is designed to reduce water flow into the waste material or may just increase the top cover layer potential for water storage before release (Yanful, et al., 2003). These dual covers are usually more effective than mono-covers as the second layer is less porous and more compacted than the first (Wates, et al., 2006). The thickness of the layer can be selected so that vegetation can be established and at the same time prevent root penetration into the storage zone. The choice of vegetation and soil material has an influence on root depth (Moreno-de las Heras, et al., 2009).

Store and release covers rely on evapo-transpiration to remove soil water from the cover before it infiltrates the wastes. They are designed to retain and store rainfall water in the cover and also promote upward movement of soil water. It is clear, therefore, that appropriate soil properties need to be selected for such a waste cover (DehghaniSanij, et al., 2004).

The main function of this cover type is to limit rainfall infiltration into the waste. The store-and-release layer does not function as a barrier to water flow, but absorbs and retains the water before releasing it (Zornberg, et al., 2003). Advantages of these covers are that they require low maintenance and can be constructed with a wide range of soils. In Figure 2-1 below a store and release evapo-transpiration (ET) cover is compared with a conventional compacted soil cover (CSC). It shows that the ET cover consistently out performs the CSC cover over a period of four years, in regard to preventing percolation into the waste substrate, with the ET cover that had approximately 200 mm of drainage compared to the CSC with 300 mm of drainage thus the ET cover had better water retention. The relationship of runoff or shedding of precipitation by the two cover types was similar with the ET cover having less runoff (+/-70 mm) than the CSC cover (+/- 110 mm) (Schnabel, et al., 2012).

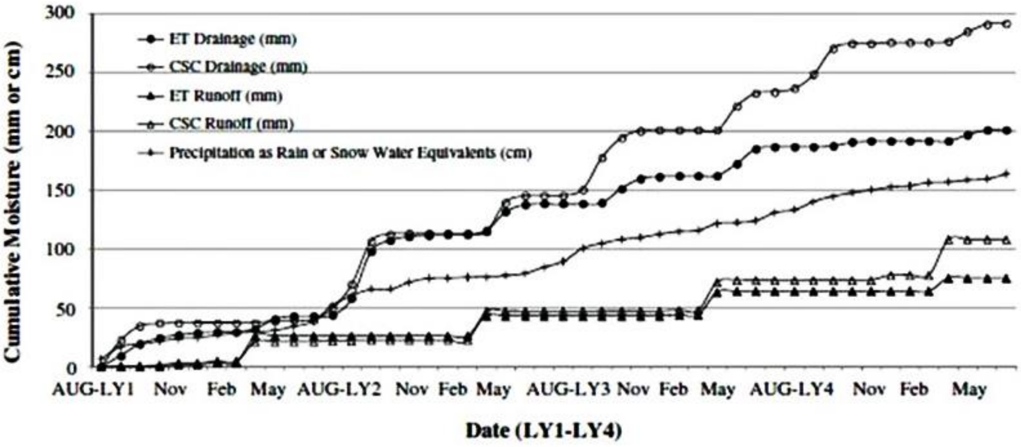


Figure 2-1: Cumulative precipitation, drainage, and runoff for ET- cover and CSC lysimeters (Schnabel, et al., 2012).

The most effective store and release covers (Figure 2-2), are constructed of soils with low susceptibility to cracking associated with desiccation. Soils with high susceptibility to cracking associated with desiccation such as silts and low-plasticity clays are poor choices for store and release covers. This is mainly because once these soils have been desiccated it permanently alters the effectiveness of such cover (Yanful, et al., 2003).

An example of a store-and-release cover would comprise a topsoil layer and a moisture retention layer. The topsoil layer consists of nutrient-rich soils to provide a growth medium for vegetation and to assist in evaporation from the soil surface. In most cases, depending on the underlying waste, the thickness of the layer can be chosen in such a way that it can be vegetated and that the root penetration does not extend out of the soil layers into the waste material. Root penetration should be prevented as preferential flow paths may form along the roots and influence the performance of the layer (Vermaak, et al., 2002; Wates, et al., 2006).

It is speculated that there are instances where water movement from the waste to the cover material may be beneficial, such as in arid or semi-arid environments, depending on the waste chemical characteristics. Soils suitable for use in store-and-release covers should have the potential to retain moisture against gravity and have a low saturated hydraulic conductivity (Yang & Yanful, 2002).

Clay waste covers have been used in store and release covers over waste due to their low permeability (Divya, et al., 2012). However covers with high clay content are not preferred as store and release covers in semi-arid environments as the disadvantage of compacted clay covers is that they are prone to desiccation and cracking even when they are covered by a protective layer of soil (Sadek, et al., 2007). Roots may also grow through cracked clay layers and thus cause preferential pathways for infiltrating water (Wels, et al., 2002) .

A vermiculite waste cover may be classified as a type of store and release cover, as the material has water retention capabilities, with a vegetation layer. Such covers are quite unique as this cover material is not readily available and are bound to a geographic resource. Due to exfoliated vermiculite’s water absorption, retention and high CEC characteristics, vermiculite waste might be a good substrate for vegetation establishment. Such a cover will rely on evapo-transpiration potential to remove water acquired through precipitation from the cover before it infiltrates into the wastes (Van der Nest & Kuit, 1993; Fonteno, 2003).

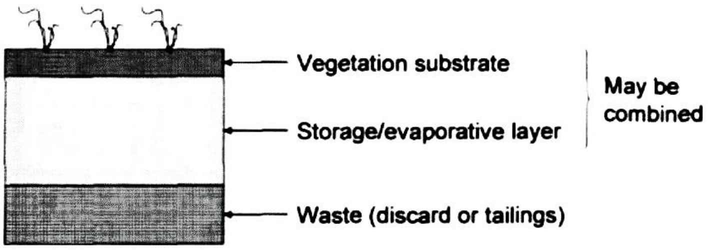


Figure 2-2: Schematic diagram of a store-and-release cover (Wates, et al., 2006)

2.1.2 Capillary barriers

Capillary barriers comprise a fine grained layer overlying a coarse layer. Moisture is retained or temporarily stored in the overlying fine material and moisture movement into the coarser layer is limited by the moisture retention characteristics of the two layers combined. A capillary barrier not only limits moisture ingress into the waste material, but also limits moisture draw up from the lower lying materials (Tami, et al., 2004).

The performance of the store and release process can be significantly enhanced by the barrier to percolation created at the interface between the coarse and fine layers (Nakafusa, et al., 2011; Smesrud & Selker, 2001).

The fine-grained layer can in itself be a store-and-release cover or a moisture retaining layer within a cover (Smith & Waugh, 2004). The effectiveness of the top layer to act as a store and release cover depends on the thickness of the overlying fine grained material, any material which provides a sharp contrast in water retention capacity can be alternatively employed in a capillary barrier system (Yang, et al., 2004).

Covers with a capillary barrier action (Figure 2-3) may therefore be used in dry or wet climates as the action is not dependent on moisture content, but in the sharp contrast of water retention capacity (Nakafusa, et al., 2011; Wates, et al., 2006). It has also been shown that lateral diversion can be obtained if there is a modest contrast between the overlying fine grained material with the underlying course material in a capillary barrier system (Smesrud & Selker, 2001).

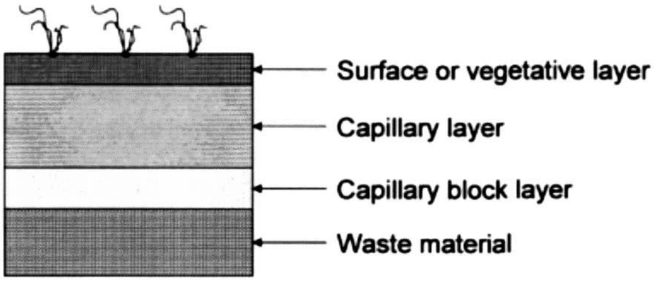


Figure 2-3: Schematic diagram of capillary barrier layers (Wates, et al., 2006).

2.1.3 Covers designed to improve precipitation shedding

Infiltration through the cover into the waste can also be reduced by increasing the slope of the cover. As the slope of the cover is increased, the runoff from the cover is increased. Covers that improve precipitation shedding are mostly dependant on dump geometry or design. This cover design can be any of the ones discussed in this review but the aim of the waste facility slope design would be on the shedding of precipitation rather than retaining precipitation (Janeau, et al., 2003). This leads to some of the water that is available to infiltrate into the barrier layer to be diverted laterally on a sloped cover, resulting in decreased saturation upslope during drying period (Song & Yanful, 2011).

Capillary barriers can also increase shedding through lateral diversion of water in the barrier system (Nakafusa, et al., 2011). For a given combination of infiltration rate, interface slope, and fine material characteristics representing the most conservative case, 80% of the maximum diversion of the infiltrated water can be obtained with an underlying coarse material that is only 2.5 times coarser than the overlying fine material.

With a coarse material that is 5 times coarser than the overlying fine material, 90% of the maximum diversion of the infiltrated water may be obtained (Smesrud & Selker, 2001)

2.1.4 Rock armouring covers

The use of approximately 40% rock and 60% soil substrate is known as rock armouring. The practice of using rock armouring is receiving considerable research attention in some sectors of the mining industry since it enhances the stabilisation of mine residue slopes, primarily against erosion from steep slopes, (Wates, et al., 2006). The aim is to limit infiltration into the waste facility without compromising the integrity of the slope by erosion.

It has been noted that vegetation grows easily on this cover material as rock fragments in the profile also play an important role in conserving soil moisture during the growing period (Poesen, et al., 1999). This may indicate that an evapo-transpiration mechanism might also be available on these covers, though the effectiveness has not received much attention.

2.1.5 Composite covers with geo-synthetics

Multi-layer composite covers are composed of up to seven layers. The primary feature of these covers is the geo-synthetic layer placed directly onto a compacted waste layer (Kim and Benson, 2004). This combination forms a barrier to both liquid and gas-phase transport. These covers can include mechanisms of store and release covers as well as capillary barriers but the main difference from the other covers in review is the multi layered characteristic with a geo-synthetic (Sun, et al., 2010).

Low oxygen permeable synthetic covers overlaying waste material such as pyritic tailings are designed to reduce oxygen diffusion, thus minimising sulphide oxidation. By this cover, being a barrier to liquid transport, reduces the infiltration rate into the waste, minimizing the potential for migration of acid or heavy metals through seepage. The effectiveness of the composite cover to reduce rainfall infiltration has been assessed by monitoring changes in pore water or phreatic levels within the tailings residue (Patterson, et al., 2006).

Lower pore water or phreatic levels would likely indicate that the cover is reducing rainfall infiltration rates into the tailings. Figure 2-4 shows a consistent exponential decline of the phreatic surface level within tailings residue after a composite cover remediation strategy was implemented (Patterson, et al.,2006).

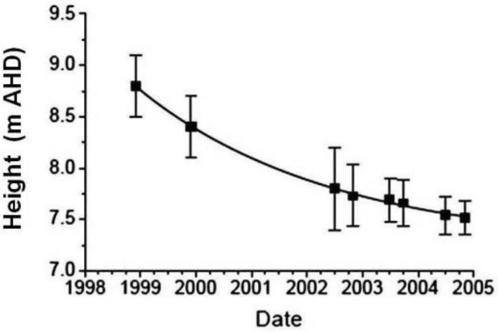


Figure 2-4: Average phreatic level data (m AHD) within tailings residue, showing level decline after a cover is placed (Patterson, et al., 2006).

2.1.6 Wet cover systems

The primary function of this cover type is to reduce acid rock or saline drainage production from wastes, by limiting oxygen ingress, through the inclusion of a moisture retaining layer. The moist layer retards the oxygen diffusion process into the waste, limiting the availability of continuous open pore space. Limiting the oxygen ingress the cover impedes the oxidation of sulphide minerals. At the same time, moisture percolation is also limited through retention of moisture by capillary forces so that near-saturated conditions can be maintained even when the cover layer occurs several meters above the phreatic level (Nicholson, et al., 1989).

Water content and hence the degree of saturation of the oxygen barrier is an important property of the soil cover. For an effective cover, the oxygen barrier must maintain a high degree of saturation, as the diffusion coefficient of oxygen is much lower than in air (Yang & Yanful, 2002).

An example of this is the use of a fine-grained soil over a coarser material such as in a capillary barrier. Moisture may be stored in a fine grained material overlying the coarse material and is prevented from downward migration by the break or discontinuity in capillary pressure at the interface between the coarse and the fine layer.

This cover type may be similar to a capillary break system but differs in that the objective is to place a “wet” zone to prevent oxygen ingress into a waste layer whereas capillary barriers does not aim to create a wet zone but rather an increase in water retention capacity and a barrier to percolation ingress into the waste (Nakafusa, et al., 2011).

2.1.7 Reactive barrier covers

Another approach to limiting oxygen movement through the cover system is to introduce materials that consume oxygen and thereby reduce the potential for oxidation of reactive wastes. Various oxygen-consuming layers have been suggested in conjunction with other cover types discussed. Oxygen consuming layers such a paper pulp may be part of the protection or vegetation substrate or it may be a separate layer in a multi-layer system (Cabral, et al., 2000). The reactive barrier layer may be an organic layer or the addition of a chemical layer, such as lime, or layers that are able to buffer acid formation. Thus if any percolation through the cover takes place the reactive barrier will neutralise acid formation as the leachate comes in contact with the waste layer (Rose, et al., 1995). This barrier cover will eventually become depleted, so the cover should be designed to exceed acid or saline production of the reactive waste material (Wates, et al., 2006).

2.2 COVER MATERIAL

The selection of soils for covers for a waste facility should be undertaken in advance of the rehabilitation planning. This should be based on baseline studies that include the geotechnical parameters required for design of the covers. This may be confirmed through laboratory testing in order to ensure that the candidate soils are volumetrically stable and have the required permeability or retention properties for the intended design. These should also be confirmed with field trials. It has been observed that mine reclamation covers are not always termed the same, for example store and release covers are not always referred to as store and release covers but also as evapo-transpiration covers which makes it difficult to review previous research on similar wastes or waste covers

The choice of cover material should be based on cover design or cover type. The selection of soil properties of the cover may range from fine grained soils to coarse or sandy soils with a specific porosity and saturated hydraulic conductivity that may be beneficial for use in capillary barriers, to absorbent soils for a store and release cover (Barbour, 1990) such as alluvial soils (Wels, et al., 2002). As a legislative requirement the soil from the area where the waste facility is to be constructed will be removed and stockpiled for use as a cover on the waste facility in the amelioration or capping process of the facility (Department of Agriculture, 1984).

The incorrect choice of cover material can lead to numerous water balance and sustainability problems for the waste facility if the design is not properly planned. Therefore it is important to understand and determine the material or soil properties that has been used or that may be available as cover material. These properties include grain size, moisture content, compaction, soil water characteristics and hydraulic properties. This will assist in determining the performance of a specific cover in relation to its design, whether it may be a store and release cover or another type of waste cover. This is an important design consideration in arid and semi-arid environments.

Figure 2-5 shows a soil water characteristic curve of an alluvial cover compared to underlying tailings. The alluvial properties in this comparison are of a fine well graded silty/clay gravel with fines ranging from 7.8 to 10.9%, whereas the tailings properties are representative of poorly graded silty sand with fines ranging from 12.4 to 48.2%. It has been shown that the coarse tailings have a higher porosity compared with the alluvial cover (Figure 2-5) indicating that the cover will have better water retention capabilities compared to the tailings (Wilson, et al., 1997; Wels, et al., 2002).

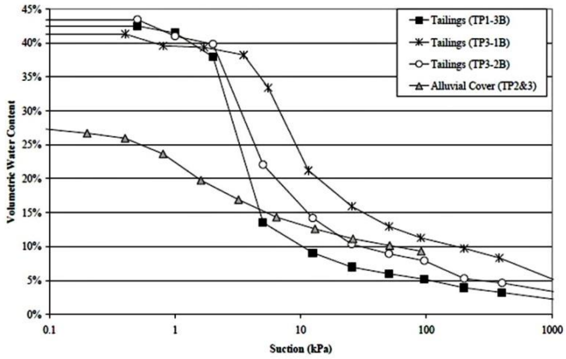


Figure 2-5: Soil water retention characteristic curves of an alluvial cover compared to underlying tailings (Wels, et al., 2002).

In a waste cover design the functionality of the cover material has rarely been taken into full account, for various reasons. These may range from legislative requirements; which may require that soil material is stockpiled before the construction of the waste facility; or requires that stockpiled soil be used for reclamation as a cover material, to company specific requirements. This soil may not be the best material for a waste cover. The economic drive or cost of the waste cover for the operation can also lead to a choice in substrate used for a cover material that may not be suitable for the cover design.

Many materials have also been tested or reviewed for cover use and efficiency in the past (Fredlund, et al., 2003; Van der Nest & Kuit, 1993; Wates, et al., 2006; Wels, et al., 2002; Yang, et al., 2004). However, in many mineral mines, the occurrence of micacious materials may provide an alternative or mix for the often thin top soils found in arid and semi-arid regions. These types of materials have however not been tested extensively and are worth considering in such areas. Vermiculite is such a micacious material and is available as a cover material in a vermiculite waste. It could prove to have excellent water retention characteristics, as it is used in its exfoliated form in many controlled agronomic practices.

Such a type of vermiculite in waste that is available as a cover material is a 2:1 phyllo- (layered) silicate mineral. These vermiculites are formed by the alteration of mica minerals. It contains a high cation exchange capacity (CEC) and has been used for horticultural purposes in its exfoliated from, Table 2-1 shows the properties that makes exfoliated vermiculite appropriate for horticultural purposes. For horticultural purposes the mineral is exfoliated through a process of heating which induces a high porosity value. Exfoliated vermiculite has been used in a trial to assess its influence on plant vitality in tailings. An increase in exfoliated vermiculite mixed into the tailings to form a cover, did show an increase in plant biomass (from 0.99 kg/ha in an untreated area to 5.68kg/ha in a treated area) in the trial (Van der Nest & Kuit, 1993).

Table 2-1: Exfoliated vermiculite properties that will influence its water retention capabilities **(Van der Nest & Kuit, 1993)**

Exfoliated Vermiculite Properties				
Bulk density kg/m^3	pH	Porosity m^2/g	CEC mEq/100g	Absorbency mg/g
56-192	8	1.9-5.19	154	46-69

Exfoliated vermiculite has a loose bulk density of 56-192 kg/m^3. The pH of this vermiculite waste is approximately 8 due to the presence of associated carbonate rock (Usher, et al., 2008; Fonteno, 2003). It has been shown that exfoliated vermiculite has a high hydraulic conductivity and good CEC properties (Reinholdt, et al., 2013) which made it sought after in the agronomy field. Due to the exfoliated properties of vermiculite it may be speculated that even in the un-exfoliated, extracted or waste form it may have some of the retention properties of the exfoliated vermiculite. This might make it a viable substrate with the related waste materials for a store and release cover. This might also be the reason why vermiculite waste was approved by government as a soil substitute for the reclamation of a mine waste facility in the Limpopo province, South Africa (Posnik & Associates, 2001). The vermiculite waste cover used for rehabilitation or reclamation may best be described as an undefined soil type as it consists of the un-exfoliated vermiculite and various waste rock fragments in different particle size mixes, which may add to its good storage properties, this includes carbonate waste rock in various sizes from loamy sized fractions to rocks, up to 100 mm in diameter. There is no literature available in which un-exfoliated vermiculite waste has been previously used or characterised as a mine waste cover.

2.3 WATER BALANCE

For the ability to effectively manage an active mine waste facility and make reliable predictions of post-closure pollution potential and to properly evaluate environmental management or rehabilitation strategies an accurate water balance is needed (Yibas, et al., 2011). A water balance is used to track and determine water losses as well as recoverable quantities from facilities during active mine waste deposits as well as after mine closure. Water balances usually contain inaccuracies during the mine’s operation stage, such as how much water is lost through evaporation or transpiration or how much contaminated water has been added to the underlying ground water. Maintenance and inaccuracies of flow meters also require that estimations be used in calculating a water balance.

For the water balance of a tailings facility to be accurate, the following needs to be determined and managed;

- Deposition rate;
- Vertical pore water flow;
- Complex physical parameters (rainfall, runoff, seepage, evapo-transpiration, percolation and seepage);

- Hydraulic conductivity (a function of volumetric water content, which varies with depth);
- Hydraulic pressure head;
- Particle size distribution;
- Complicating factors – mineralogy & preferential flow paths and
- The position of the phreatic surface

Some of these parameters or water balance mechanisms would then be necessary to assess or evaluate the water balance contribution of a waste facility's rehabilitation cover (store and release) and how it will behave in regards to mentioned mechanisms of precipitation; Infiltration, storage characteristics, evaporation, transpiration, seepage as well as the interaction of the vermiculite cover with the underlying waste material (Wates, et al., 2006; Yibas, et al., 2011).

2.3.1 Infiltration

Various soil cover types such as those that have been discussed above have been used to restrict infiltration into mine wastes. Covers comprising volumetrically stable soils with a depth greater than 0.7 m might be used to significantly reduce infiltration of water and ingress of air (Wates, et al., 2006). A good characteristic of a cover layer is that saturation should take place due to infiltration from rainfall precipitation, thereby reducing water ingress into the underlying wastes. This is mainly dependant on the cover layer's storage properties (Woyshner & St-Arnaud, 1994). This mechanism may have the same effect as a capillary barrier if the storage layer is finer grained than the underlying waste so that the resulting interface will enhance storage in the overlaying finer material and reduce infiltration. The potential for further reduction of infiltration rates by combining soils with specific properties is not always available as a single soil cover may be placed over the waste material for the reduction of infiltration.

It is anticipated that vermiculate waste may have the properties of a good cover material, as it may have some of the potential of exfoliated vermiculite, as referred to in Table 2-1, for absorption and storage. In a study with a mixture of exfoliated vermiculite and tailings material, as a waste cover (Figure 2-6) increasing rainfall infiltration into tailings- vermiculite cover mixtures was demonstrated with increase vermiculite percentages in the mix.

The mass distribution of tailings-vermiculite mixture in this study ranged from 0 kg/ha to 12000 kg/ha, this allowed infiltration due to the addition of exfoliated vermiculite that increased the absorption capability of the study areas (Van der Nest & Kuit, 1993).

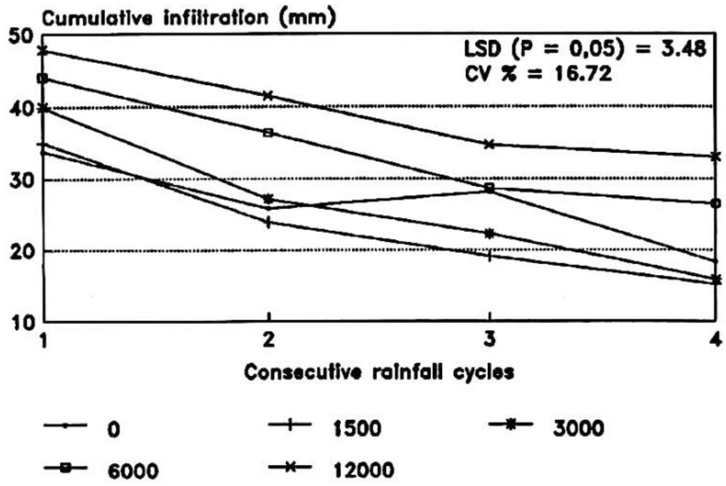


Figure 2-6: Infiltration rate in cumulative mm of precipitation is shown with different application levels of exfoliated vermiculite in kg/ha 0-12000 kg/ha (Van der Nest & Kuit, 1993).

The field infiltration characteristic of an un-exfoliated vermiculite waste cover should be determined to see what its storage capabilities are (Toama & Albergel, 1992).

The slope and design of the tailings facility must also be considered as this may either increase or decrease infiltration into the facility (Wates, et al., 2006). If the slopes of a waste facility are at a steep 1:3 gradient it will increase shedding of precipitation, which will further reduce infiltration especially if the cover is close to saturation. It does have the disadvantage that this type of slope has a tendency to increase erosion on the cover due to increased precipitation runoff velocity. Infiltration (and erosion) could be further reduced by a stable vegetation cover that is used to reclaim the covered mine waste (Dye, et al., 2008).

2.3.2 Storage characteristics

A typical configuration for a store-and-release cover comprises a topsoil layer and a moisture retention layer (Wates, et al., 2006); in the specific case of vermiculite waste covers the waste has only been covered with a layer of vermiculite waste of various thicknesses depending on the waste. Therefore for a cover material such as vermiculite to work as a store and release cover it should have the ability to both store precipitation as well as to provide a good growth medium for vegetation to enable the release of soil water through evapo-transpiration (Van der Nest & Kuit, 1993). The vegetation cover in general contributes to the storage capacity of the cover layer and it would be beneficial if the vegetation cover can be optimised to cater for a short intense rainfall season. This is difficult, though, as short intense rainfall seasons are usually associated with arid or semi-arid regions with limited vegetation cover (Schnabel, et al., 2012).

A vermiculite cover moisture retention layer should not only be able to retain and store infiltrating precipitation but also promote upward movement of soil water by evapo-transpiration, through capillary action. The effectiveness of the design in the placement of 200-300 mm of vermiculite waste in regards to storage capacity has not been investigated. This design also does not guarantee that roots do not penetrate the waste as some grass species can have a root depth of up to 2 meters, thus creating preferential paths that may influence the performance of the layer (Sadek, et al., 2007). To evaluate the effectiveness of a vermiculite waste cover in relation to water storage capacity it may be compared to other waste covers, an example of such a cover is a sandy loam or alluvial cover. The soil storage capacity of a typical sandy loam soil profile may average 120 mm depending on the vegetation cover (Dye, et al., 2008). Figure 2-7 compares suction and moisture content profiles in three test plots with an alluvial cover for selected dates during the first year of monitoring. The depth of the alluvial cover is shown in these profiles for reference. The suction and moisture content (storage) profiles illustrate a deeper wetting that occurred in lysimeter test plots TP-2 and TP-3 with vegetation compared to the *in-situ* profile TP-1. The alluvial material is much coarser than the tailings thus the lower porosity of the cover relative to the tailings. This results in a deeper wetting, indicating the storage capability of alluvial cover material. It also shows that the choice of cover substrate has a large effect on its storage potential (Wels, et al., 2002).

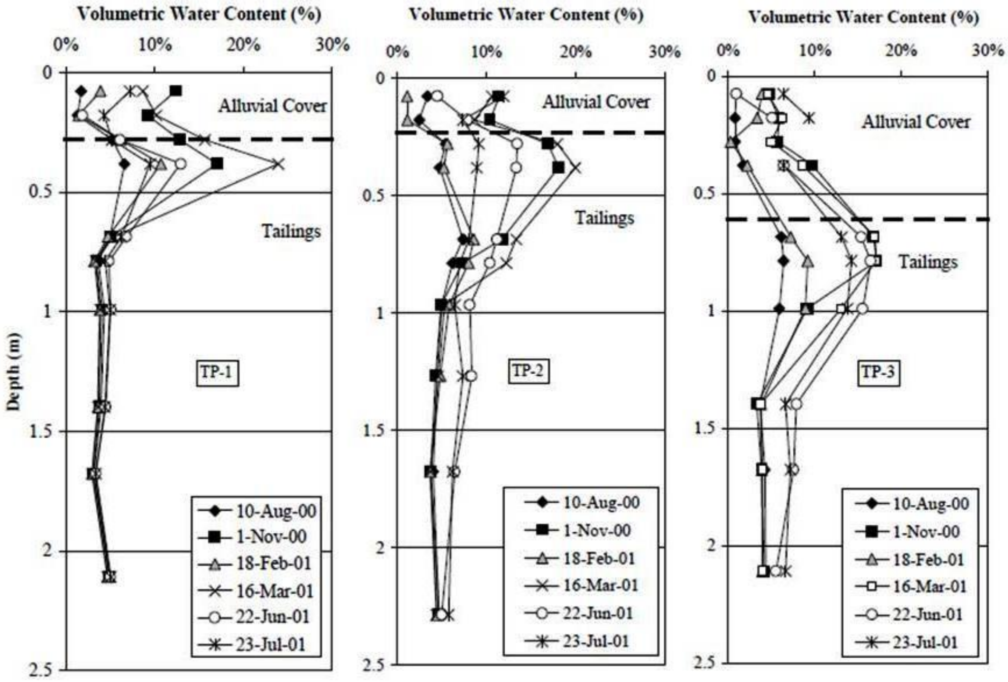


Figure 2-7: Comparing Volumetric Water Content profiles for TP-1, TP-2 and TP-3 test plots with an alluvial cover (Wels, et al., 2002).

A vermiculite waste cover's storage capabilities as well as susceptibility to desiccation still need to be determined. It may have a high saturated conductivity due to the properties exhibited by exfoliated vermiculite and it may be expected to perform well in a semi-arid environment such as where it is currently situated even in its un-exfoliated form. (Van der Nest & Kuit, 1993)

2.3.3 Soil Water Evaporation

Determining evaporation from the cover material is critical for managing drainage processes in the storage facility (Ren, et al., 2000). This mechanism includes the loss of water to the atmosphere from the soil cover. In store and release covers evaporation is regulated by the ability of the soil to store or release water, the organic content added by the vegetation cover in the soil may increase this ability. The areas where store and release covers may be useful are areas known for their high evaporation and low precipitation rates (Yang & Yanful, 2002).

Soil water evaporation and drainage significantly affect soil moisture redistribution and water content. Both evaporation and drainage processes are influenced by seasonal changes in the water table elevation. This evaporation varies for different soils or substrates; in a comparison between coarse sand, fine sand, silt and clayey till (Figure 2-8) it was shown that there is a difference in the evaporation from these different soils. To assess the long term performance of a waste cover, it is necessary to study the total water balance, including evaporation and drainage, in candidate cover soils (Yang & Yanful, 2002).

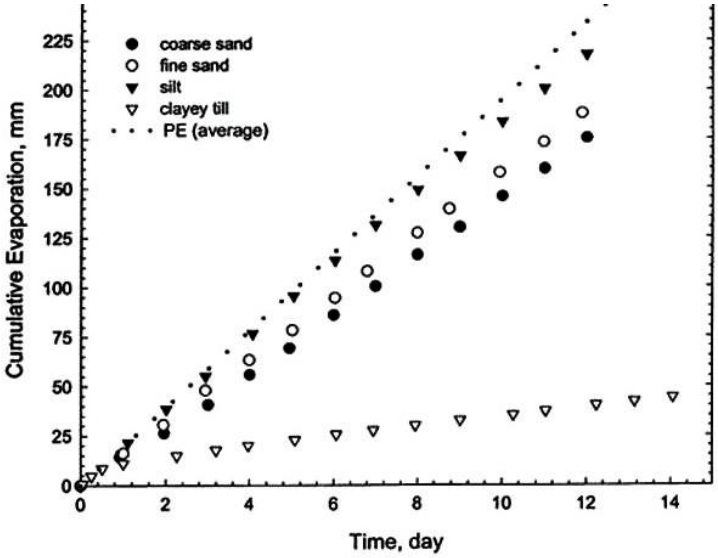


Figure 2-8: Evaporation from different soils with a phreatic level at 0.25 m, with PE being the Potential Evaporation average (Yang & Yanful, 2002).

Because the current vermiculite waste cover in question is placed only to a thickness of 300 mm it may allow water ingress into the mine tailing wastes as well as draw water from the mine wastes during times of high evaporation. This might cause the salinity to increase in the cover material and prevent sustainable vegetation establishment which may influence other water balance mechanisms (Dye, et al., 2008; Wenninger et al., 2010).

2.3.4 Transpiration

Vegetation established along the sides and tops of a waste facility can take up, store and transpire a significant proportion of the rainfall, thereby contributing to the water balance mechanisms of such a facility (Wates, et al., 2006). It may be speculated that the cover materials water loss or loss of water from the underlying wastes though vegetation transpiration can have a big influence on the waste facility water balance. Transpiration promotes the upward movement in vegetation of soil water deposited by precipitation (DehghaniSanij, et al., 2004).

The driving force of this upward movement of water is the strong hydraulic gradient caused by transpiration that cause water uptake by roots at different levels. Transpiration is influenced by humidity, temperature, light intensity, soil properties, wind and CO_2 concentration. It can also be the key in the effectiveness of store and release covers. It should be able to retain and store the annual precipitation and also promote the upward movement of soil water through transpiration. The transpiration through the water use of vegetation is dependent on the type of vegetation as well as the relative abundance of the vegetation in a certain climatic zone or area (Dye, et al., 2008).

It may be difficult to measure evaporation accurately alone, therefore in some studies the measurement of evaporation and transpiration together are measured as evapo-transpiration (Or, et al., 2013).

Figure 2-9 indicates a study that modelled the daily evapo-transpiration for a natural savannah system in the Limpopo Province. The vegetation cover and climatic factors might be similar to cover that might be found on some mine waste reclamation sites in a semi-arid environment. In arid or semi-arid climates such as in the study presented in Figure 2-9, the potential evapo-transpiration far exceeds the annual rainfall. However the timing of rainfall often results in excess rain that cannot be immediately transpired. Therefore storage is necessary to allow for uptake of water through evapo-transpiration in the ensuing period.

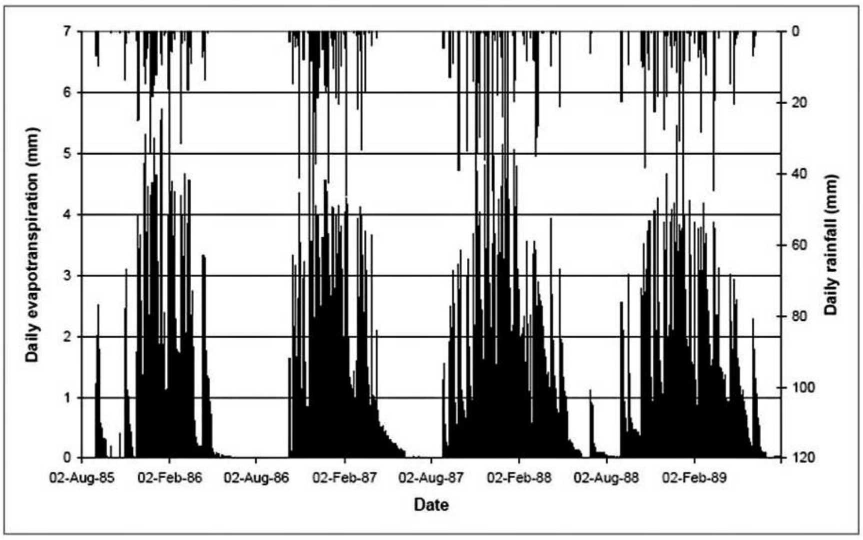
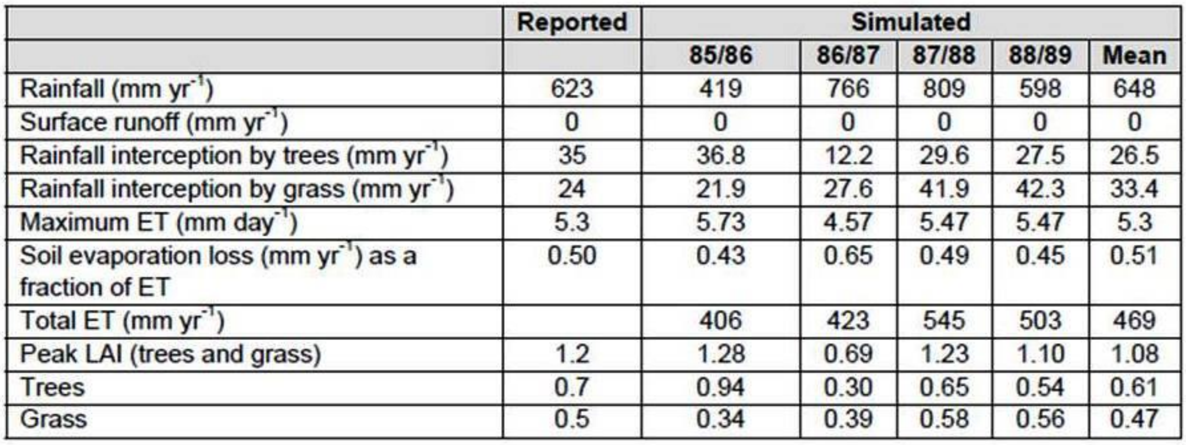


Figure 2-9: Pattern of daily evapo-transpiration (lower bars) and daily rainfall (upper bars) simulated for natural savannah vegetation in Limpopo Province (Dye, et al., 2008).

Table 2-2 shows the correspondence between measured and simulated hydrological and structural properties pertaining to the savannah site. The root depth extended up to 1 m contributing to storage for evapo-transpiration.

Table 2-2: Correspondence between measured and simulated hydrological and structural properties pertaining to a savannah site (Dye, et al., 2008)



	Reported	**Simulated**				
		85/86	**86/87**	**87/88**	**88/89**	**Mean**
Rainfall (mm yr^{-1})	623	419	766	809	598	648
Surface runoff (mm yr^{-1})	0	0	0	0	0	0
Rainfall interception by trees (mm yr^{-1})	35	36.8	12.2	29.6	27.5	26.5
Rainfall interception by grass (mm yr^{-1})	24	21.9	27.6	41.9	42.3	33.4
Maximum ET (mm day^{-1})	5.3	5.73	4.57	5.47	5.47	5.3
Soil evaporation loss (mm yr^{-1}) as a fraction of ET	0.50	0.43	0.65	0.49	0.45	0.51
Total ET (mm yr^{-1})		406	423	545	503	469
Peak LAI (trees and grass)	1.2	1.28	0.69	1.23	1.10	1.08
Trees	0.7	0.94	0.30	0.65	0.54	0.61
Grass	0.5	0.34	0.39	0.58	0.56	0.47

At most mine waste reclamation sites indigenous vegetation adapted to the local climate have been used on the cover material. Natural evapo-transpiration may be a good indicator of transpiration in rehabilitation areas, if the soil characteristics and vegetation cover with climatic conditions are similar. The flux densities due to evaporation loss either through soil evaporation or transpiration may be obtained simultaneously by measuring both the water vapour pressure difference and the air temperature difference between the same two vertical heights above the canopy or soil, and measuring the net irradiance and the soil heat flux density (Savage, et al., 2009).

2.3.5 Seepage

The monitoring of seepage is an essential part of any tailings management strategy to understanding how the facility is performing within. In general engineered structures such as drains, cut-off trenches and collection systems are used to manage seepage or control the phreatic surface at a waste facility

(Smith & Waugh, 2004; Rykaart, et al., 2001). Cover materials and other water balance mechanisms are critical issues (Figure 2-10) in the development of sustainable solutions to the problems due to the seepage of contaminants or pollutants from mine waste facilities seepage contributes to groundwater pollution as well as localised surface pollution depending on the phreatic surface associated with the water level in the mine waste facility (Dye, et al., 2008). On covered dumps assessed where soil cover depth was in excess of 0.50 m, cover performance was good. However seepage was evident in localised areas associated with thinner soil depths where drains cut into the slope (Wates, et al., 2006).

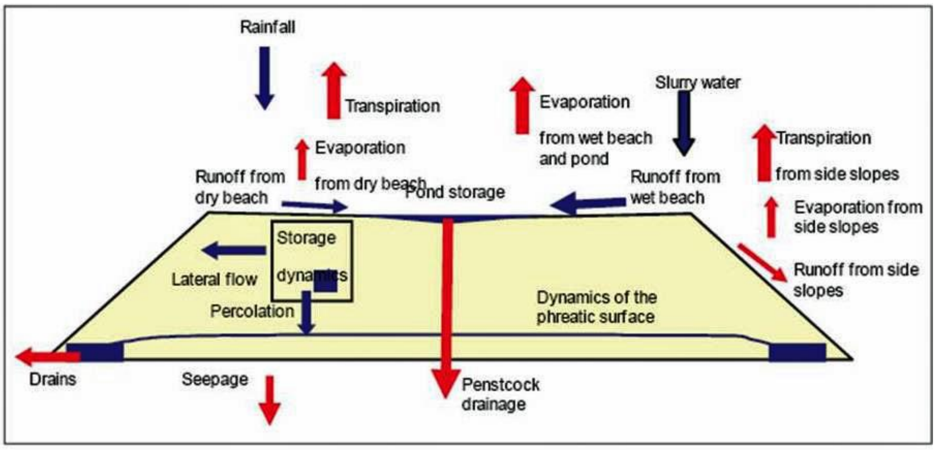


Figure 2-10: Water balance and mechanisms influencing seepage (Yibas, et al., 2011).

The mentioned mechanisms (Figure 2-10) should be designed to reduce the rate of recharge into the dump and thereby decrease the seepage problem (Yang & Yanful, 2002) . It is also important to know that the different capping or waste covers are affected by factors over time that can influence infiltration and increase seepage (Figure 2-11). These factors that have an influence on the water balance mechanisms may be chemical or physical. Erosion would be a example of a physical factor, with either vegetation that composts, or vegetation root penetration as biological factors (Waygood & Ferreira, 2009). Monitoring and evaluation of the water balance mechanisms can help detect the effects of these influences.

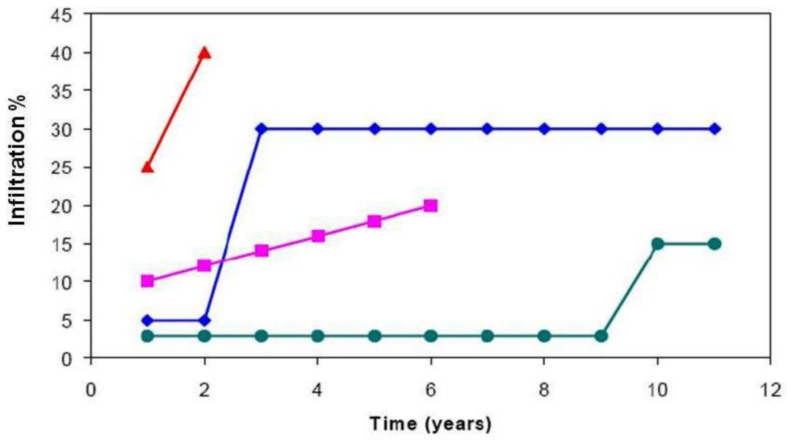


Figure 2-11: Long term data indicating the change in infiltration rates (as a percentage of mean annual precipitation) with time at four different sites with covers and a deterioration of performance of the capping systems (Waygood & Ferreira, 2009)

Certain mining sites have implemented a paddock and terrace design, with the aim of shedding and evaporating soil water. It would be beneficial for such sites to determine if the water balance mechanisms in place are sufficient to limit ground water seepage and for the cover to add to the environmental and management sustainability of the waste complex (Williams, 2008).

2.3.6 Vermiculite cover interaction with waste material and its water balance

Establishing a stable water balance for a mine waste facility during the design stage is one of the most important considerations to prevent water management problems. The amount of water that is circulated or contained in the facility or has contact with the waste material has a direct influence on its stability (Wates, et al., 2006). Mine wastes generally have low levels of nutrients for plant growth and often potentially toxic levels of metals or metalloids with high levels of soluble salts which are mobilised in the presence of oxygen and water. Coarse wastes with unsaturated pore space are conductive to pollutant mobility this is due to the increased permeability that allow ingress of water and oxygen to considerable depth (Yibas, et al., 2011). The interaction between cover and waste materials is due to upward and downward fluxes. Upward interaction due to evaporation and transpiration, through the waste and cover material and downwards due to drainage from the cover to the waste material, after most of the moisture is removed from the soil- waste profile (Figure 2-12) (Wels, et al., 2002).

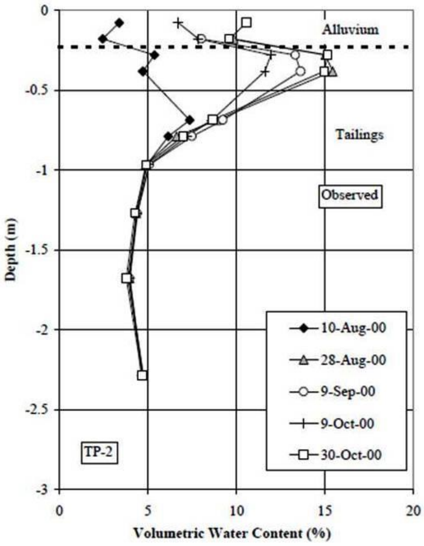


Figure 2-12: The observed profile of the volumetric water content in an alluvial cover with vegetaion over tailings, indicating upward flux (Wels, et al., 2002)

A badly managed water balance through neglect of the waste cover and vegetation can have a negative effect on a waste facilities structural integrity. The water balance within the waste material is mainly monitored with piezometers to determine the phreatic surface. This is true for most mine waste facilities. Through the monitoring of water balance mechanisms or factors influenced by the mechanisms as proposed in this study, the water balance and influences on the phreatic surface may be better understood. Understanding the interaction of the capping or cover material with the waste material and its water balance can assist in determining ground water movement through seepage and contamination. Increased concern has been developing in regards to the danger of impact on aquifers in areas where valuable ecosystems occur (Acero, et al., 2009). Lowering the water content in the waste facility can lower seepage losses and ground water contamination and thus a reduced waste load discharge to the water environment.

2.4 PHYSICAL INFLUENCES ON THE WATER BALANCE

2.4.1 Erosion

One objective of water balance mechanisms, through mainly reclamation covers and design, is erosion control on the waste facility. Erosion and the extent of erosion have a large impact on the sustainability of the cover layer and water balance of a mine waste facility (Benson, et al., 2007). The waste facility shape and geometry have a definite influence on the susceptibility of the facility and waste cover to erosion. Capping, with a cover material with established vegetation as discussed earlier, is usually implemented to limit water ingress into the waste facility. It also has the added function to stabilise slopes and prevent erosion (Blight & Fourie, 2005). If with the initial design slopes are too steep, cover material will be washed off - due to excessive run-off velocities (Wates, et al., 2006). This results in the exposure of the underlying waste and an increase in infiltration into the waste facility with possible instability and increase in seepage.

Another characteristic that is a factor in a covers' susceptibility for erosion is particle size and aggregation. In soils these are important for the stability and the ability of the cover to withstand drivers of erosion such as water and wind. The aggregation in soil is linked largely to soil texture and the organic fraction of the soils. This also contributes to the ability of the waste cover to act as a store and release cover (Zornberg, et al., 2003). Thus where texture is clayey or loamy with a high organic carbon there is a good aggregation. Whereas with the two extremes of very clayey or very sandy soils in conjunction with low levels of organic carbon will yield soils with low aggregate stability and is thus more prone to erosion (Haagner, 2011; Six & Paustian, 2014).

For vermiculite waste as a cover material to have suitable integrity against erosion, it should have the properties to form soil aggregates (Abate & Masini, 2005) which, in turn will result in a good store and release cover. Soil aggregates are essential for the formation of soil colloidal particles that is essential for soil fertility and the ability of the soil to absorb and retain water. Vermiculite has been known to be a good inorganic additive in compost processing where exfoliated vermiculite has been used as a bulking agent (Seo, et al., 2004). It is also known that vermiculite has a high CEC which contributes to aggregate formation (Van der Nest & Kuit, 1993).

Local salination can also occur that can increase vegetation die-off and further the probability of erosion. Clay mineral such as vermiculite has been used in studies as adsorbent materials for heavy metals and salts, with a relative high pH this might allow for the metals to be immobilised at a pH of 8 and thus protect plants to a certain extent against heavy metals and salts. Waste facilities or covered areas that show resistance against erosion will display evidence of good cover integrity this can be due to good aggregate formation due to the ability of the soil to form colloidal particles which is important for soil fertility. Practices or different contributors that are implemented in these areas should be studied. Water balance mechanisms evaluated can contribute to recommendation for the amelioration of affected areas (Abate & Masini, 2005; Zhang & Xu, 2005).

2.4.2 Slope Instability

The water balance may have a negative influence on slope stability if it is managed poorly. A poor water balance may induce weaknesses in the slope. This can happen if there is too much water in the pore spaces or by the creation of a phreatic surface that impinges on the side slope, thus causing slip potential. When selecting a cover, the portion of fine grained particles are important in selecting the source material as this will have an influence on the shear strength of the cover on a slope. When a cover with high water content is placed care should be taken to ensure that shear strength and associated stability of the soil are not compromised as this could lead to slope failure within the cover (Wates, et al., 2006).

2.5 EFFECTIVENESS OF COVERS IN SEMI-ARID ENVIRONMENTS

For the study to be conducted in a semi-arid environment, previous studies onsimilar waste covers and within a similar environment have been reviewed. Hydrologically semi-arid areas may be highly variable and extreme, mostly due to rainfall patterns characterized by events of short duration and high intensities and large heterogeneity of the landscape (Andersen, 2008). In the review it was found that low permeability covers (capillary barriers) as well as store and release covers seem to be able to perform well in arid and semi-arid environments with store and release covers the better of the two over a long period (Vermaak, et al., 2002; Wates, et al., 2006). Significant drying of the infiltration barrier may occur during the dry season, resulting in desiccation, and a thick protection layer may be required to prevent desiccation (Yanful, et al., 2003). For arid regions, designers also used simple covers on mine waste and incorporated erosion control measures; this is because arid climates do not support vegetation (Vermaak, et al., 2002). The main functions of the topsoil cover are to promote vegetation growth, to promote evapo-transpiration and to act as protection against water and wind erosion (DehghaniSanij, et al., 2004). Where there is no permeability barrier in place the interaction between cover and waste may also be important as the underlying layers may be less protected against intrusion by plant roots, burrowing animals and desiccation (Zornberg, et al., 2003)

Store-and-release covers are effective because they are constructed of soils that have low susceptibility to desiccation cracking (Zornberg, et al., 2003). Although these soils have higher saturated conductivities than those used in resistive barriers, they are expected to perform better in the long term than conventional covers in arid and semi-arid climates (Yang & Yanful, 2002), because evaporation can typically remove 90% or more of all rainfall infiltration semi-arid and arid climates. Slopes steeper than 1:5 do not perform as well as slopes of 1:5 as these climates may be characterised by short intense rainfall events, which may cause steeper slopes to erode quickly. The poorer vegetation performance and higher erosion from these steeper slopes, greater that 1:5, appears to be influenced by both more arid soil conditions, as there is less infiltration on steeper areas, and hotter slopes in north or North West facing areas. Design of these covers is site-specific as the storage potential of the cover must take into account the expected local weather conditions (Wates, et al., 2006; Vermaak, et al., 2002)

In capillary barrier covers as with store-and-release covers, the mechanism that governs moisture ingress into material below the cover is the unsaturated hydraulic conductivity characterisation of the material (Wates, et al., 2006). In dry climates, the use of moisture storage layers may not be feasible due to high evaporation rates, but the inclusion of a capillary barrier to limit upward migration of moisture may still be warranted. This due to evaporation being strongly depended on the soil moisture conditions (Yamanakaa & Yonetanib, 1999). A major drawback of store-and-release systems is that breakthrough occurs once the critical saturation point is reached, resulting in unacceptable infiltration into the waste. In arid and semiarid climates, the critical saturation point is rarely reached because of evapo-transpiration removing soil water from the capillary layer. However, the evapo-transpiration potential is not adequate to remove soil water in temperate climates (Vermaak, et al., 2002).

3. METHODOLOGY

The evaluation of the water balance mechanisms of the vermiculite cover is done through the assessment of the material hydraulic properties, measuring and assessing the soil volumetric water content status, surface runoff and drainage from or into waste materials to determine the flux and water stutus in the cover and waste materials.

Selection of representative sampling plots on waste facilities in the related area was also an important component of the study. This aimed to determine the influence of the vermiculite cover in its contribution to the waste facilities waterbalance, as well as the influence of the interaction between the cover and the underlying waste.

The hydraulic characterisation of vermiculite is very site specific as this will depend on the mineral materials that were mined with the vermiculite cover types and the material properties of the covers which will have a specific influence on the water balance, this needed to be identified and quantified to assist in determining if an accurate water balance was done. The observed fluxes and soil water status are used in a simple simulation of the soil water fate using the HYDRUS unsaturated/saturated soil water physics to derive estimates of the overall water balance.

The study area is located in the North-Eastern part of the Limpopo Province of the Republic of South Africa, some 5km southeast of the town of Phalaborwa and adjacent to the western boundery of Kruger National Park. The area is, on average 380 metres above mean sea level and is gently undulating, with occasional rocky outcrops or “koppies”. The region experiences sub-tropical, summer rainfall conditions with high temperatures and low rainfall. Due to the hightemperatures and low rainfall the area is described as semi-arid.

Figure 3-1: Phalaborwa sampling sites, with the map indicating site placement of Runoff Plots and Lysimeters

Eight (8) sampling sites (Figure 3-1) were identified that were seen as representative of the area. There are several differences in the sites, not only in cover type and material properties, and these will be described below. The sampling sites included 5 Runoff Plot (ROP) sampling sites on a Tailings Storage Facility (TSF), with 2 Lysimeters as well as a runoff plot on a waste rock dump (WRD).

3.1 METEOROLOGICAL OBSERVATIONS

A Davis Weather station was used to obtain continuous climatic data of the site (Figure 3-2). The station monitoring system was setup to obtain temperature, wind speed, air pressure, humidity and rainfall measurements at 30 minute intervals over the period of the study.This station was situated at a central point at the mining complex. The resolution of the measurements was set and calibrated to one decimal of the measured aspect. Additional climatic data from similar Davis weather stations with the same monitoring frequency were also obtained from other sites in the vicinity of the mine. This additional data was used to confirm or correct data that was obtained from the on site weather station.

For potential evaporation measurements the mean A-pan evaporation as a function of climatic ambient conditions, for the area has been used, data of the Department of Water and Sanitation (DWS) was used to obtain mean A-pan evaporation for the area. A-pan evaporation combines and integrates the climatic effects such as temperature, humidity, precipitation, wind and solar radiation to obtain estimated evaporation for an area.

Figure 3-2: Davis Weather Station used to monitor continuous on site climatic data.

3.2 HYDRAULIC CHARACTERISTIC MEASUREMENTS

To assist with the assessment of water balance mechanisms such as infiltration, material characteristics, evaporation, transpiration, seepage and the interaction of cover material with the underlying waste the following tests were performed at the mentioned sites; Double-Ring Infiltrometry, Tension Infiltrometry and Guelph Permeametry. These tests were performed before the study period that started in December 2016 until March 2018.

Figure 3-3: Double-Ring infiltrometer used for material characterisation at a sampling site with TDR placement indicated on the side(TSF).

Cover substrate as well as underlying waste material hydrological characterisation was done by using the mentioned tests. The instruments were used on surface and at depths of 100 mm, 500 mm and a 1000 mm at the mentioned eight sampling sites (Figures 3-3 and 3-4). For the double ring infiltrometry, volume over time measurements were done until a steady state was reached. The volume in the outer-ring was kept constant while in the inner-ring the volume of water infiltrating over time was measured. The 100mm depth was seen as close to the interface between the vermiculite cover substrate and underlying waste. These tests were performed to determine soil saturated and unsaturated substrate hydraulic conductivity. Vegetation root depth was observed as up to 500mm deep in the TSF. The tests on each of the instruments were performed until a steady state was reached.

Figure 3-4: Material hydraulic characterisation with Tension Infiltrometer (TSF)

A Tension Infiltrometer (Figure 3-4) as well as a Guelph Permeameter have also been used to determine substrate hydraulic characteristics on surface and depths of 100mm, 500mm and 1000mm at sampling sites on the tailings facility and the waste rock dump.

By determining the material hydraulic characteristics at the different sampling sites we will get insight into the hydraulic responses of the material, when materials are saturated, or how they will behave when there is capillary tention influencing water or moisture movement under tention. These hydraulic characteristics will assist in the understanding of infiltration and runoff responses. It will also assist with the understanding of the interaction at the interface between the vermiculite waste cover and the underlying waste. By determining the hydraulic characteristics we will also understand the moisture hold and release capability of a material.

The substrate hydraulic characteristic data will be used to calibrate a soil water flux model for the vermiculite waste cover and the undelying waste layers. To understand the material or soil water flux, for the evaluation of the vermiculite waste cover contribution to the waste facilities waterbalance, understanding the hydraulic characteristics is of major importance.

To determine the water retention characteristics of materials, repacked samples with vermiculite cover or tailings material from Runoff Plot 5 were used to derive the water retention characteristic of the materials in a laboratory (Lorentz & Wessels, 2015). A controlled outflow apparatus was used measure the retention characteristics and the results were compared to the water retention characteristic of a Hutton silty loam soil (Figure 3-5) The water retention characteristics of vermiculite cover was seen to be similar to a Hutton soil under capillary pressures less than 20 m.

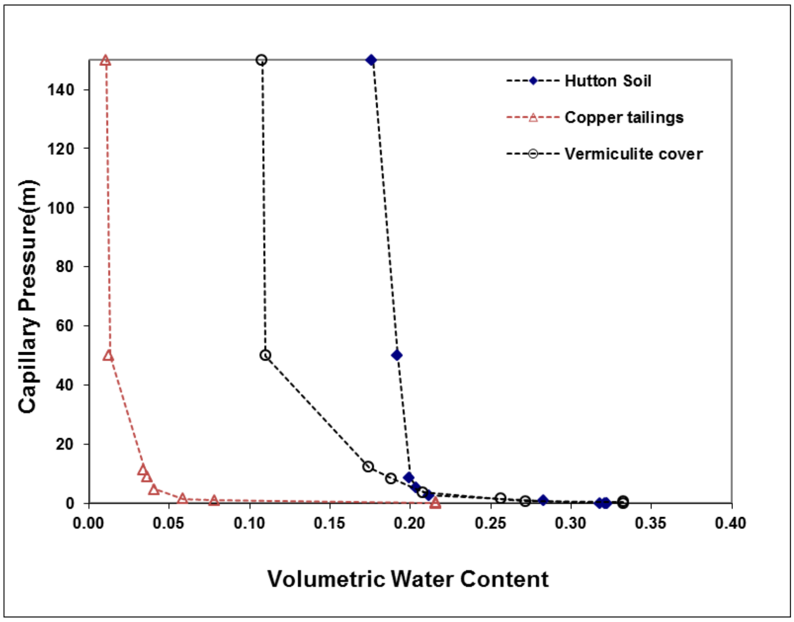


Figure 3-5: Water retention Characteristics for Copper tailings, Vermiculite Cover and Hutton Soil.

3.3 SOIL WATER CONTENT OBSERVATIONS

Next to each sampling site Time Domain Refractometry (TDR) probes were installed at depths of 100 mm, 500 mm and 1000 mm below the surface. These served as volumetric water content sensors and is refered as K1; K2; K3 in the data sets (Figure 3-6) from the relevant runoff plots. At Runoff Plot 5 the TDR probes were joined to a Cambell Scientific TDR100 wave generator or response analyser which delivers a volumetric water content and bulk electrical conductivity measurement to a Campbell CR800 logger at pre-set one hour intervals via co-axial cables. At the remaining sites a “roaming” TDR100 was used to link the TDR probes directly to a readout device with a program called PCTDR to log a volumetric water content at the time at which the measurement was logged manualy. This was done at intervals over a period of one year, more than 500 logs were taken over this period.

TDR probe calibration comprised a TDR measurement and subsequent laboratory evaluation of the the wet or saturated volumetric water content for the vermiculite waste cover at 0.468 and for tailings 0.435. This was repeated for the unsaturated volumetric water content for the vermiculite waste cover at 0.146 and tailings at 0.114. These readings were then used to evaluate in situ readings reflecting the volumetric water content on different levels after precipitation and during drying periods. Factors such as cable lengths were taken into account in the interpretation of the wave forms collected at each measurement. These saved wave forms were resolved in a spreadsheet to determine the VWC for each TDR measurement.

Interaction between cover material and the underlying waste was interpreted from the results of the Palabora Copper-TDR sampling. Volumetric water content of cover material and underlying waste was monitored to estimate water movement as well as interaction between the cover material and underlying waste (Figure 3-6).

Figure 3-6: TDR probes at Runoff plot 5 inserted into tailings for monitoring of Volumetric Water Content (TSF)

3.4 RUNOFF PLOTS AND LYSIMETERS

During the selection of the runoff plot sites consideration have been given to slope, aspect, vegetation and cover materials. Vegetation root depth at the WRD was observed to be up to 2 meters deep, at the TSF vegetation root depth was not more than 500 mm deep. Runoff plots on sites 1, 2, 3 & 4 have been established on the side slopes of the TSF. Runoff plot 5 has been established on a top surface or bench of the TSF, whereas runoff plot 6 with a very steep slope was established on the side of a waste rock dump.

Conditions at the various sites may be described as follows; Runoff Plot 1 (ROP 1) faces an easterly direction on the main Tailing Storage Facility (TSF): slope = 1:3. Its cover consists of mostly a homogeneous vegetative cover comprising *Cenchrus ciliaris* and *Dodonea viscosa.* Other species are also present but are without significant population densities. Root penetration for mainly *Dodonea* can be up to 500 mm. The typical surface soil of this area is a vermiculite waste cover which is well graded with a mix of the geology that is found in the area, size of the particles in this area varies from fist size rocks to fine weathered vermiculite placed at 150 mm to 200 mm thickness over the waste substrate. In some areas around ROP 1 the surface may be described as partially cladded with vermiculite fines inbetween.

Runoff Plot 2 (ROP 2) faces a southern direction on the main TSF: slope = 1:3. Its cover consists of mostly *Cenchrus ciliaris* and *Dodonea viscosa.* Other species are present but without significant population densities. Root penetration for mainly *Dodonea* can be up to 500 mm. The typical surface soil of this area is a vermiculite waste cover with a mix of the geology that is found in the area. The size of the particles in this area varies from fist size rocks to fine weathered vermiculite with a 150 mm to 200 mm thickness over the waste substrate. In some areas around ROP 2 the surface may be described as sparsely cladded

Runoff Plot 3 faces a western direction on the main TSF: Slope =1:3 Cover; vegetation cover comprises sparse *Cenchrus ciliaris* and *Dodonea viscosa.* Oher species are present but without significant population densities. Root penetration for mainly Dodonea can be up to 500 mm. Contamination through wind erosion by tailings on this site is evident. The typical surface soil of this area is a vermiculite waste cover with a mix of the geology that is found in the area. The size of the particles in this area varies from fist size rocks to fine weathered vermiculite with a 150 mm to 200 mm thickness over the waste substrate.

Runoff Plot 4 faces east north east on the main TSF: slope=1:3 vegetation more or less the same cover as with ROP 1 with sparse *Dodonea viscosa*. Root penetration for mainly *Dodonea* can be up to 500 mm. Contamination through wind erosion by tailings on this site is evident. The typical surface soil of this area is a vermiculite waste cover with a mix of the geology that is found in the area, size of the particles in this area lends itself to fine weathered vermiculite with sparse rocks with a 150 mm to 300 mm thickness over the waste substrate.

Runoff Plot 5 is on the eastern side of the main TSF: slope = 0 gentile undulating flat surface sloping towards the inside of the tailings facility. The typical surface of the vermiculite waste of this area can be described as cladded with various sized rocks with fine vermiculite in between. The vermiculite waste layer has a thickness of between 150 mm to 200 mm. The material is not well graded. The vegetation cover is homogeneous with *Dodonea viscosa*. Other indigenous grass species are visible with low population densities.

Runoff Plot 6 is on a western very steep slope of almost 1:1 on the Waste Rock Dump (WRD). Vegetation is mostly homogeneous with *Cenchrus ciliaris* and *Pennisetum setaceum. O*ther indigenous grass species are visible but with insignificant population densities. The typical surface cover of this area is a thick vermiculite waste cover with a mix of the geology that is found in the mica complex, size of the particles in this area is finer material mostly smaller that 2 mm and on first observation seems to have a higher vermiculite content with a vermiculite waste layer of between 200 mm and 300 mm thick.

Lysimeter 1 and 2 were established on Waste Rock Dump 4 on top surfaces or benches. The large lysimeters on Dump 4 were established by excavating and shaping an 8x8x2 m cavity in the waste rock. The base and sides of the lysimeter were lined with a plastic liner and an aggregate drain was placed at the bottom centre. The base of the lysimeter sloped towards the centre and the drain. An outflow pipe connected the drain to a tipping bucket approximately 6 meters away from the lysimeter. A tipping bucket was placed in an excavation lower than the drain to allow for gravity flow from the lysimeter drain to the tipping bucket (Figure 3-7).

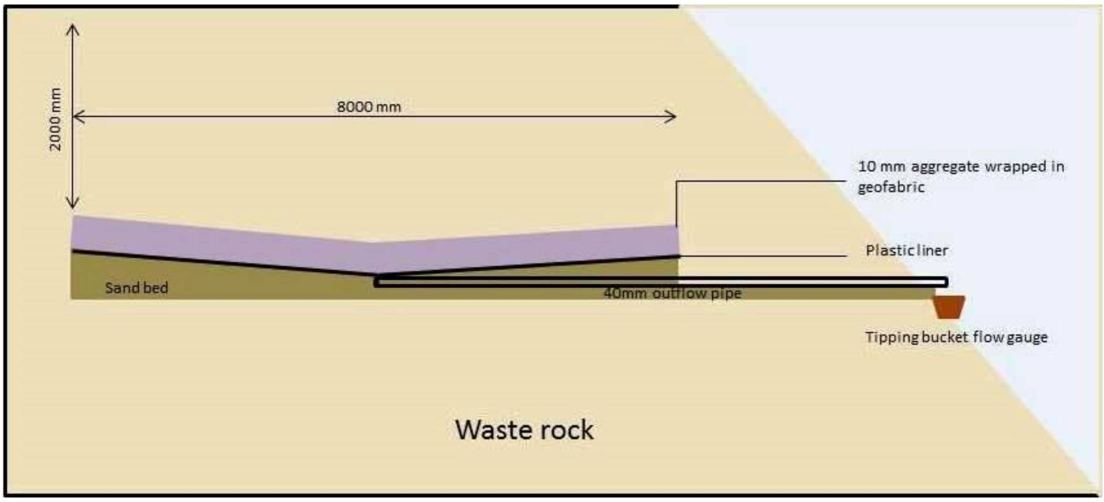


Figure 3-7: Schematic profile of a waste rock Lysimeter as was placed on Waste Rock Dump 4

Lysimeters were used to infer the amount of actual evapo-transpiration released by vegetation and soils. This was done by recording the amount of precipitation in the area and the amount of water seepage through drainage through the soil by monitoring the event-loggers on the tipping buckets for the Lysimeters on the Waste Rock Dump (WRD).

The Lysimeter drain was deeper than 2 meters, no vegetation roots were detected deeper than 2 meters. The seepage that discharged into the tipping bucket could therefore be assumed as contributing to ground water recharge. The effective root zone was physically measured and photographed during the characterisation of the cover and waste material to determine the effective roots zone.

To determine the general infiltration and run-off, sampling sites were constructed that consisted of a 2.5x10 meter area surrounded by metal sheeting with a tipping bucket with an event data logger to measure precipitation run off. Metal sheeting was used to ensure that only the 2.5x10 meter area's precipitation and runoff were used for measurement in the tipping bucket (Figure 3-8). At the bottom or in the down slope area of the runoff plot the water was channelled to the tipping bucket through a trough. Each bucket was calibrated by using a standard laboratory flask to add water to the bucket until it tipped. This was done at least 3 times per bucket to determine the mean volume of water that resulted in the tipping of a bucket. The process was repeated for all tipping buckets at the various sites. An average volume of 1.3 litres for each tip were determined through this mentioned calibration. Tipping of the buckets during precipitation events was logged by using Hoboware event loggers that logged each tip of a bucket to determine the run-off of that specific plot. Mean infiltration was determined by subtracting average rainfall measured for the area from the amount calculated from bucket tips during the same period.

Figure 3-8: Runoff plot with a tipping bucket and event logger as installed on the Tailings Storage Facility, with barriers on the side to ensure that only runoff inside the test area would be measured.

3.5 HYDRUS SIMULATIONS

In order to estimate long-term water fluxes, a numerical simulation model was used. The model was calibrated against the observed runoff (Runoff plots); infiltration (lysimeters and water content profiles) and estimated evapotranspiration losses (lysimeters). The model selected was the HYDRUS-1D finite element model, which simulates the mass balance in a vertical direction by combining Darcys law with the continuity equation. The resultant differential equation solved numerically in the model is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S$$

Where

h = pore water pressure head, [L]

θ = volumetric water content. [L^3/L^3]

t = time, [T]
z = spatial coordinate [L] (positive upwards)
S = sink term ($L^3/L^3/T$ and
$K(h)$ = unsaturated hydraulic conductivity [L/T].

A vertical profile with the appropriate hydraulic characteristics as measured in the field (Section 3.2) is specified in finite element layers. Given a starting pore water pressure distribution in a vertical profile and a time series of the atmospheric top boundary condition comprising potential rainfall and evapotranspiration demand, the infiltration, seepage, runoff and evapotranspiration fluxes and soil water content changes are simulated in the profile. These output fluxes and water storage changes, calibrated against the observed pore water pressures and volumetric water contents, are then interrogated and compared with lysimeter or runoff plot observations, in order to determine long term water balances.

4. RESULTS AND DISCUSSION

4.1 METEOROLOGY

While a meteorological station is located near the site (Figure 3-2), the record is comparatively short for statistical analysis of the rainfall and evaporation. The data from this station will be used for detailed simulations of the water balance, in conjunction with the observed runoff, percolation and soil water status.

Statistical analyses have been conducted using the Phalaborwa Airport rainfall station (0681226 W) for a 59 year record (1955-2014) and the Phalaborwa Barrage A-pan station (B7E004) of the Department of Water and Sanitation (DWS), for a 17 year period (1990-2006).

4.1.1 Rainfall

The Mean Annual Precipitation (MAP) for the 59 year record is 517mm. The annual variations are high, though; the maximum recorded annual (calendar year) precipitation is 911 mm, (2000), the 95th percentile is 753 mm and the median 538 mm.

Monthly precipitation also varies significantly around the medians. Monthly rainfall listed in Table 4-1 indicates the much lower rainfall during the study period (2017), compared to the maximum and average rainfall for a 60 year recording period. The highest monthly recorded precipitation is 413 mm for February 2000, illustrating the propensity for extreme events in this relatively dry climate. On average, rainfall is lowest in August, peaking in February and declining again to September (Figure 4-1).

Table 4-1: Average, maximum and annual rainfall indicating the much lower rainfall period during study.

Rainfall	Total	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Max	995.5	29.0	145.5	121.1	148.0	271.5	336.0	413.4	227.0	123.6	57.8	50.9	75.0
Average	508.1	4.6	15.7	34.9	65.7	91.1	98.4	89.5	55.9	29.1	10.9	6.2	5.9
2017	337.2	3.6	0.4	70.0	29.8	62.5	4.9	105.5	17.4	27.5	11.9	0.0	3.7

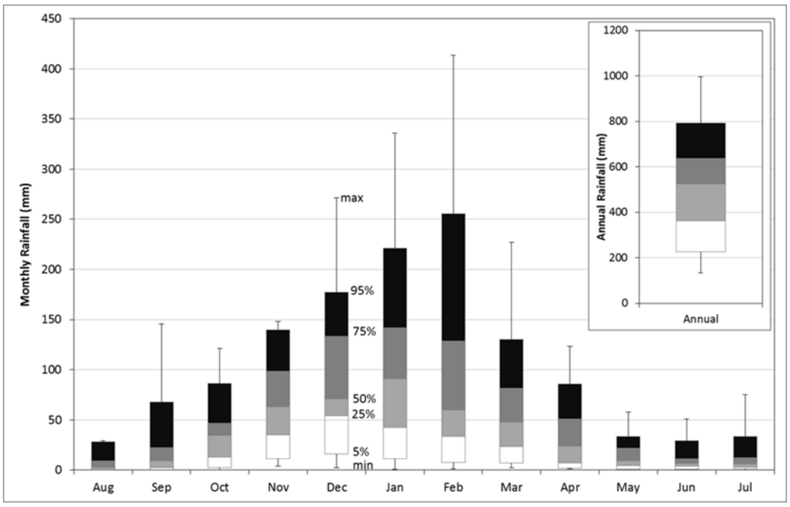


Figure 4-1: Monthly and annual rainfall statistics for gauge 0681266W

4.1.2 Potential Evapotranspiration

The Mean Annual Evaporation, as measured with A-Pan apparatus, is 1774mm. The A-Pan evaporation estimated from the S-Pan listing in the Water Resources 2005 (WR2005) database is 1694 mm, which is comparative to the 1990-2006 Phalaborwa Barrage (B7E004) measurements. Clearly, variations in annual and monthly evaporation are not as high as rainfall, as illustrated in Figure 4-2.

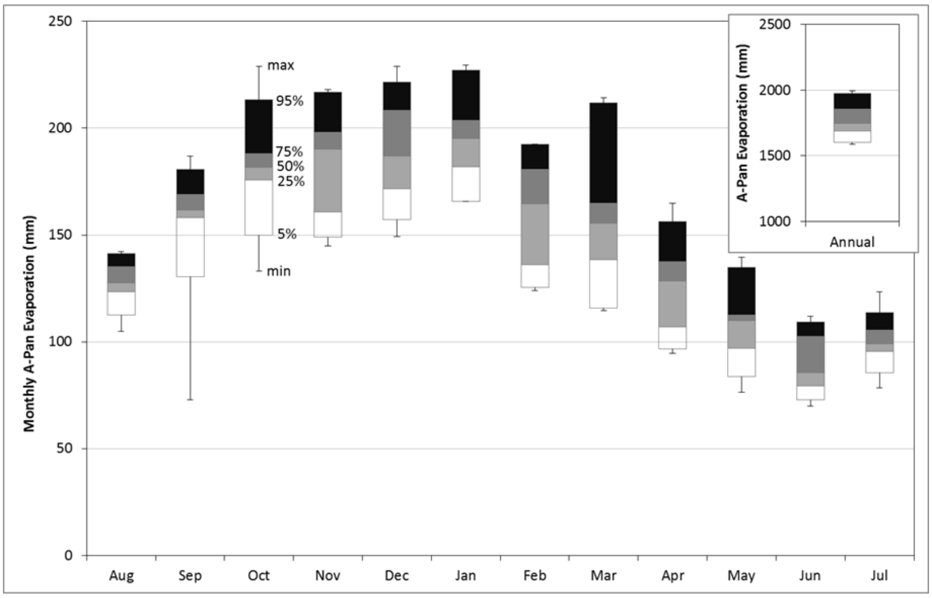


Figure 4-2: Annual and Monthly statistics of A-Pan evaporation for the Phalaborwa Barrage.

The rainfall and A-Pan evaporation records for the Phalaborwa area indicate that the average potential A-pan evaporation (1774mm) far exceeds the average rainfall (508mm) per annum. Evapotranspiration is therefore a major component in the water balance which is controlled mostly by the porous media physics of the upper layers of the substrate materials. Hence it is necessary to characterise and observe the behaviour of these upper layers.

4.2 MATERIAL HYDRAULIC CHARACTERISTICS

Hydraulic characterisation of vermiculite waste cover as well as material hydraulic characteristics of the underlying waste material are found to be site specific as these depend on the mineral waste materials that were mined with the vermiculite. Deposition method of the waste material at the specific site as well as the grading of the material at the site also contribute to this site specific hydrological character.

4.2.1 Comparison of Typical Hydraulic Characteristics of the Tailings Facility

Typical hydraulic characteristics at surface and depth 100 mm, 500 mm and 1000 mm of two sites, one level (Runoff Plot 5) and one sloped (Runoff Plot 3) on the tailings storage facility are compared first as an overview. Hydraulic conductivity characteristics at Runoff Plot 3 and 5 reveal significant differences between material characteristics of sampling sites on the tailings storage facility (Figures 4-3 and 4-4). The hydraulic conductivity of the vermiculite waste cover and tailings material of the flat surfaced Runoff Plot 5, have unsaturated hydraulic conductivities of almost an order of magnitude lower (6.61 mm/h; 16.08 mm/h) than the unsaturated hydraulic cunductivity at Runoff Plot 3 (96.09 mm/h; 195.18 mm/h), (1:3 side slope) which relates to the water holding capability of the material at the site.

Table 4 2: Summary of Saturated Hydraulic Conductivity

	Saturated Hydraulic Conductivity Ksat (mm/h)							
	TSF					WRD		
Depth	ROP1	ROP2	ROP3	ROP4	ROP5	ROP6	LYS 1	LYS 2
Surface	298.98	477.27	225.30		267.00	267.00	236.89	187.90
100mm	139.32	477.30	336.37	592.24	180.30	279.30	69.39	
190mm								212.10
500mm	270.15	755.67	730.64	823.97	47.08	180.00	21.42	
1000mm	380.05	385.79	745.73	827.57	25.60	82.50		

The saturated hydraulic conductivities of the tailings at Runoff Plot 5 (25.6 mm/h) are also lower than those at Runoff Plot 3 (745.3 mm/h), by an order of magnitude (Table 4-2). These differences in hydraulic conductivities of the tailings material may be attributed to the method of tailings deposition, in this case a peripheral deposition by spigot on the tailings, which leads to a difference in particle size distribution between Runoff Plot 5 and Runoff Plot 3. The saturated hydraulic conductivity of the materials relate to the water ingress capability or potential of the material at the site.

Table 4 3: Summary of Unsaturated Hydraulic Conductivity

		Unsaturated Hydraulic Conductivity Kunsat (mm/h)							
Tension	Depth	TSF					WRD		
cm	mm	ROP1	ROP2	ROP3	ROP4	ROP5	ROP6	LYS 1	LYS 2
	Surface								
0,5				96,09	152,02	6,61	25,99	2,29	21,48
3		8,69		33,52	98,76	6,30	17,34	1,79	16,57
9		6,42		18,94	52,09	3,04	5,90	0,81	7,70
16		4,34		11,20		1,26	2,79	0,35	4,16
	100mm								190mm
0,5		9,18	12,16	78,07	79,75	30,10	18,54	16,94	63,23
3		5,35	14,41	16,13	50,04	21,28	16,56	12,76	20,18
9		2,61	8,63	7,42	34,33	5,83	12,88	6,18	7,29
16			4,07	7,29	22,05	1,34	5,29	3,46	
	500mm								
0,5		82,88	199,95		106,13	23,88	14,95	21,22	
3		37,22	98,09	173,31	132,66	15,64	9,88	9,03	
9		13,01	40,93	119,29	44,40	8,99	8,69	2,59	
16			16,81	30,74	18,37		6,05	1,38	
	1000mm								
0,5		42,94	38,01	195,18	51,08	16,08	1,97		
3		21,64	48,20	123,94	80,00	12,07	2,07		
9		7,15	34,22	48,14	38,00	6,87	1,99		
16			18,45	21,77	16,07	4,07	1,58		

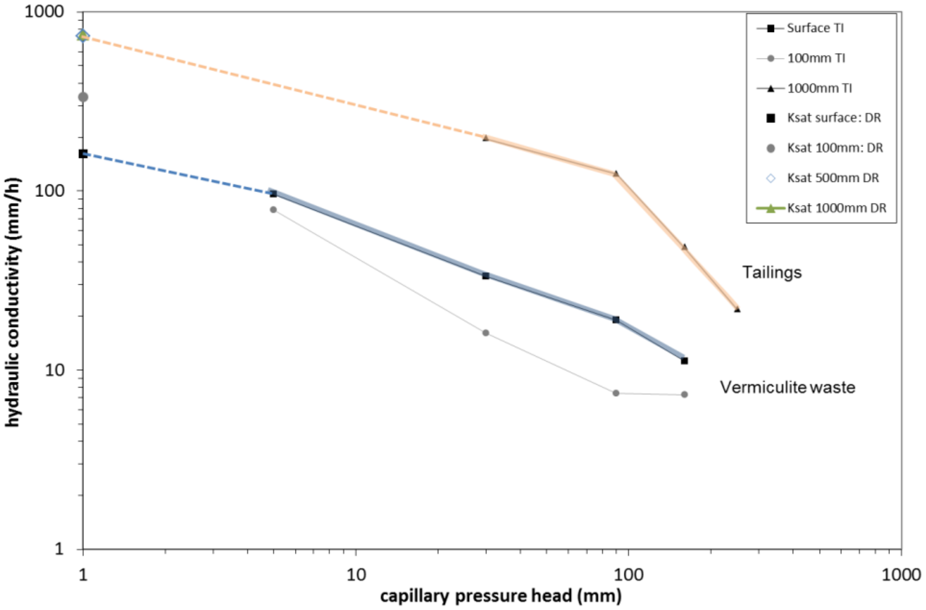


Figure 4-3: Hydraulic conductivity characteristics at Runoff Plot 3 – Blue line indicate vermiculite waste unsaturated hydraulic conductivity. Pink line indicate tailings unsaturated hydraulic conductivity (TSF).

Due to the lower saturated hydraulic conductivities at Runoff Plot 5 it may be expected that the runoff results from the flat surface at Runoff Plot 5 could be similar to that of Runoff Plot 3 the sloped site. This lower hydraulic conductivities indicate to a reduced ingress of water. It was observed that the materials in the Runoff Plot 5 profile are more compacted than the materials at the sloped site. This major difference as said may also be attributed to the method of deposition. Therefore at sloped sites on the tailings near to the deposition point particles are more coarse, due to the coarse material that settles first from the deposition point. Whereas at the flat site toward the centre of the facility, Runoff Plot 5, finer tailings settled further from the deposition point as the finer tailings particles is light and could be carried further by the water in the deposision process. Runoff Plot 5 is also a much older site where the vermiculite cover on an almost flat surface were applied with a dozer, which may contribute to compaction and thus lowering of the unsaturated hydraulic conductivity. Sloped areas on the tailings facilities at this operation are always reworked with an excavator before the vermiculite cover is applied, which leads to looser less compacted material.

The unsaturated hydraulic conductivities of these two sites' cover materials (96.09 mm/h; 6.61 mm/h) are generally lower than in the tailings (195.18 mm/h; 16.08 mm/h) (Table 4-3). This lower unsaturated conductivity of the vermiculite cover is commensurate with the behaviour of a sandy loam type soil, in that saturated or ponded infiltration will enter the profile rapidly due to the high saturated hydraulic conductivity, but apon drying, fluxes drop off significantly due to the low unsaturated hydraulic conductivity. Thus the cover acts as a capillary break limiting or controlling evaporation from the surface and retaining moisture in the subsurface layers to allow for vegetation uptake and transpiration.

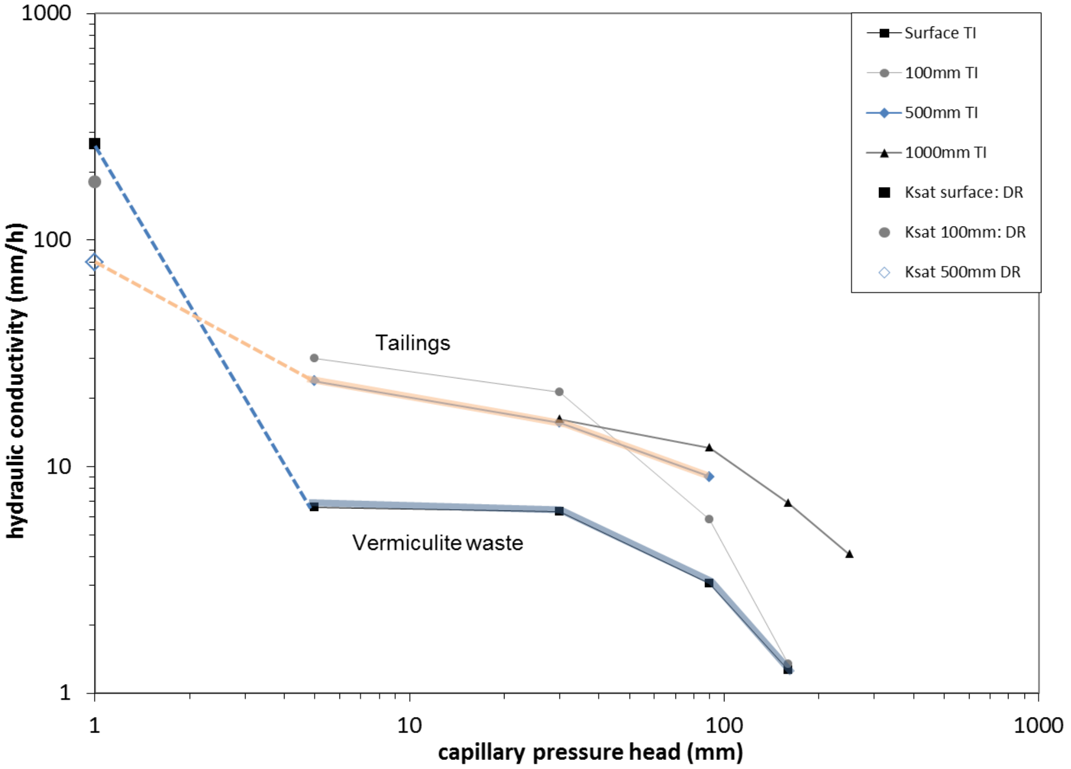


Figure 4-4: Hydraulic conductivity characteristics at Runoff Plot 5 – Blue line indicate vermiculite waste unsaturated hydraulic conductivity. Pink line indicate tailings unsaturated hydraulic conductivity (TSF).

Although the saturated conductivity in the vermiculite cover material is higher than the underlying tailings at the flat Runoff Plot 5 site, which will allow for good infiltration into the vermiculite waste, the unsaturated hydraulic characteristic of the vermiculite cover material is much lower than in the underlying tailings material, on surface and at capillary pressure heads lower than 100 mm (Figure 4-4) which will allow the vermiculite waste cover to release moisture much slower than the underlying tailings.

The high saturated conductivities of the vermiculite waste cover at both Runoff Plot 3 and 5 allow for adequate infiltration. The higher unsaturated conductivities in the tailings at Runoff Plot 5 compared to the vermiculite in the cover materials at the site is indicative of the fine nature of the tailings at this site, while the coarser nature of the vermiculite material loses water slowly, even at low capillary pressures. The vermiculite cover at Runoff Plot 5, (Figure 4-4), has a larger percentage of coarse material compared to the sloped Runoff Plot 3, (Figure 4-3), contributing to a higher effective saturated hydraulic conductivity, lower unsaturated hydraulic conductivity and thus contributing to superior moisture retention.

4.2.2 Hydraulic Characteristics of the Waste Rock Dump

Results of the saturated hydraulic conductivity at Waste Rock Dump Lysimeter1 (Figure 4-5) show that the saturated conductivity (236 mm/h) of the vermiculite at surface, is higher than the saturated hydraulic conductivity of the waste rock material (10.4 mm/h) found deeper in the WRD. The higher saturated hydraulic conductivity of the vermiculite cover on the WRD contributes to a high infiltration capability at this site. This increased saturated hydraulic conductivity may be due to the surface cover material being loosely compacted compared to the vermiculite mixed in the first 2 meters of the waste rock dump. The first 2 meters of the WRD profile contains considerable vermiculite and other fines witin the matrix. This together with the large proportion of impermeable rock, results in a lower effective saturated hydraulic conductivity below surface. The same can be said for the saturated hydraulic conductivity of Lysimeter 2. As mentioned loose vermiculite and other fines allowed high saturated conductivity on surface and at a depth of 190 mm. Because of the large proportion of impermeable rock at Lysimeter 2 hydraulic conductivity tests could not be done at depths below 190 mm.

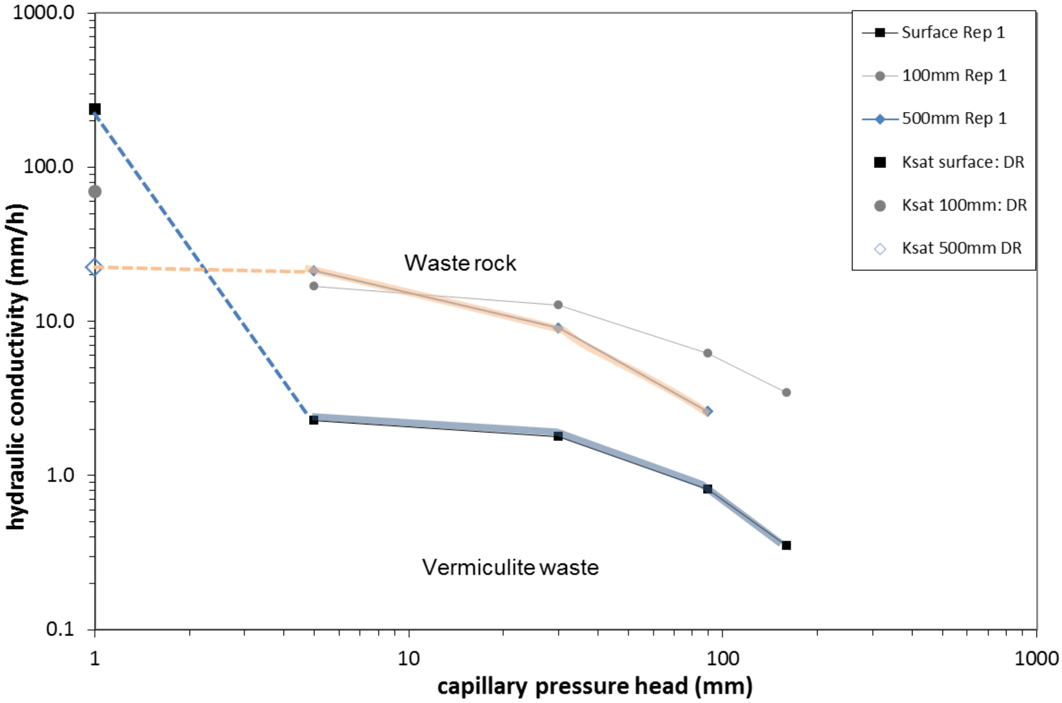


Figure 4-5: Hydraulic conductivity characteristics at Lysimeter 1 - Blue line indicate vermiculite waste unsaturated hydraulic conductivity. Pink line indicate waste rock unsaturated hydraulic conductivity (WRD).

The occurence of fines inbetween large impermeable rock was observed in 2 to 3 meter deep cuttings in the waste rock dump (Figure 4-6). The relatively high saturated conductivity on surface at Lysimeter 2 (Table 4-2), again, reflects the high infiltration capability of the loose vermiculite cover. However, the saturated hydraulic conductivity at 190 mm below surface remains high, reflecting the depth of the loose material with large rock fragements at this site.

Saturated hydraulic conductivity (Ksat) of the vermiculite waste cover at surface and depth 100 mm at all the sampling sites (Table 4-2) compare well with the Ksat of Sandy or Sandy Loam soils, which have a Ksat of 152 to 508 mm/h. This will allow for rapid infiltration of moisture into the waste cover with the vermiculite cover able to make this moisture available for evaporation and transpiration processes. At all sites on the TSF except for Runoff Plot 5 the underlying waste have a higher infiltration rate than the vermiculite waste cover, this is due to the method of deposition as dicussed previously, indicating that the ultra fine tailings deposited migrated to the centre of the tailings facility, giving this site at depth 500 and 1000 mm a Ksat characteristic of a loam type soil. Though the Ksat of the underlying waste is lower than that of the vermiculite waste cover, the unsaturated hydraulic conductivity of the vermiculite waste cover is much lower than that of the underlying waste which will allow the vermiculite cover to control the flux into the underlying waste. The Ksat at Lysimeter 1 on the WRD is lower at depth 100 mm than when compaired with the Ksat at surface this is due to the large amount of impermeable rock in the WRD that has been mentioned. The higher Ksat at 190 mm at Lysimeter 2 will not affect the flux as the unsaturated hydraulic conductivity measured at surface is much lower than the unsaturated hydraulic conductivity measured at depth 190 mm.

The higher unsaturated hydraulic conductivity of the waste rock material at the Lysimeter 2 site (Table 4-3) contributes to the limiting of excessive evaporation due to the vermiculite fines controlling the flux from the surface area, thus retaining the moisture in the subsurface layers.

Unsaturated hydraulic conductivity of the vermiculite cover material on surface at Lysimeter 1 at capillary tensions of 100 mm or more are two orders of magnitude lower than the saturated hydraulic conductivity of 236.89 mm/h (Figure 4-5) which will allow the vermiculite cover to control the flux into the underlying waste. The high saturated hydraulic conductivity will allow for saturated or ponded infiltration to enter the profile rapidly. The unsaturated conductivity results of the vermiculite cover at Lysimeter 2 (Table 4-3) similar to Lysimeter 1 also showed a difference of an order of magnitude when compared to the saturated hydraulic conductivity tests (Table 4-2) done at surface and at 190 mm depth in the vermiculite cover. This indicate that upon drying, fluxes will drop significantly due to the lower unsaturated conductivity. Enabling the cover to act as a capillary break, limiting excessive evaporation, this is comparable with the behaviour of a sandy loam soil and means that it can retain or hold water obtained through precipitation for evaporation and transpiration on the waste rock dump.

Hydraulic conductivity of the vermiculite cover material characterised at Runoff Plot 6, which is also on the WRD, correspond in general with the hydraulic charchteristics found at Lysimeter 1 and 2. It was found that the hydraulic conductivity of the vermiculite cover material at surface (Table 4-2) of Runoff Plot 6 was high (231 mm/h) when compared to the saturated hydraulic conductivity of the underlying waste rock material (78 mm/h) at a depth of 1000 mm, The high saturated conductivity of the vermiculite waste will allow for rapid saturated or ponded infiltration at this site.

Figure 4-6: Excavation at Lysimeter 1 indicating vegetation roots at depth of 2 meters with vermiculite fines migrating deep into the waste rock.

The unsaturated hydraulic conductivity of the vermiculite cover material at tensions of 100mm or more at runoff plot 6 was also found to be an order of magnitude lower (Table 4-3) than the saturated hydraulic conductivity. This will allow for the flux to drop off significantly at this site in the vermiculite cover due to the low unsaturated conductivity when the material is drying and will limit excessive evaporation from the surface.

The Tailings Storage Facility’s (TSF) hydraulic conductivity results of the vermiculite cover material at surface does not seem to be that varied when compared (Table 4-2) as they do not vary at any site by an order of magnitude. The small differences are due to the variation in percentage of larger stone or rock found in or absent in the vermiculite cover material that was placed at the different sites. As mentioned before the hydraulic conductivity of the vermiculite cover commensurate with the behaviour of a sandy loam type of soil, in that saturated infiltration will enter the soil profile rapidly due to the high saturated conductivity, but when drying, the low un-saturated hydraulic conductivity of the vermiculite cover material cause the flux to drop significantly allowing the cover to act as a capillary break, limiting evaporation from the surface. Through this, moisture is retained in the subsurface layers to allow vegetation moisture uptake for transpiration. This hydraulic behaviour for saturated and unsaturated hydraulic conductivity can be seen at all the runoff plots on the tailings storage facility (Table 4-3).

The underlying waste at the tailings storage facility's runoff plots on all sites tested higher for saturated hydraulic conductivity than when compared to the vermiculite cover, except for runoff plot 5 where there was a difference of an order of magnitude (Table 4-2), the reason for this has been discussed in previous paragraphs. The higher saturated hydraulic conductivity of the tailings would have allowed for rappid saturated infiltration into the tailings facility if the vermiculite cover material did not control the flux because of the vermiculite material's low unsaturated hydraulic conductivity (Table 4-3) creating a capillary break.

4.3 SOIL-WATER DYNAMICS

The volumetric water content, measured by TDR, reflects the soil water dynamics. The water content measured meanually using PC-TDR at Lysimeter 1 and 2 on the WRD will be considered first. Responses of the volumetric water content are shown as a time series with the rainfall over a period of just over a year, from January 2017 until March 2018 (Figure 4-7).

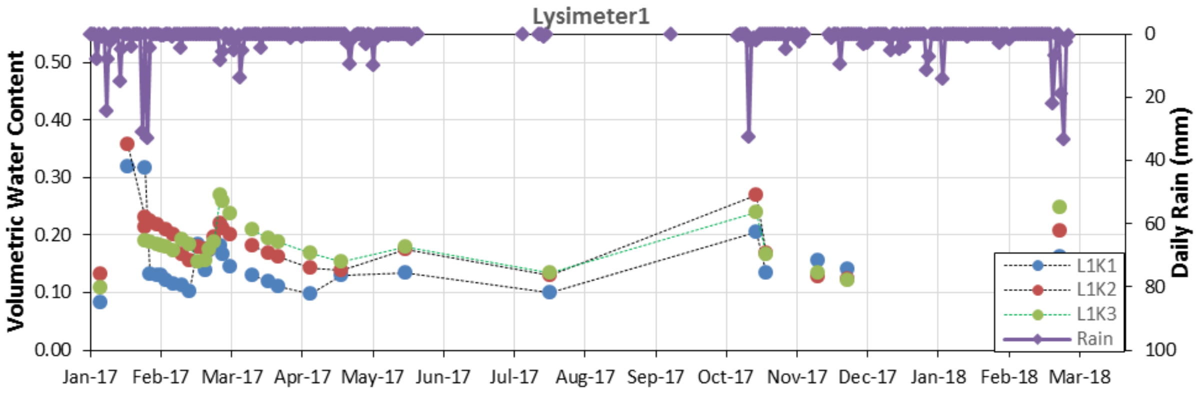


Figure 4-7: Volumetric Water Content and Rainfall time series for Lysimeter 1 (WRD)

At Lysimeter 1 the TDR probe at depth 100 mm (L1K1) (Figure 4-7) measures the VWC in the vermiculite cover material near the surface of the waste rock dump while the TDR probes at 500 mm (L1K2) and at 1000 mm (L1K3) measure the VWC in the underlying waste. The increase and decrease of VWC or the absence of change at the different levels can be interpreted to reflect of the soil water flux and the interaction between vermiculite cover material and underlying waste of the WRD. A significant increase in VWC at the 100 mm depth was observed from a dry VWC of 0.082, to a wet VWC of 0.318 in January 2017, as a result of infiltration after a rain event of 60 mm in 72 hours (Figure 4-7). This response to the rainfall event is commensurate with the high saturated hydraulic conductivity and rapid infiltration into the vermiculite as discussed in the previous section. The effect of the low unsaturated hydraulic conductivity in the vermiculate cover is also confirmed since the high VWC value only reduced marginally to 0.317 (from 0.318) after 8 days (17 – 25 January) in response to drying. The dryer VWC measured in the underlying waste rock is an indication that the lower unsaturated hydraulic characteristic of the vermiculite cover material is effective in controlling the flux into the waste (L1K1 increases rapidly in January 2017 with L1K2 and L1K3 not showing the same increase – Figure 4-7).

The change in VWC is influenced by the intensity and depth of events as can be seen by responses to events before February 2017 where a relative intense rainfall event, of more than 10 mm fell in 30 minutes, increasing the VWC to a 0.358 (from 0.132) at a depth of 500 mm (L1K2). VWCs in the vermiculite cover and the underlying waste increase after the rain event in late February 2017. During the subsequent drying period the VWC decreases to 0.201 (from 0.224) at a depth of 500 mm after the rainfall event of more than 30 mm of rain on the 27th of January. During February 2017 the VWC at a depth of 500 mm (0.201) was continuously wetter than the dryer VWC (0.173) at a depth of 1000 mm (L1K3). This is evidence of the vermiculite cover controlling the flux into the waste due to its low unsaturated hydraulic conductivity.

There is not always a direct response in VWC to a rain event and an increase with a increase in VWC only generally occurs after precipitation of a certain depth or intensity rainfall event, such as seen from 3 to 20 March 2017 (Figure 4-7). This lack of response is due to the vermiculite cover controlling the flux and evapotranspiration processes that take place continuously reducing VWC and drying the soil over a non-rain period or a period with very low intensity rainfall, as indicated in Figure 4-7 during the 3 to 20 March period, with a change in VWC from 0.209 to 0.180, at a depth of 1000 mm (L1K3).

The measurement of a dry VWC (0.134) at a depth of 1000 mm (L1K3) with dryer VWC (0.100) at depth 100 mm (L1K1) during the dry season of June to August 2017, with the vermiculite waste controlling the flux, is indicative of an interaction of underlying waste with the vermiculite cover, with the upper layers (at least to a depth of 1000 m) receiving water from and contributing water back into the vermiculite cover material. The VWC (0.131) at a depth of 500 mm (L1K2) is generally higher or wetter than at 100 mm (L1K1) during the dry season (June to August 2017), indicating water movement to the surface cover layer for evaporation and transpiration from the underlying waste.

In October 2017 the VWC increased after a rain event of 32.8 mm to VWCs of 0.206 at 100 mm, 0.269 at 500 mm and 0.239 at 1000 mm (Figure 4-7), with the VWC at depth 500 mm slightly more wet than at 1000 mm indicating that the vermiculite within the rock interstices inhibits rapid wetting into the waste rock. Here evapotranspiration losses at the near-surface, inhibit further percolation and deeper wetting. The VWC started a reduction from 0.206 to 0.141 in the month after rain event of 17 October 2017 (L1K1 – Figure 4-6). Similar changes in VWC to a dryer state at depth (500 mm (L1K2) and 1000 mm (L1K3)) during this month indicate the limited deeper wetting. This is evidence that the precipitation was of insufficient intensity or depth to cause wetting of the profile and water was released to evapotranspiration demands following the rain during this period.

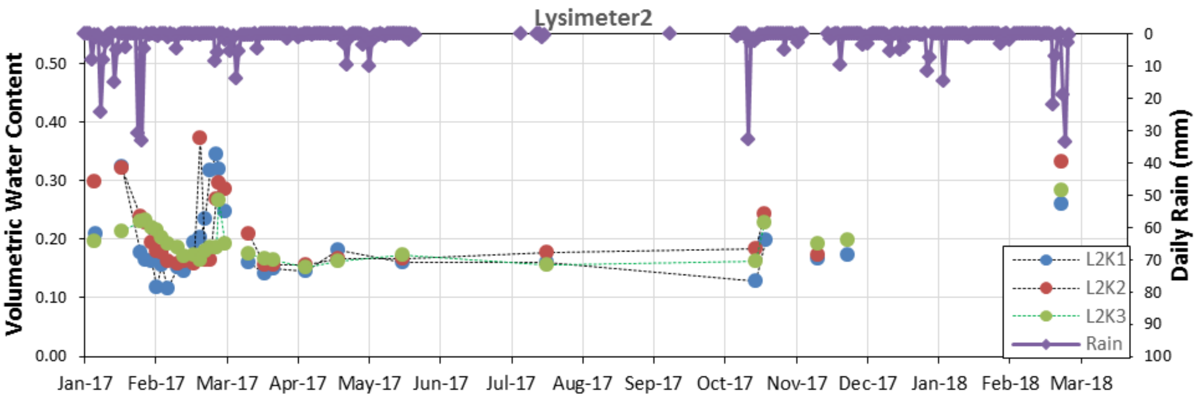


Figure 4-8: Volumetric Water Content and Rainfall time series for Lysimeter 2 (WRD).

Behaviour of soil water dinamics at Lysimeter 2 (Figure 4-8) is very similar to Lysimeter 1 with minor changes that is observed in a bit wetter VWC. This can be seen in the higher VWC 0.268 (L2K2) at 500 mm on the 27th of February compaired to the VWC 0.219 (L1K2) at Lysimeter 1 after an precipitation event. It seems evident that the vermiculite cover material may be a little less effective at Lysimeter 2 as a deeper wetting is allowed with the VWC 0.266 at 1000 mm

(L2K3) with a dryer VWC 0.260 (L1K3) on the 28th of February at Lysimeter 1. However, the minor rainfall events are still inhibited from deeper penetration and water is lost to evaporation with the vermiculite cover controlling the flux.

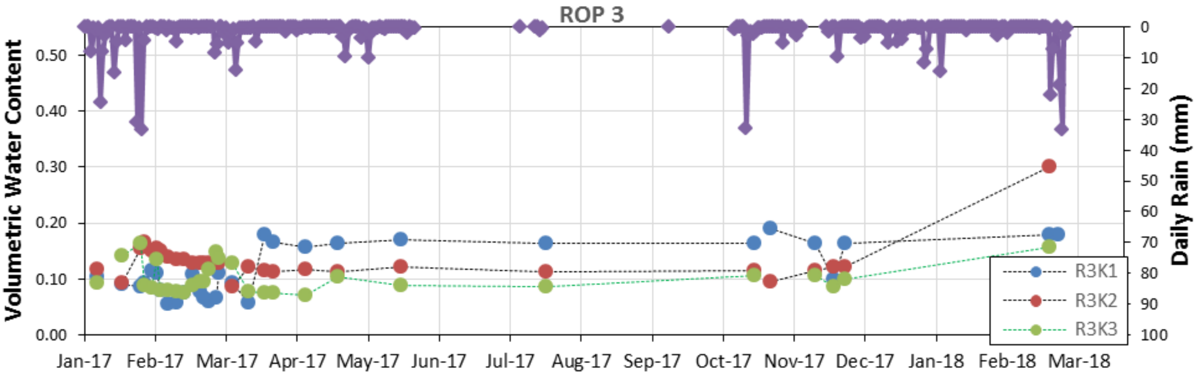


Figure 4-9: Volumetric Water Content and Rainfall time series for Runoff plot 3 (slope = 1:3) (TSF).

Certain differences have been observed between VWC measured at the WRD and at the TSF. Lower VWC change or wetting has been observed at the TSF than at the WRD sites, in response to rain events. The vermiculite cover with the underlying tailings has a generaly more consistent water content during the dry period, indicating to a good water holding capacity. This is due to the strong flux control by the vermiculite cover over the underlying tailings.

At Runoff plot 3 the (VWC) in the vermiculite cover at depth of 100 mm (R3K1) responds to precipitation in late January and mid February 2017. VWC at 500 mm (R3K2) and 1000 mm (R3K3) represent responses in the underlying tailings waste in Figure 4-9. During January 2017 an increase in VWC 0.114 (from 0.085) at 100 mm was recorded in the vermiculite cover material with the underlying waste at depth 500 mm VWC drying from 0.166 to 0.151. Though VWC values show an VWC at depth 100 mm increased from a VWC of 0.093 to 0.114 the VWC at 500 mm dried from 0.166 to 0.151 and the VWC at depth 1000 mm dried from an initial 0.163 to 0.084, after an event of more than 30 mm of precipitation on 24 January. This increase of moisture of the VWC at depth 100 mm and the drying of the VWC at 500 mm and a 1000 mm indicate to the low unsaturated hydraulic capability of the vermiculite cover controlling the flux into the tailings material (Figure 4-9). The rain fall event of 15 mm at the end of February caused an increase in VWC at depth of 100mm from a VWC of 0.065 in mid February to a wetter VWC of 0.111 at the end of February. Similarly at depth 1000 mm there is an increase to a wetter VWC from 0.095 to 0.136 in the same period. Although there is an increase in the WVC at 1000 mm after the rain event the VWC at 500 mm (0.129) in general is more constantly high than the VWC at 1000 mm (Figure 4-9) suggesting moisture movement from depth 1000 mm to 500 mm with the vermiculite cover controlling the flux, in that it retains moisture longer for evaporation and transpiration by having the lower unsaturated hydraulic conductivity, this movement also contribute to hinder the deeper wetting at ROP3. The VWC value at 1000 mm decreases to a dry VWC of 0.085 (from 0.088) in July (Figure 4-9) with the VWC at 100 mm decreasing to 0.163 (from 0.170) indicating that moisture is released for evaporation and transpiration.

In October 2017, an 32 mm rain event caused an increase in VWC of 0.106 (from 0.085) at depth of 1000 mm. This event did not cause a continued increase in VWC although an increase in VWC (0.189) was measured at depth 100 mm in the vermiculite cover material just after the event. This again indicate to vermiculite cover material controlling the flux through it higher unsaturated hydraulic conductivity enabling the cover to retain its WVC longer for release through evapotranspiration . The reduction to a dryer VWC 0.085 (from 0.106) in November 2017 at the depth of 1000 mm after a rain event indicate that evapotranspiration is having an influence on the moisture at this site by reducing the VWC in the tailings as well as in the vermiculite cover from 0.163 to 0.098 with the vermiculite cover controlling the flux.

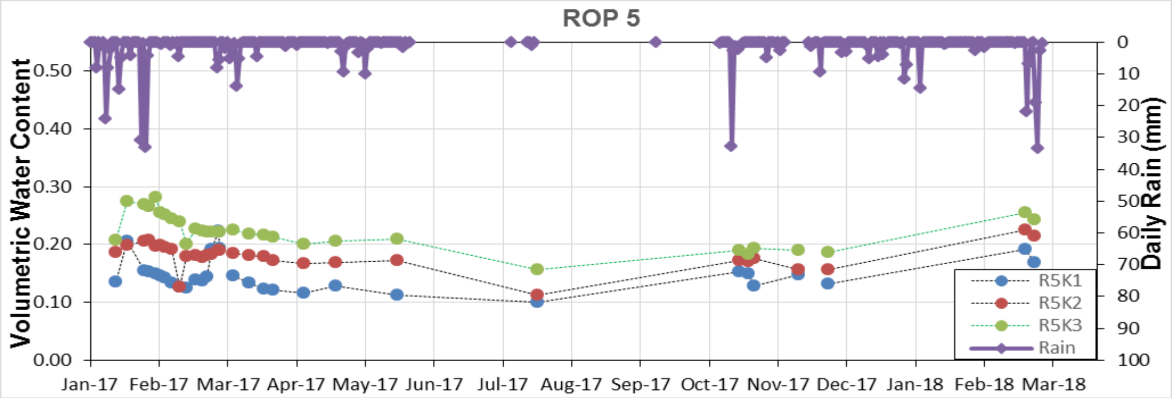


Figure 4-10: Volumetric Water Content and Rainfall time series for Runoff plot 5 (slope = 0) (TSF)

The observed differences in VWC at all three depths between Runoff plot 5 and Runoff plot 3 are related to the differences in hydraulic conductivities, a deeper wetting is observed at ROP5 with the VWC at 1000 mm remaining higher in general than at ROP3. The vermiculite cover is as an opposite more dry in general than when compared to the vermiculite cover at ROP3. This more dry vermiculite cover could induce a flow gradient from the tailings into the vermiculite cover due to the vermiculite's ability to control the flux and hence a interaction between tailings and cover material.

At Runoff plot 5 which has an 0 slope the VWC at a depth of 100 mm (R5K1) below surface reflects the water content of the vermiculite cover. The interaction between the vermiculite cover and the underlying waste can be observed by a drying VWC of 0.154 (from 0.206) at a depth of 100 mm after a rain event in January 2017 (Figure 4-10). The VWC at depth 1000 mm (R5K3) over the same period decreased from 0.274 to a dryer of 0.269. After this VWC decrease there is a further drying of the VWC at a depth of 1000 mm to 0.265 with the VWC at depth 100 mm, 0.153 drying from 0.154. The WVC at 500 mm, increase to 0.207 from 0.206 during this same period thus getting more moisture. This decrease in the VWC at depth 1000 mm and increase in moisture at 500 mm be an indication of the flow gradient towards the surface and water being made available by the vermiculite cover for evaporation and transpiration. The drying of the VWC to 0.157 (from 0.209), at depth 1000 mm of the tailings material during the dry season (July to August 2017), with the VWC of the vermiculite cover drying more to 0.100 may be a further indication of the vermiculite controlling the flux and a upward flow gradient.

An increase of VWC to 0.153 from 0.100 in the vermiculite cover can be observed after the October 2017 precipitation event of 32 mm. The vermiculite cover though remains dryer than the underlying tailings with a VWC values of 0.173 and 0.189 at 500 mm and 1000 mm respectively therefore systaining the upward flow gradient (Table 4-2). The capability of vermiculite cover controlling the flux can also be observed after precipitation in February 2018. Where after an event of 33mm a wet VWC of 0.191 at depth 100 mm dried to a VWC of 0.168, with the VWC at depth 500 mm drying to 0.214 (from 0.243) and at depth 1000 mm drying to 0.243 (from 0.254). Thus indicating that the vermiculite waste made moisture available for evaporation and transpiration by controlling the flux.

The reduction in the VWC to a dryer VWC after each mentioned precipitation event in Figure 4-10 indicates the evapotranspiration influence on the VWC in the vermiculite waste cover and the vermiculite cover controlling the flux. It is observed almost throughout the ROP5 time series record that the vermiculite layer is drying out more than the underlying tailings at 500 mm and 1000 mm, this could induce an upward flow gradient from the tailings to the vermiculite cover material. It is this mentioned loss of moisture from the vermiculite cover that create an upward flow gradient after rain events and may also indicate to the interaction of the underlying waste with the vermiculite cover. The lack of continued increase in the recorded VWC values or moisture at depth 500 mm (R5K2) and 1000 mm (R5K3) indicate the lack of deeper wetting as well as the capability of the vermiculite cover to store and release precipitation (Figure 4-10).

4.4 RUNOFF AND SEEPAGE

Runoff of two sites, one level (Runoff plot 5) and one sloped (Runoff plot 3) on the tailings storage facility are compared as data at these sites could be recorded most consistently and with ROP5 the only site on a level slope.

4.4.1 Runoff and seepage comparison of a sloped site with a more level site on the Tailings Storage Facility area.

At Runoff Plot 3 (ROP3) for the period of January 2017 to February 2018 (Figure 4-11) it is seen that the steep slope of 1:3 yields only 7.1 mm (2%) runoff for the entire period with a total precipitation of 441.4 mm. Though this is perceived as very little runoff, it can be accounted for by the high saturated conductivity of the vermiculite waste cover as seen in the hydraulic characteristics of the vermiculite waste cover (Table 3), where the saturated hydraulic conductivity of vermiculite waste can be compared with that of a sandy loam type of soil. The precipitation at Runoff Plot 5 for the period January 2017 to February 2018 (Figure 4-12) of 441.4 mm only produced 5.9 mm (1.3%) runoff in total for the period. This not a major difference for a runoff on a 1:3 slope (ROP3) compared with a site with a slope = 0 (ROP5). The relative high runoff at Runoff Plot 5 may be attributed to the lower saturated hydraulic conductivities of ROP5 as described by the hydraulic conductivity characteristics of runoff Plot 5 (Figure 4-4).

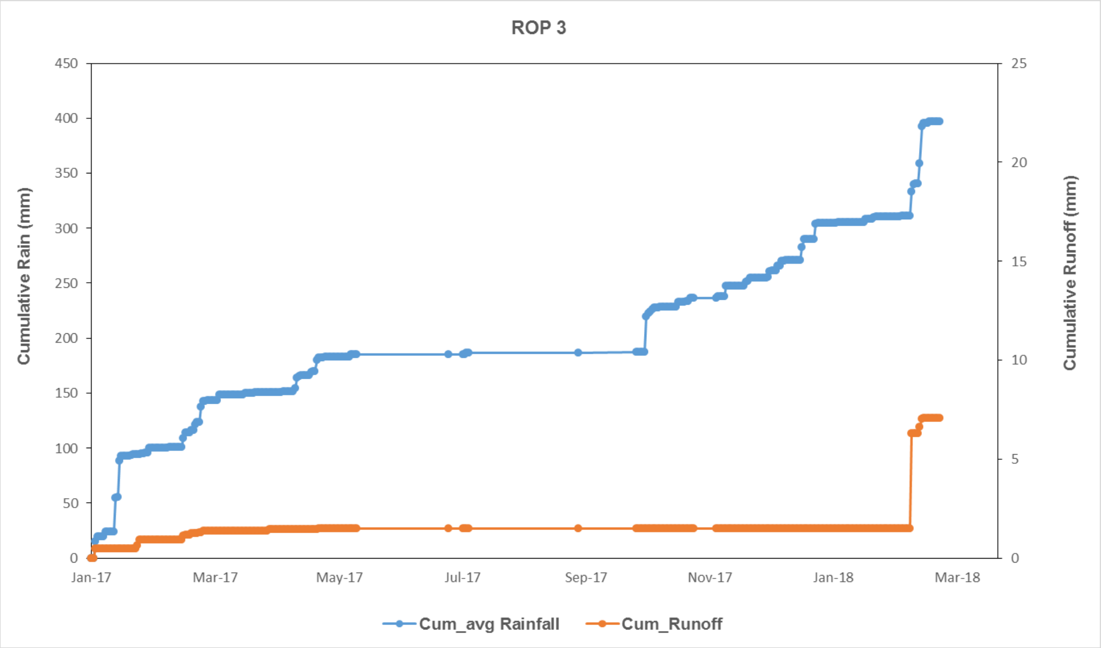


Figure 4-11: Rainfall and Runoff at Runoff plot 3 (slope 1:3) (TSF)

Comparing Runoff Plot 3 and 5 the runoff does not always occur in response to precipitation according to records obtained during rain events in April 2017 and October 2017 at Runoff Plot 3 and 5 (Figures 4-11 & 4-12). This may be attributed to the infiltration capability of the vermiculite waste cover, the antecedent conditions as well as the intensity of the rain event. During the April 2017 event 31 mm of rain precipitated in 15 days and in October 2017, 41 mm of rain precipitated in 8 days. When this is compared with the rainfall event in February 2018, where more than 81 mm of rain precipitated in 6 days, with 52 mm of the rain event precipitating in just 2 days. This event had an intensity that produced more runoff and had a much higher rainfall intensity than when this event data was compared to the data of the previously mentioned two rainfall periods with lower rainfall intensities, this indicates that a rain event of a certain intensity would be needed before runoff is produced.

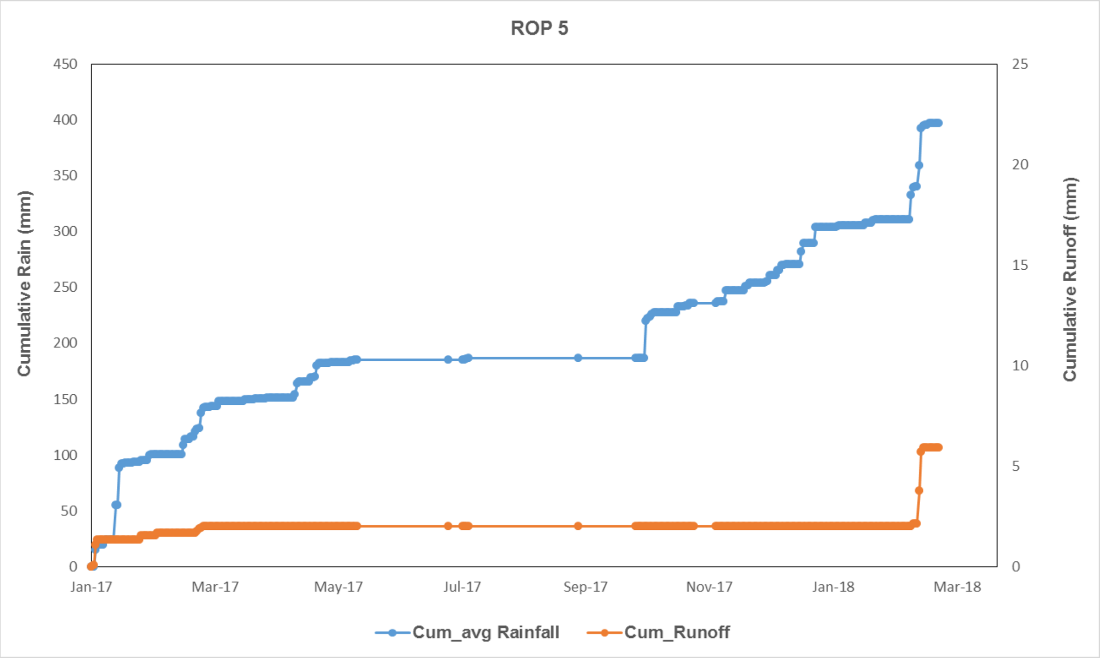


Figure 4-12: Rainfall and Runoff at Runoff plot 5 (slope = 0) (TSF).

4.4.2 Infiltration and seepage at the Waste Rock Dump.

At Lysimeter 1 for the period from January 2017 to February 2018, only 1.5 mm of seepage is recorded for the entire period with a total precipitation of 441 mm. No runoff evidence was observed at Lysimeter1 and after the site hydraulic conductivity results was assessed, it was expected that of the 441 mm of rain that precipitated at this site, 100% of the precipitation either infiltrated or evaporated due to the nature of the cover material. It was observed with the hydraulic conductivity characteristic measurements (Figure 4-5) that the vermiculite cover at the Lysimeter site had a high saturated conductivity which confirmed the validity of the infiltration records after and during precipitation at this site. It was seen during the excavation of the Lysimeter sites that the fine vermiculite material migrated deep into the waste rock, up to 2 meters (Figure 4-6) which can also contribute to the infiltration capability at these sites. At this site (Figure 4-13) the seepage was recorded only after a higher intensity rainfall event but not directly after. This lag in seepage recording can be seen during the February 2018 event where the event started on the 16th of February 2018 and the seepage was only recorded on the 22nd of February 2018. The lag in the recording as well as the limited amount of seepage may be in part be attributed to the low unsaturated hydraulic conductivity (Figure 4-5) of the vermiculite cover and the fine vermiculite particles that migrated deep into the WRD at this site. A further contribution to the limited seepage that was observed may be evapotranspiration taking place at this site. Potential evaporation for the project area was estimated as 1774 mm A-pan evaporation per annum. This was estimated from the S-pan evaporation listing in the South African Water Resource database. With the area measuring only an annual average precipitation of 508 mm it could be said that evapotranspiration plays a major role in limiting seepage.

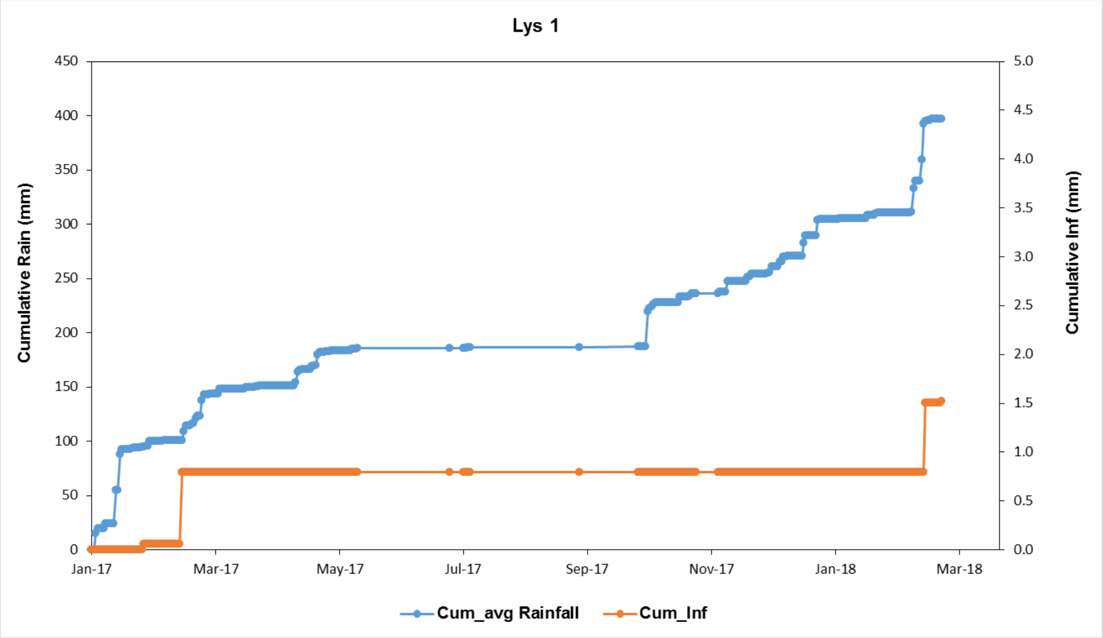


Figure 4-13: Rainfall and Seepage at waste rock Lysimeter 1 plot (WRD)

All runoff plot data available are shown in the Appendix with no significant differences were noted on the TSF runoff plots, exept for those discussed, with minimal runoff for 1:3 sloped sites, for the 441mm received during the study period. This correspond with the mentioned high saturated conductivity of the vermiculite cover material.

4.4.3 Evaluating runoff data from specific events

A more detailed series of events including a relative high intensity rainfall event, of 81 mm, and runoff plot discharges, from 14 February 2018 until 28 February 2018 are shown for Runoff Plot 3 in Figure 4-14 and for Runoff Plot 5 in Figure 4-15. Comparing these sites, it reveals that the steep slope of 1:3 yields more runoff (5.6 mm or 7%) than the runoff plot on the tailings surface with a slope of almost 0 (3.9 mm or 5%) which is not much difference in runoff when comparing a sloped site of 1:3 with a flat site.

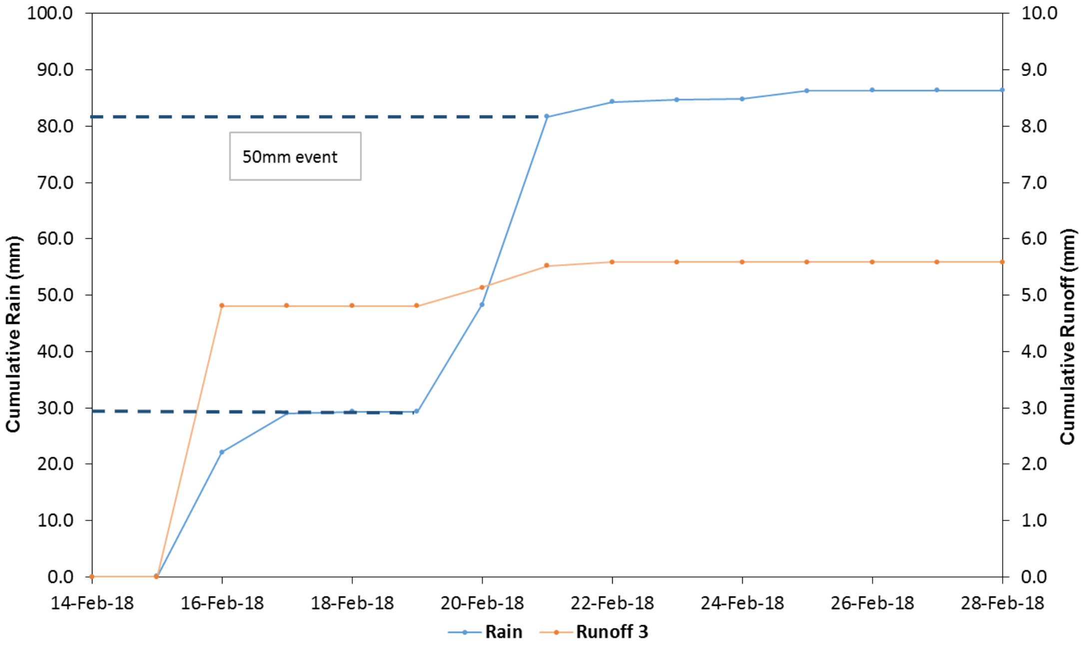


Figure 4-14: Rainfall and Runoff time series at Runoff plot 3 (slope 1:3)

Some 75.4 mm (93%) of precipitation infiltrated at the Runoff plot 3 side slope site (Figure 4-14), while 77.1 mm (95%) infiltrated at the flat plot, Runoff Plot 5 (Figure 4-15). This surprisingly small difference in the runoff (5%-7%) and infiltration volumes suggest again to a high infiltration capability of the vermiculite waste cover. The higher runoff percentage during a higher intensity rainfall event also indicates that with prolonged high precipitation intensity more runoff can be expected. The lack of deeper wetting was indicated by the TDR soil volumetric water content probes (Figure 4-10) for the period of February 2018 at runoff plot 5, by not indicating consistent elevated or wetter VWC at depth it can indicate that there is no major seepage with this amount of precipitation. This lack of deeper wetting further suggests to the high water retention capability in the vermiculite waste cover as seen by its low unsaturated hydraulic conductivity (Table 4-3). Vegetation root depth at the tailings facility site was observed as not deeper than 500 mm. When these results are compared to the waste rock Lysimeter 1, the infiltration at the Lysimeter site yielded approximately 0.7 mm or 0.9% of seepage for the same period and rainfall (Figure 4-18) at 2 meters below surface. Indicating that the vermiculite fines within the waste rock matrix are highly effective in retaining the ingress of rainfall. Root depth was observed as up to 2 meters below surface at the waste rock dump facility with very few deeper roots detected (Figure 4-6). Indicating that evapotranspiration contributes to the low seepage and the ability of the vermiculite waste cover to retain precipitation, as the vegetation roots will assist in the moisture uptake of infiltrated precipitation.

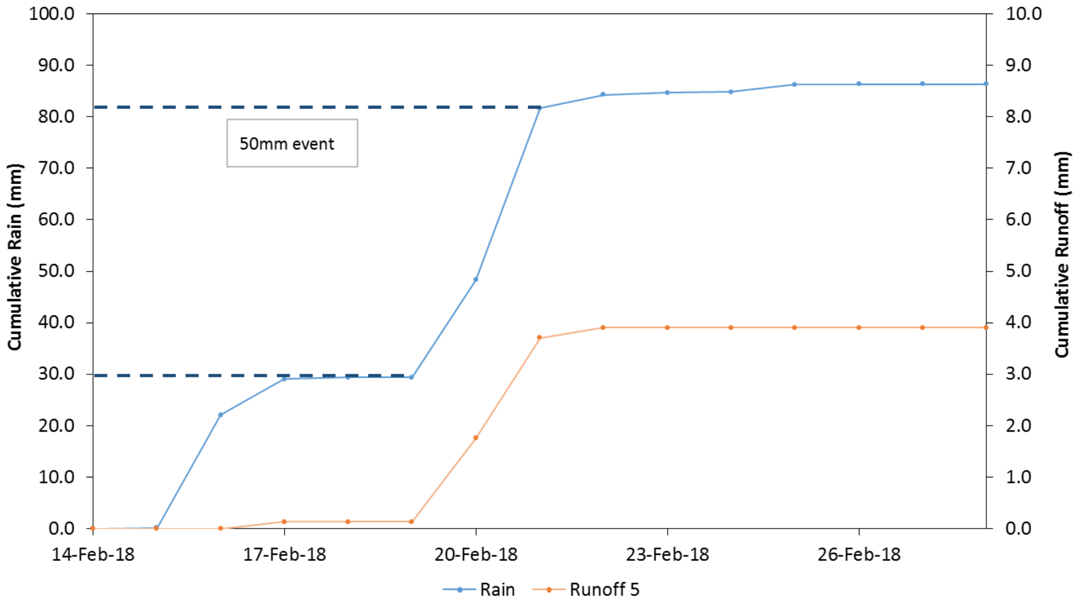


Figure 4-15: Rainfall and Runoff time series at Runoff plot 5 (slope = 0)

The effect of event intensity as indicated by data obtained from the events from 14 February to 28 February 2018 at Runoff Plot 3 (figure 4-14), shows very little runoff for the 1:3 sloped area as observed by the volume calculated from the tipping bucket record. The change with the increase of precipitation between 19 February 2018 and 21 February 2019 shows very little increase in runoff. This may indicate again to the high infiltration capability of the vermiculite waste cover at this site. But it can also be seen that the first rainfall event on 16 February happened at a much higher intensity (22 mm) over a period of less than 12 hours. This event at runoff plot 3 produced more runoff (4.8 mm), where the second event (33 mm) happened over a period of more than 24 hours, which would give the precipitation more time to infiltrate than when compared with the previous event and produced less runoff (0.4 mm). This comparison indicates that rain intensity has an influence on infiltration capability of the vermiculite waste.

Data for runoff plot 3 (Figure 4-16) shows little runoff for the event time series 23 Dec 2016 to 4 Jan 2017 as observed from the data obtained from the rainfall event during this time period. During this period 64mm of precipitation only produced a cumulative runoff of 2.2 mm. This means that 61.8 mm infiltrated into the vermiculite waste cover. Taking into account that the site has a slope of 1:3 this is only 3.2% runoff. This indicates again to the high infiltration capability of the vermiculite waste cover (96.8%). The results at this site also indicate that with an increase in precipitation over time, the runoff at the site increase as well, but not linear. It can be seen during a rain event of 25 mm from 26 to 29 December that there was only 1.8 mm runoff (7.2%), with a previous 8 mm rain approximately only 0.4 mm runoff was recorded (5%).

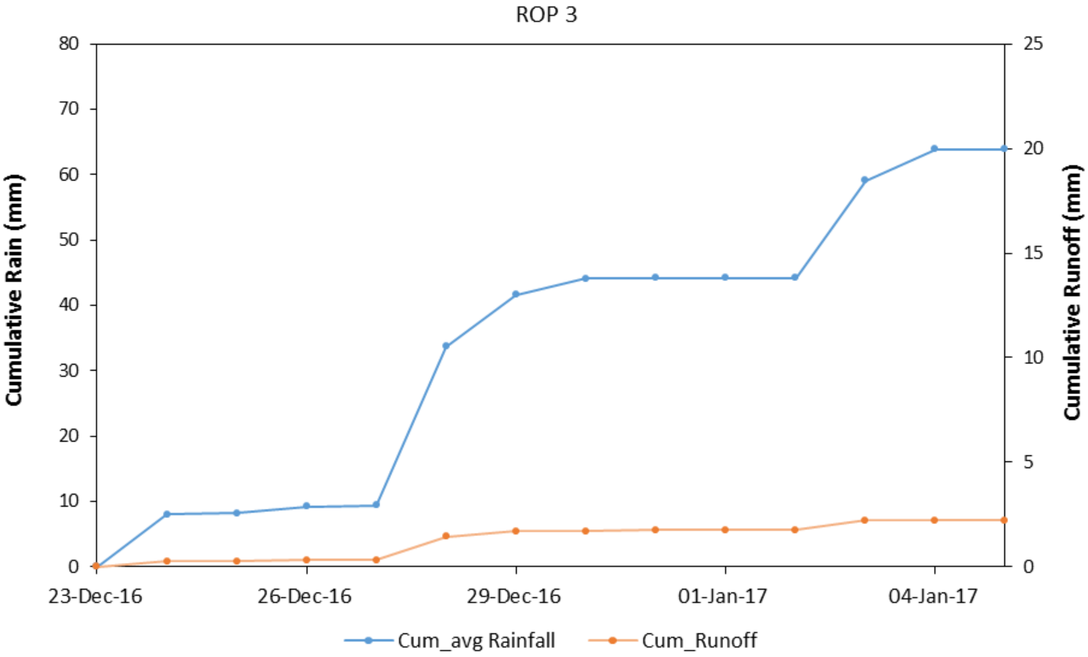


Figure 4-16: Rainfall and Runoff time series at Runoff plot 3 (slope 1:3)

This small amount of runoff can be contributed to cover material being not yet saturated. As seen with the soil volumetric water content data series at ROP 3 using TDR sensors (Figure 4-9), there is at the beginning of January 2017 only low or dryer VWC measured with a VWC value of around 0.1 at a depth of 100 mm in the vermiculite waste cover. As mentioned the absence of deep wetting indicated to the vermiculite cover material’s capability to retain water. The lower runoff detected at runoff plot 3 may also again be indicative of the high infiltration capability of the vermiculite waste when not saturated and un-compacted.

The percentage of measured runoff at runoff plot 3 for the different time series of events indicate that the runoff is very low for a sampling site with a slope of 1:3.

The runoff range is calculated as between 2-7% for the time period December 2016 until March 2018. This may again indicate to the high saturated hydraulic conductivity of the vermiculite waste cover.

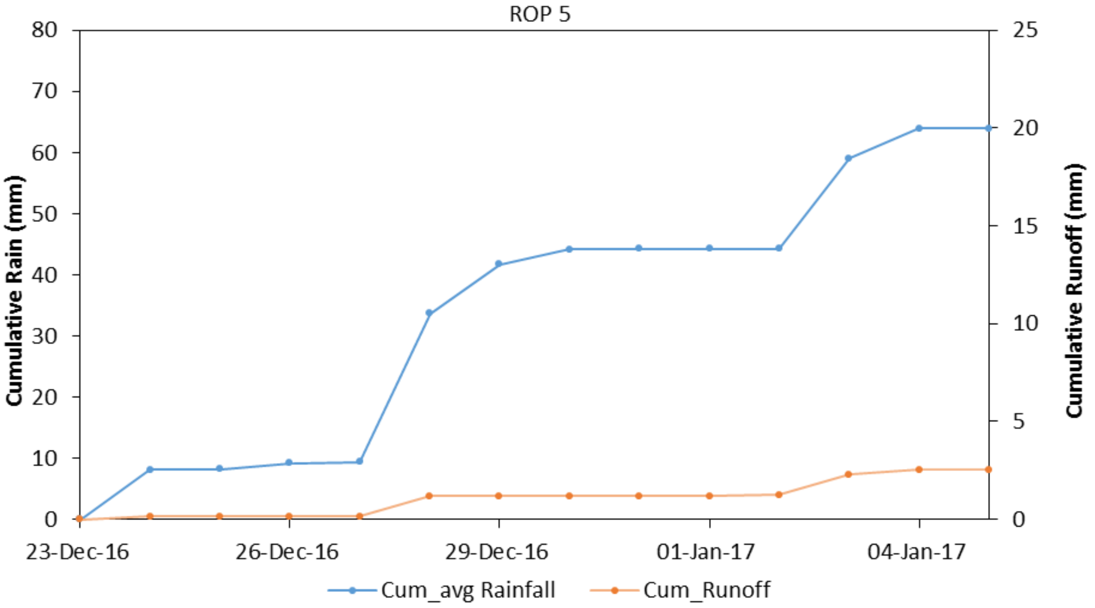


Figure 4-17: Rainfall and Runoff time series at Runoff plot 5 (slope = 0)

Runoff Plot (ROP5) shows little runoff for the time series 23 Dec 2016 to 4 Jan 2017 (Figure 4-17) as observed from the data obtained from the rainfall event during this time period. During this period 64mm of precipitation only produced a cumulative runoff of 2.5 mm (3.9%). This supports the high infiltration capability of the vermiculite cover material. The results also indicate that with an increase in precipitation over time, the runoff at the site increase as well, but not linear to the precipitation. This can be attributed to cover material being at more saturated levels compared to earlier dates. It was seen at the beginning of January 2017 that with the TDR probes a lower dryer VWC was measured (Figure 4-10) with a VWC value of around 0.136 at a depth of 100 mm in the vermiculite cover with the VWC increasing to 0.206 after an additional rain event of 30 mm on the 13th of January, with also the intensity of one rain event being higher than the previous one. During 24 December 8 mm of precipitation fell within a period of an hour that allowed for 0.1 mm of runoff where on 28 December 24 mm precipitation took place in a period of 2 hours that allowed for 1.1 mm of runoff, indicating again that the precipitation intensity also has an effect on the runoff volume. The reduced runoff at the site may again be attributed to evapotranspiration continually taking place; this will allow the vermiculite cover material to keep its infiltration capability by lowering the VWC of the vermiculite cover material. As was seen with soil volumetric water content data series using TDR sensors there is an absence of deep wetting indicating the cover's ability to retain and release water at this site.

At Runoff Plot 5 for the period 14-28 February 2018 (Figure 4-15) approximately 30 mm of accumulated precipitation occured in 24 hours (16-17 February), this was needed before any surface flow was generated. This supports the high infiltration capability findings of the vermiculite cover. Changes in the soil VWC for the period 26 February to 2 March 2018 (Figure 4-10) indicate that evapotranspiration plays a major role in the soil water dynamics at the sampling site. To support this we can consider that the wetter VWC measured at a value of 0.191 at depth of 100 mm in the vermiculite waste cover after the rain event on 26 February, with the following dryer VWC measuring a lower value of 0.168 on the 2 of March at a depth of 100 mm.

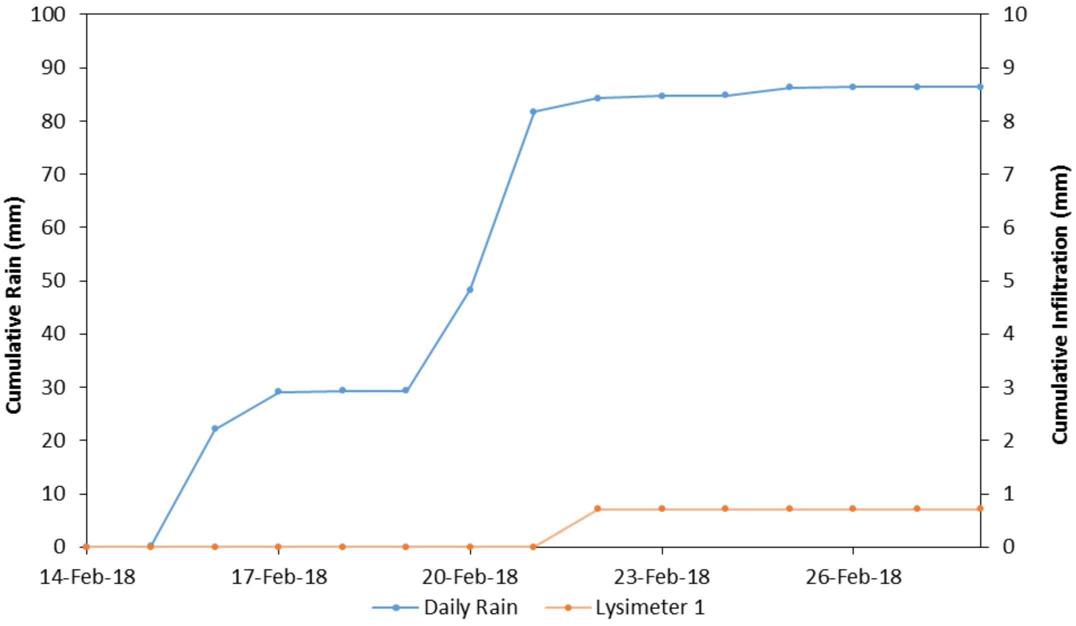


Figure 4-18: Rainfall and Seepage at the waste rock plot, Lysimeter 1.

The seepage at WRD Lysimeter1 (Figure 4-18) for the specific time series of 14 February 2018 to 28 February 2018, indicated major infiltration at the site. Since there was no runoff however, the effectiveness of the vermiculite waste capability as a store and release cover was supported by the deep percolation of precipitation at 2 meters that yielded just 0.7 mm of seepage. This also indicates that the vermiculite fines within the waste rock matrix are highly effective in retaining the ingress of rainfall during this event and releasing the water to evaporation, either by upward capillary flow or by vapour diffusion. There is also an indication that there is a lag between the precipitation event with 22 mm of precipitation and the infiltration of the precipitation being captured on 16 February to 20 February with 18.9 mm on the 20th and 33.4 mm on the 21st. Seepage only started to be recorded on the 22nd of February 2018. This can be attributed as discussed before, in part due to the low unsaturated conductivity of the vermiculite cover material and the vermiculite fines that migrated deeop into the waste rock dump. The seepage also only continued during the 22nd of February, were after no seepage was recorded even with a recorded 5 mm of precipitation that was received on the 26th of February 2018. The evapotranspiration in the area, as discussed, are also attributing to the low seepage in allowing vermiculite cover to retain the ability to absorb and retain precipitation. Root depth was observed as up to 2 meters at the waste rock dump facility with very few deeper roots detected (Figure 4-6) confirming the role of evapotranspiration at this site.

4.5 WATER BALANCE

While the main purpose of this study was to provide observations and quantification of components of the water balance, a simple simulation, using HYDRUS-1D (Šimůnek et al., 2006) has been performed initially, to quantify net fluxes, which are not measured directly.The water balance in the tailings and waste rock is simulated using measured material properties and confirmed against observations. The soil water balance, resulting in the estimated evapotranspiration and seepage components in the TSF and the evapotranspiration in the waste rock were simulated, using the observed soil volumetric water content measured by the TDR probes at depth and runoff as calibration in the tailings. Volumetric water content and seepage was used as calibration in the waste rock dump. The surface runoff in the TSF and the seepage in WRD were confirmed through observed fluxes.

4.5.1 HYDRUS Simulations

A 2 meter deep profile was simulated in the tailings ROP3 and ROP5 sites and at the waste rock LYS1 site. Atmospheric boundary conditions were specified at the upper surface of the profiles to allow rain and potential evapotranspiration inputs. At the tailings sites, the lower boundary condition was specified as free drainage, while the waste rock lysimeter simulation had a seepage face lower boundary condition. The rooting depths at the tailings sites was restricted to the vermiculite cover layer, while at the lysimeter, where vermiculite fines had infiltrated into the waste rock matrix, and roots observed well into the rock waste, the rooting zone was specified to a depth of 1 200 mm. Daily observed rainfall and potential evapotranspiration (PET), based on S-Pan observations, were applied at the atmospheric surface boundary. The PET was divided into potential evaporation and potential transpiration drivers using a crop factor, whereby 80% of the PET was assigned to evaporation and 20% to transpiration. These fractions were dictated by the observed responses and derived during the modelling. In order to match the simulated water contents with those observed at each depth over the simulation period, as well as ensuring the model simulated the observed runoff. The hydraulic conducitivites of the material required significant reduction. In fact the measured hydraulic conductivities at 16 mm of tension used as a start, but required further reduction in the tailings sites by between 20% and 90%. At the lysimeter site, the cover material required a reduction of 65% from observed Ksat, while the Ksat measured below surface . The lysimeter site required no adjustment in the modelling.

Resultant simulated and observed water contents at ROP3 and the associated runoff are illustrated in Figures 4-19 and 4-20.

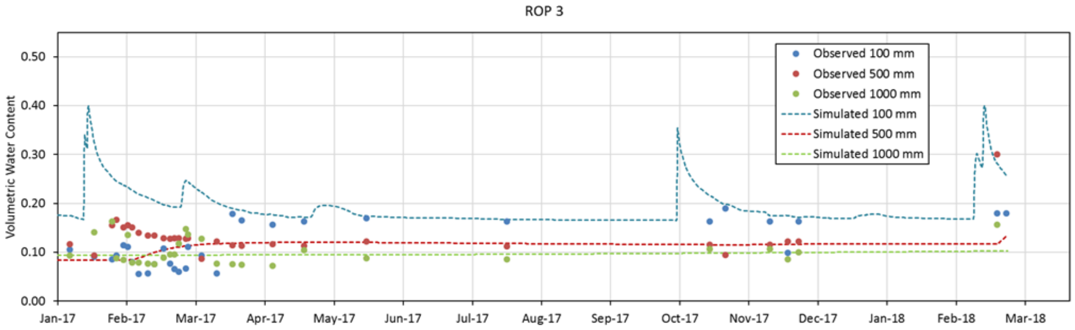


Figure 4-19: Comparison of simulated and observed water contents at Runoff plot 3.

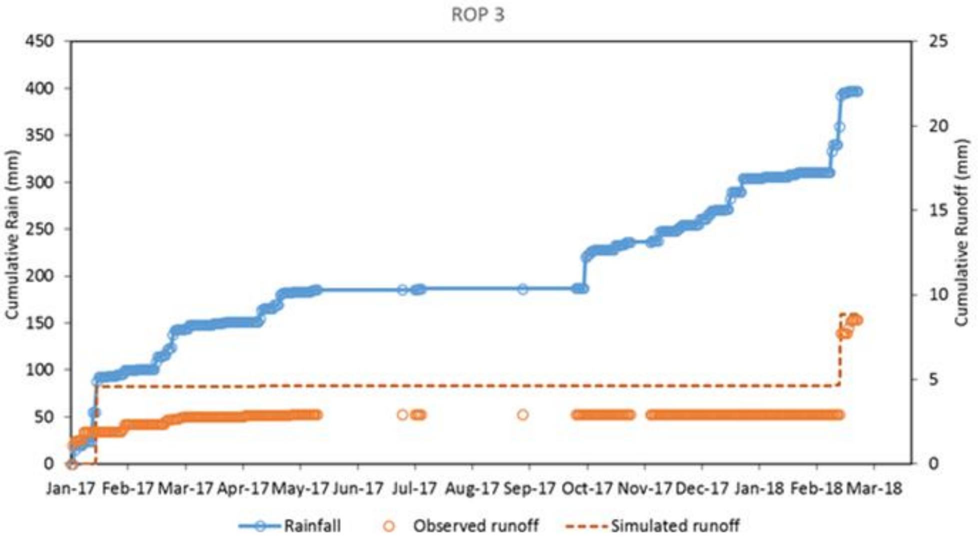


Figure 4-20: Comparison of simulated and observed runoff at runoff plot 3.

It is evident that the simulated ingress of water to the tailings is not faithfully simulated at all times as can be seen by the lack of response of the simulated water content at 500 mm during the events of late January 2017 (Figure 4-19). In addition, the single simulated runoff response in the same period does not follow the observed cumulative runoff between January and March. The simulation could be improved by considering a dual permeability material, where high hydraulic conducitivities are permitted during intense events, and allowing deeper wetting to occur, but significantly lower conductivities at small soil water tensions. Similar responses are observed at Runoff Plot 5 in Figures 4-21 and 4-22 although the simulated and observed responses at 500 mm are closer than for ROP3. Interesting to note is that the lower layers in the flat ROP5 are wetter than the upper layers, unlike at the sloped ROP3. This has been verified by the existence of marshy areas in the flat, top surface, where the surface elevations drop at depressions in the surface. This, despite the ROP5 area being long since closed and rehabilitated.

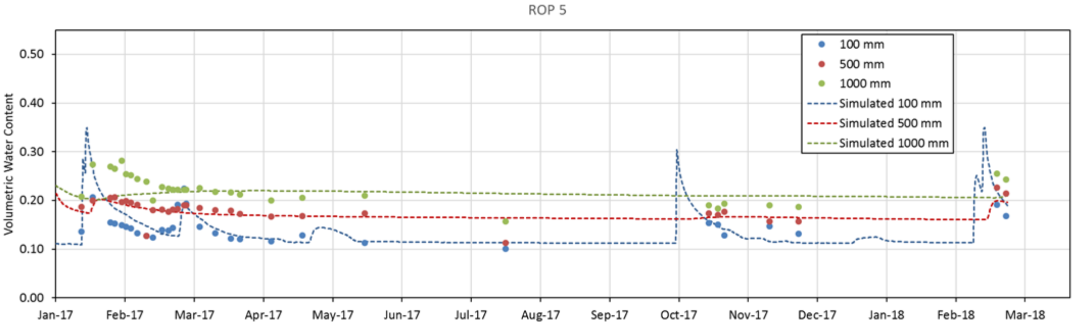


Figure 4-21: Comparison of simulated and observed water contents at Runoff Plot 5.

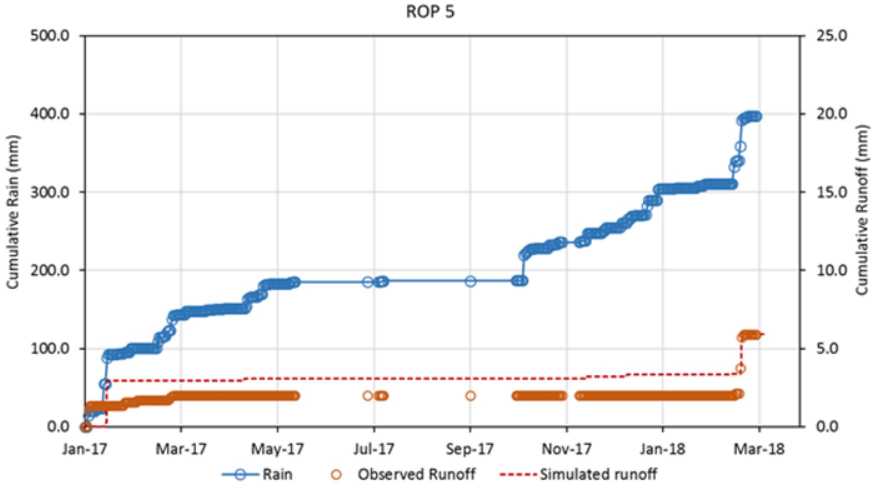


Figure 4-22: Comparison of simulated and observed runoff at Runoff Plot 5

The need for higher conducitivities at the wet end of the characteristic are again evident in the waste rock simulation of Lysimeter 1, where deep wetting is not simulated to the degree observed (Figure 4-23). Seepage events are faithfully simulated (Figure 4-24), although the simulated responses appear retarded in time, compared to the rapid observed responses. Again, this warrants the higher hydraulic conductivities during high rainfall events and saturated surface layers.

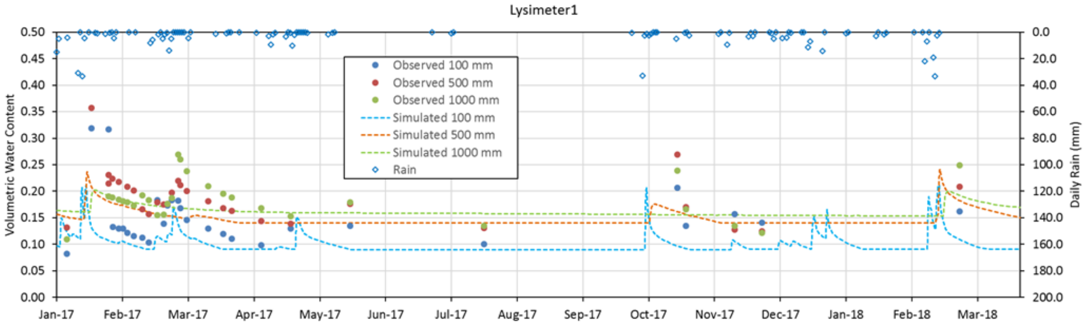


Figure 4-23: Comparison of simulated and observed water content at Lysimeter 1

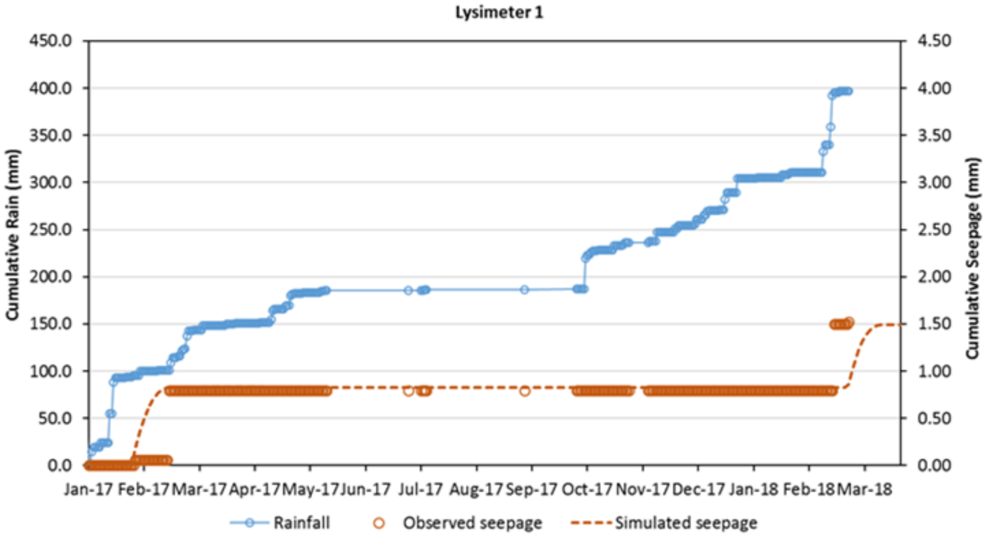
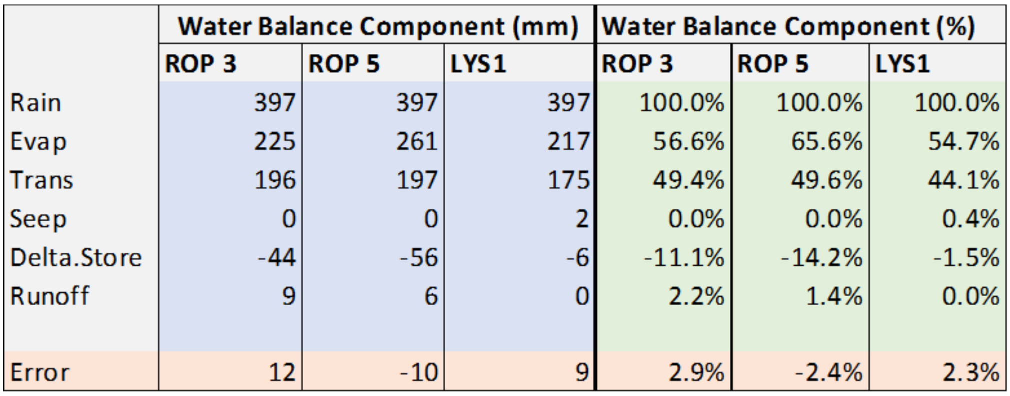


Figure 4-24: Comparison of simulated and observed seepage at Lysimeter 1

A summary of the simulated water balance components is presented in Table 4-4. Here, it is clear that the evapotranspiration process is by far the most significant component of the water balance, being over 100% of the rainfall, in the tailings sites, where antecedent water has been extracted from the profile during the monitoring period.

Table 4-2: Summary of the simulated water balance components



	Water Balance Component (mm)			Water Balance Component (%)		
	ROP 3	ROP 5	LYS1	ROP 3	ROP 5	LYS1
Rain	397	397	397	100.0%	100.0%	100.0%
Evap	225	261	217	56.6%	65.6%	54.7%
Trans	196	197	175	49.4%	49.6%	44.1%
Seep	0	0	2	0.0%	0.0%	0.4%
Delta.Store	-44	-56	-6	-11.1%	-14.2%	-1.5%
Runoff	9	6	0	2.2%	1.4%	0.0%
Error	12	-10	9	2.9%	-2.4%	2.3%

4.5.2 Water Balance Components

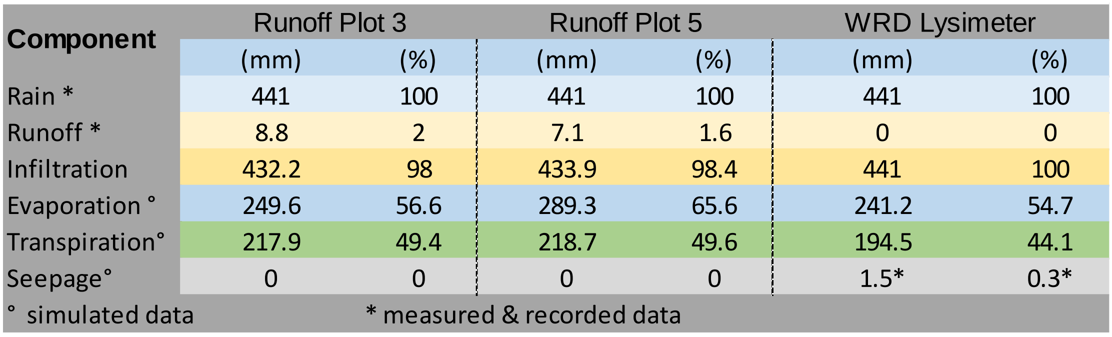
At the runoff plot 3 site with a slope of 1:3 (Figure 4-11) the precipitation for the time period December 2016 to February 2018 in terms of contribution to the site water balance, was recorded for the time period as an average 441 mm of precipitation received. This amount of precipitation only produced 7.1 mm runoff for the mentioned period which is very low being only 2% of the precipitation. It is observed (Figure 4-11) through the representative data, that for this site, that the vermiculite waste cover has a major contribution, with its hydraulic characteristics (Table 4-2 & 4-3), to the water balance of the TSF. This is mainly due to its related ability to store and make moisture available for evaporation and transpiration.

At the runoff plot 5 site with a slope of 0, in terms of contribution to the site water balance, similar results is oberved as at the runoff plot 3 site (Figure 4-11 & 4-12). Precipitation of 441 mm only produced 5.9 mm of runoff for the period of December 2016 until February 2018. This is only 1.3% of precipitation. Taking results into consideration, that there is an absence of deep wetting as indicated by the volumetric water content measurements at depth and the low unsaturated hydraulic conductivities of vermiculite waste, it indicates to evapotranspiration as a main contributor to the sites water balance (Table 4-4).

Seepage measured at the Lysimeters on the WRD confirms the evapotranspiration driver of the water balance with only 1.5 mm of the 441 mm precipitation infiltrating beyond 2 meters during this period which is only 0.3% seepage of the 441 mm precipitation. As mentioned vegetation root depth was observed up to 2 meters deep at the mentioned WRD Lysimeters. Again indicating that with the unsaturated hydraulic conductivity of vermiculite waste, evapotranspiration will be a major contributor to the site water balance with vegetation abstracting water from the vermiculite waste.

The resultant water balance is summarised in Table 4-5, showing volumetric water balance components in mm and as a percentage of total rainfall during the observation period from 21 December 2016 to 2 March 2018 (Figures 4-11 to 4-12). The total rainfall observed during the period was very low (441 mm) and produced very little runoff (1.3% - 2%) or seepage (0.3%). This rainfall can be typical of the savanna in which the site is located, but is considered a low rainfall sequence during a relative dry period.

Table 4-3: Summary of the site Water Balance



Component	Runoff Plot 3		Runoff Plot 5		WRD Lysimeter	
	(mm)	(%)	(mm)	(%)	(mm)	(%)
Rain *	441	100	441	100	441	100
Runoff *	8.8	2	7.1	1.6	0	0
Infiltration	432.2	98	433.9	98.4	441	100
Evaporation °	249.6	56.6	289.3	65.6	241.2	54.7
Transpiration°	217.9	49.4	218.7	49.6	194.5	44.1
Seepage°	0	0	0	0	1.5*	0.3*

° simulated data

* measured & recorded data

In the TSF, runoff varies from 2% (sloped surface) to 1.6% (flat surface) of the rainfall for the entire time series. For shorter time series runoff varies from 7% (sloped surface) to 5% (flat surface) of the rainfall (Figure 4-14 & 4-15) for the period of 14 February 2018 until 28 February 2018 and the amount is dependent on the intensity of the rainfall event. Simulated seepage average 6.4% of the rainfall for the sloped and flat surfaces, while the evapotranspiration losses comprise more than 100% of the rainfall total.

In the WRD lysimeters, no runoff was observed, while seepage comprised only 0.3% of the rainfall recorded during the observation period. Here, the evapotranspiration is estimated to comprise over 99% of the rainfall. This is deemed feasible as attributing vegetation rooting systems were observed in the entire 2 m of the WRD upper profile that contribute to evapotranspiration. It was observed though that there are seepage below the WRD, the sources of these seepage points should still be confirmed.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Preliminary examination of the three years of monitoring the tailings and waste rock sites indicate that the vermiculite cover materials over the tailings and within and over the waste rock provides an excellent medium for allowing infiltration of rainwater at the surface, but also provides an effective storage medium for later release of water to evapotranspiration demands. The little variation in runoff observed from the data collected for the period December 2016 to March 2018 confirms the infiltration findings and the low percentage seepage observed confirms that vermiculite waste provides and effective storage medium unders the conditions measured.

- The high saturated hydraulic conductivity of vermiculite waste as well as the low runoff volumes at the runoff plots where vermiculite waste has been used as cover material, confirms the infiltration capability of the vermiculite waste cover This confirms an inward flux under high rainfall conditions.

- Runoff percentages were observed between 1.3 to 2% of precipitation, confirming vermiculite waste's infiltration capability. With seepage as little as 0.3% into the waste rock dump, confirming vermiculite waste's water retention capability. The low seepage during high rainfall events indicates that vermiculite controls the flux into the waste rock.

- High unsaturated hydraulic conductivity values ensured the effectivity of vermiculite waste as a storage medium, equating its behaviour to that of a loam type soil.

- The volumetric water content measurements confirmed, through the lack of deeper wetting, that vermiculite does not readily under the measured conditions allowt excesive percolation into the underlying tailings waste, thereby confirming the vermiculite cover's ability to control the flux.

- The changes in volumetric water content at specific depths indicate that there is an ongoing interaction between the vermiculite cover material and the underlying waste, making water available for vegetation use and evaporation through the vermiculite layer.

It is recommended that, because the data collection period fell within a drought period, the study be extended to include periods of average rain as well as above average rain. Observations and measurements during the extended study should assist to confirm the vermiculite waste cover’s ability to perform and control the flux under different conditions. Further modelling with additional data and calibration will give a more accurate indication of the vermiculite waste covers’ contribution to the site’s waterbalance and the flux interactions at the cover and waste interfaces.

The findings of this study will greatly assist in accurately determining the site’s water balance, to plan for water management structures, as well as to either change the current cover design or to have confidence in the current design, during the current operational phase and the closure phase of the mine. Furthermore, the measurements and observations have been invaluable in calibrating current and future water balance modelling for the waste facility’s water balance.

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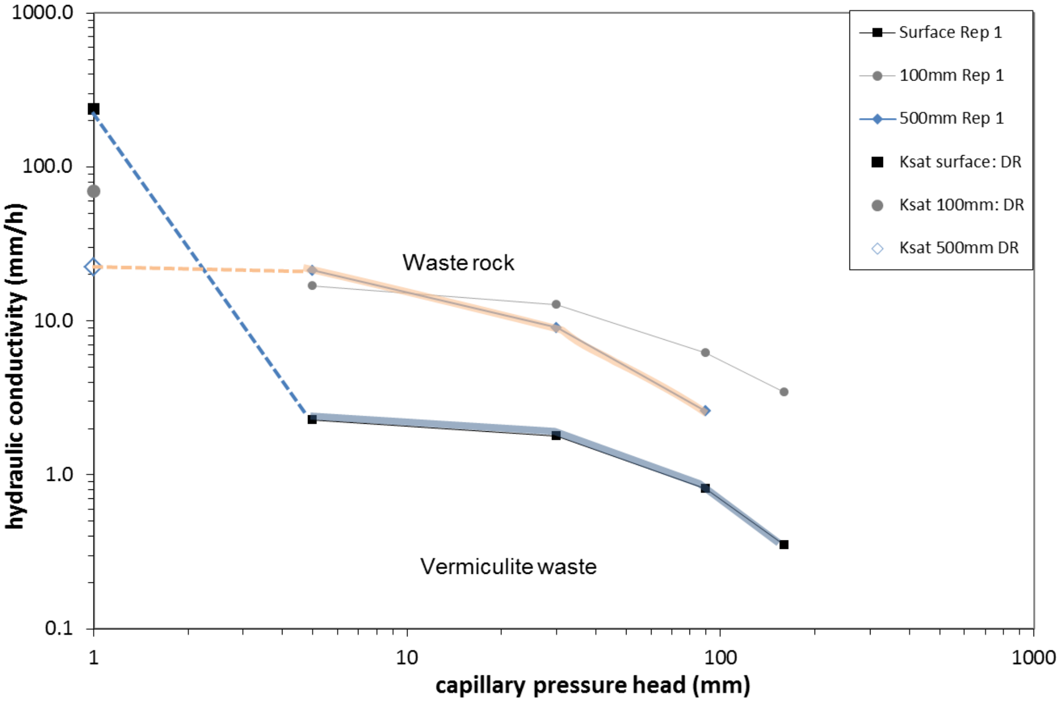
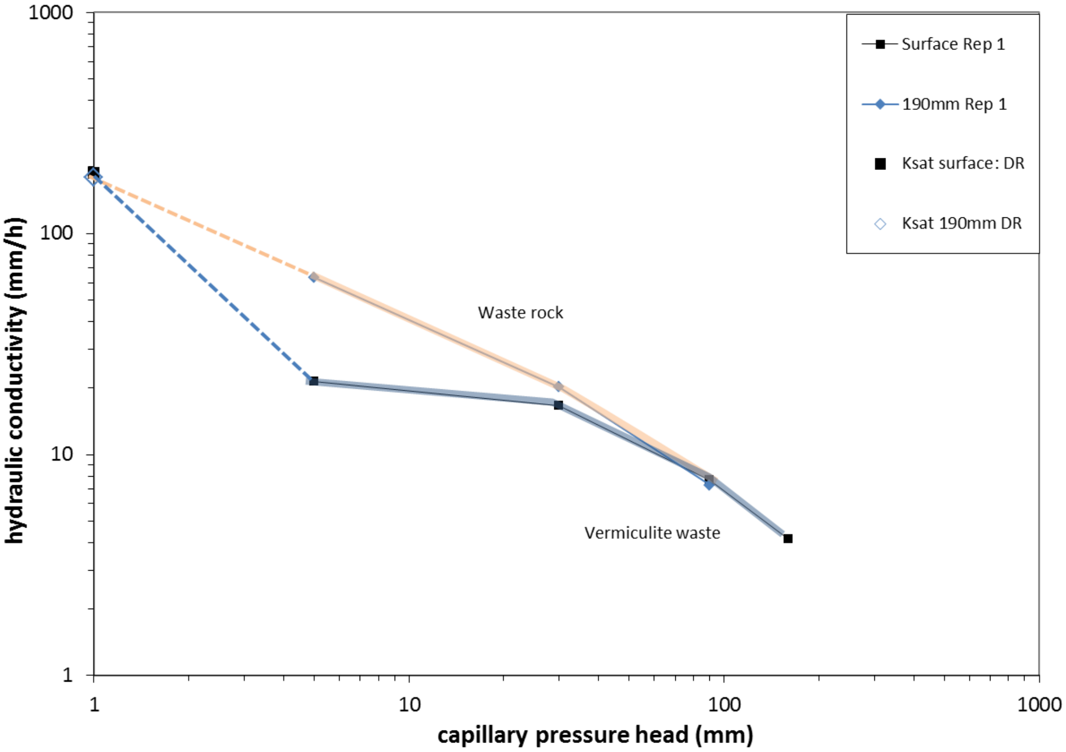
Annexure 1: Hydraulic Characterisation

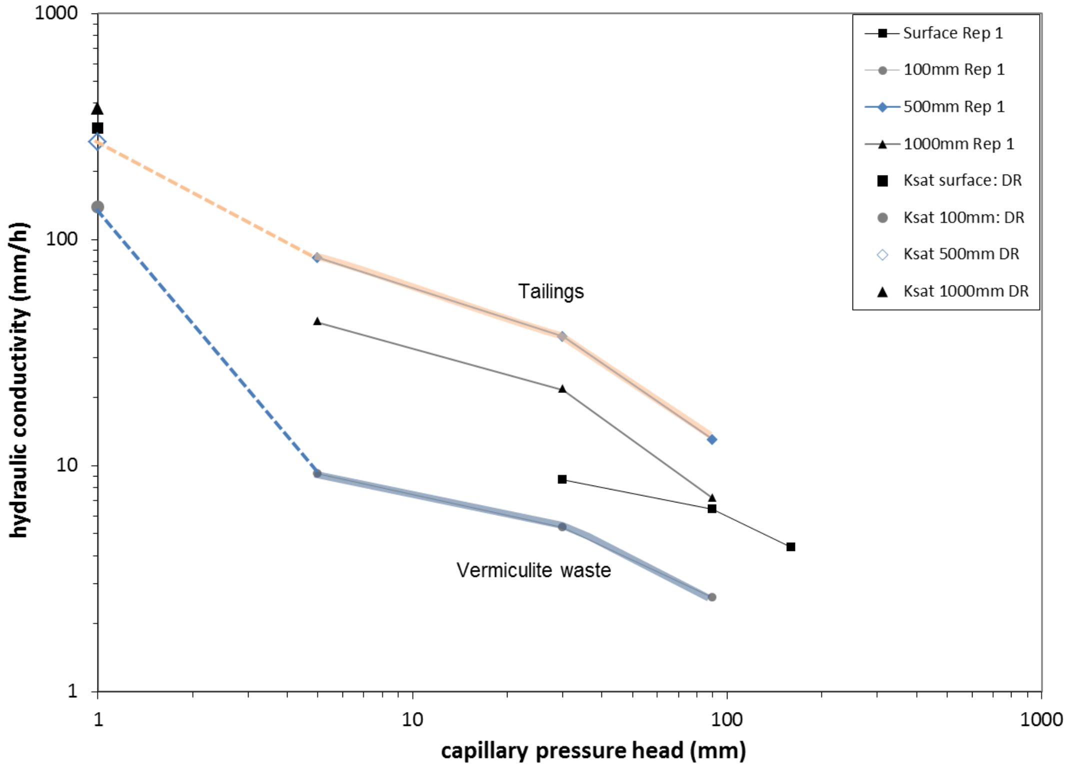
Lysimeter 1



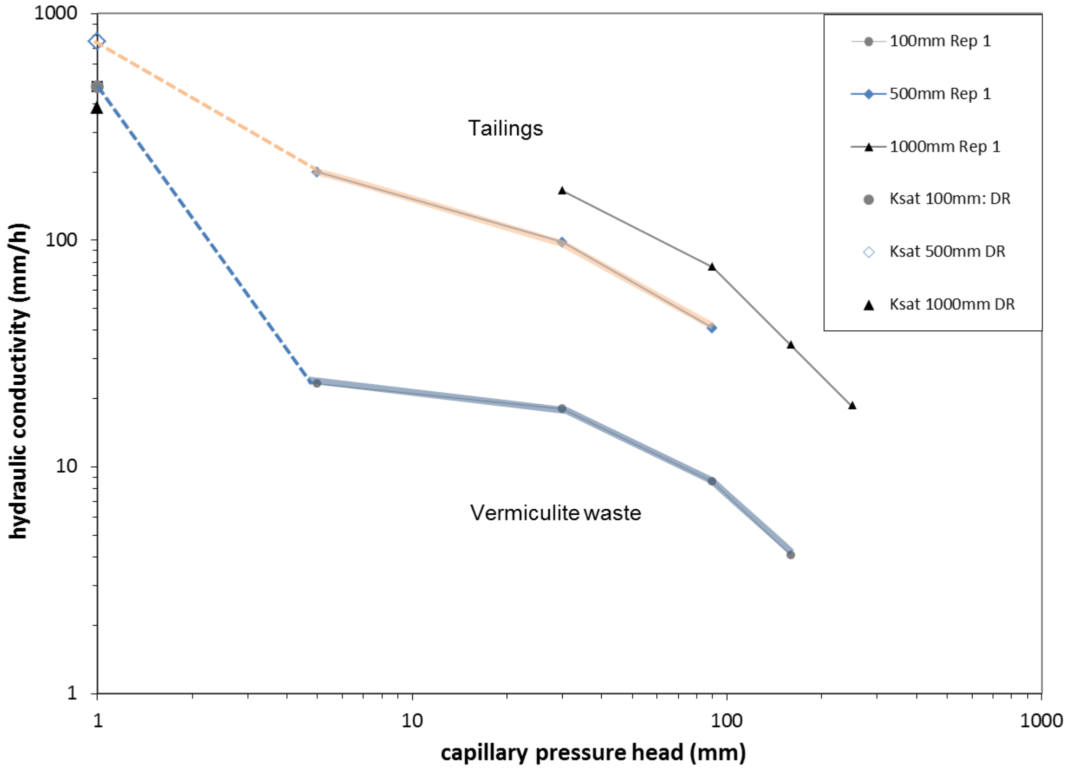
Lysimeter 2



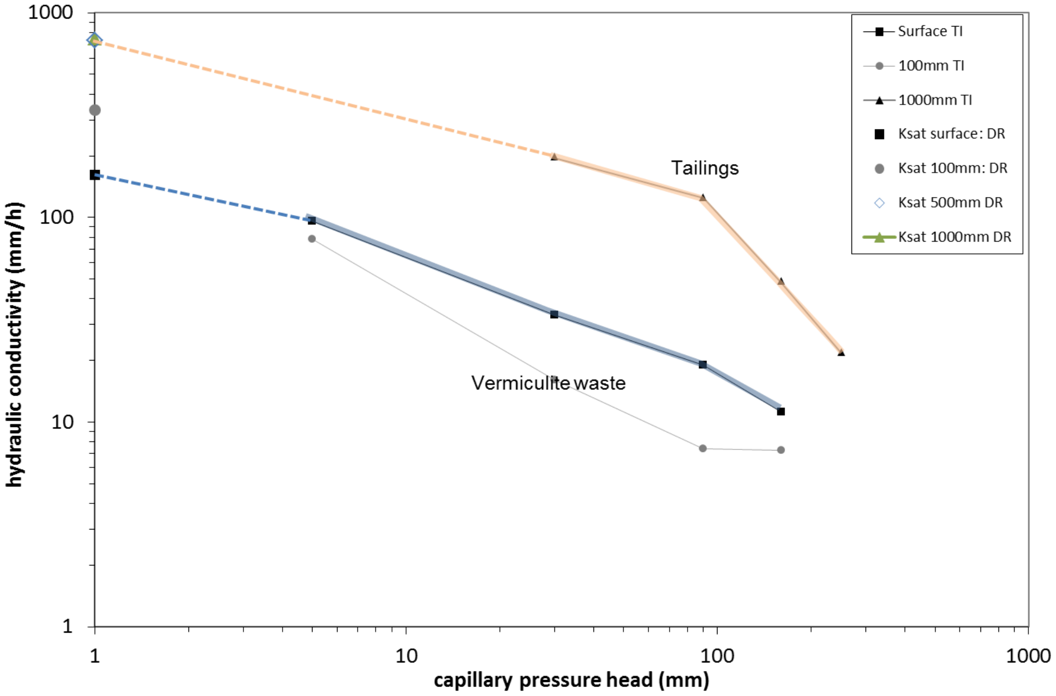
Runoff Plot 1



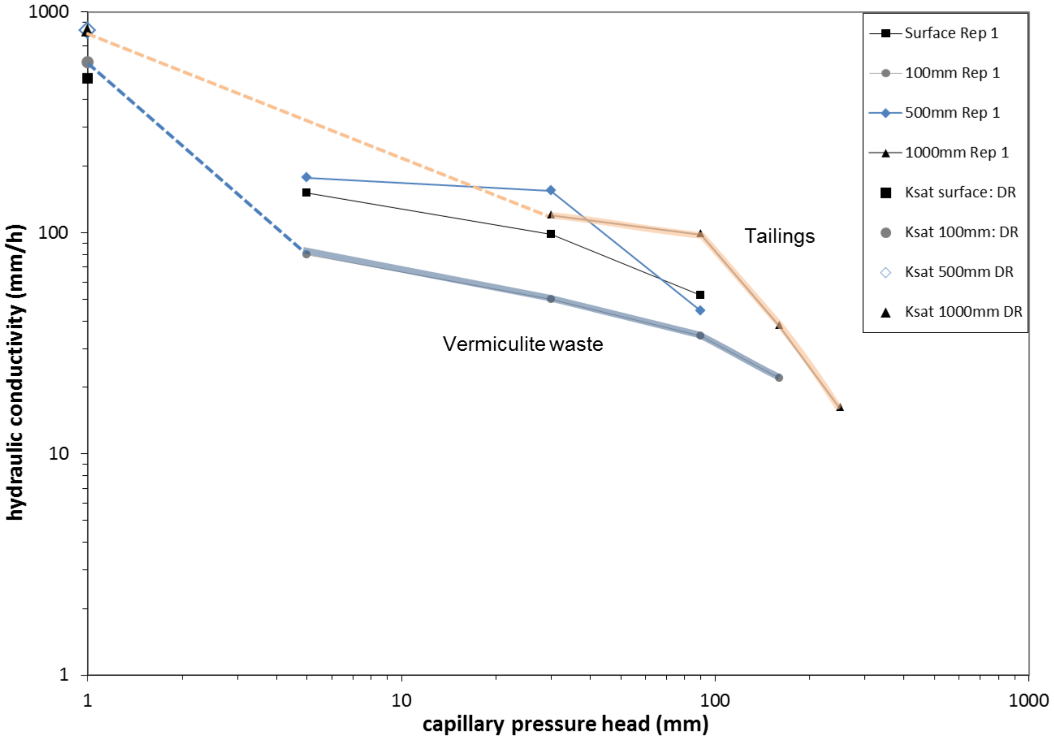
Runoff Plot 2



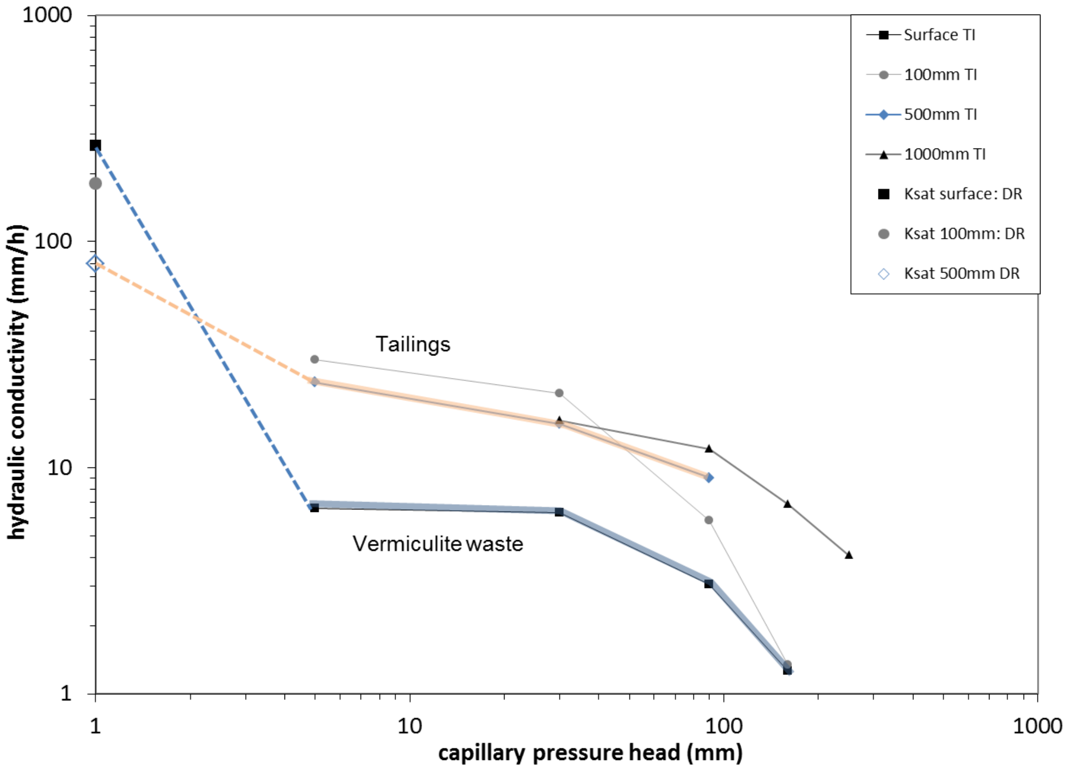
Runoff Plot 3



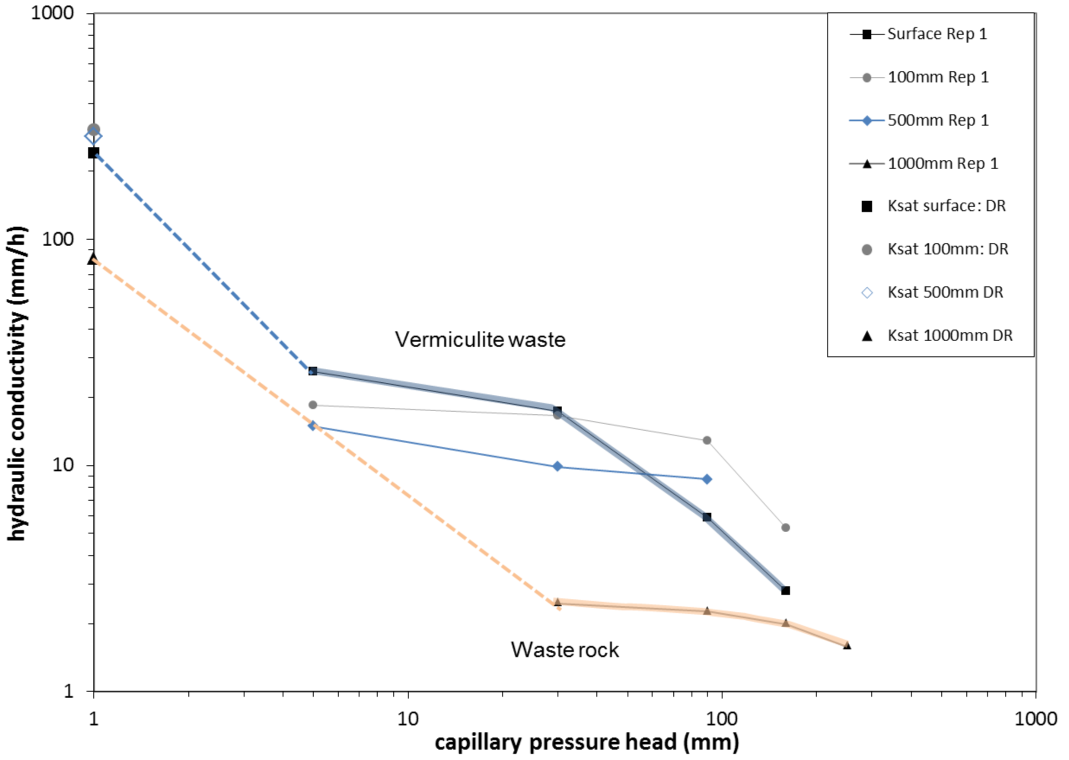
Runoff Plot 4



Runoff Plot 5



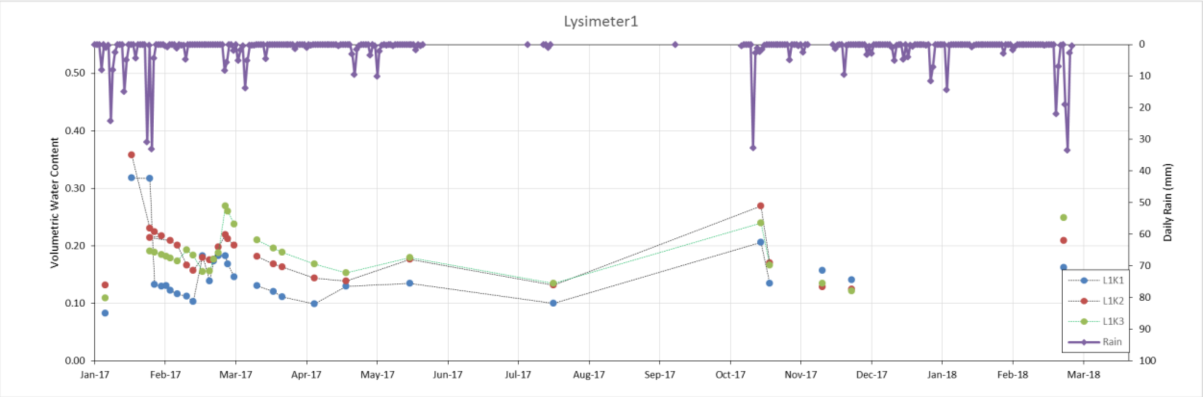
Runoff Plot 6



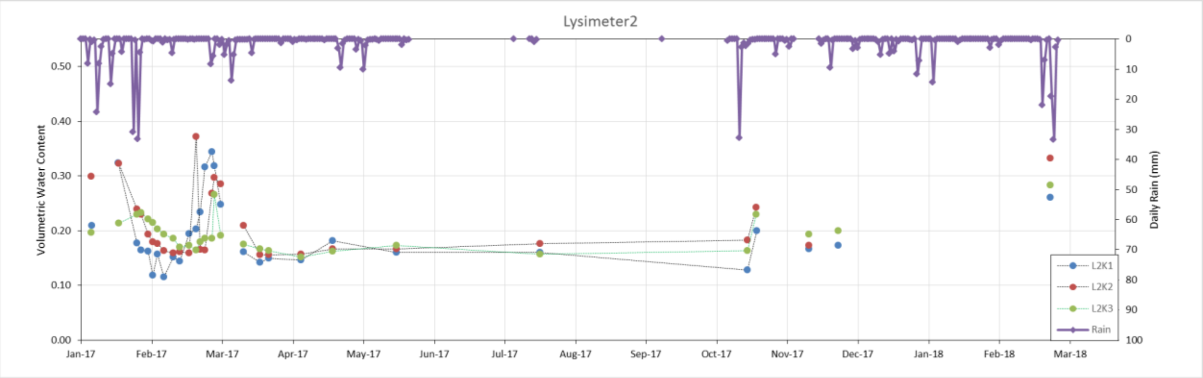
Annexure 2: Soil-water Dynamics

(TDR- Water Volume Content)

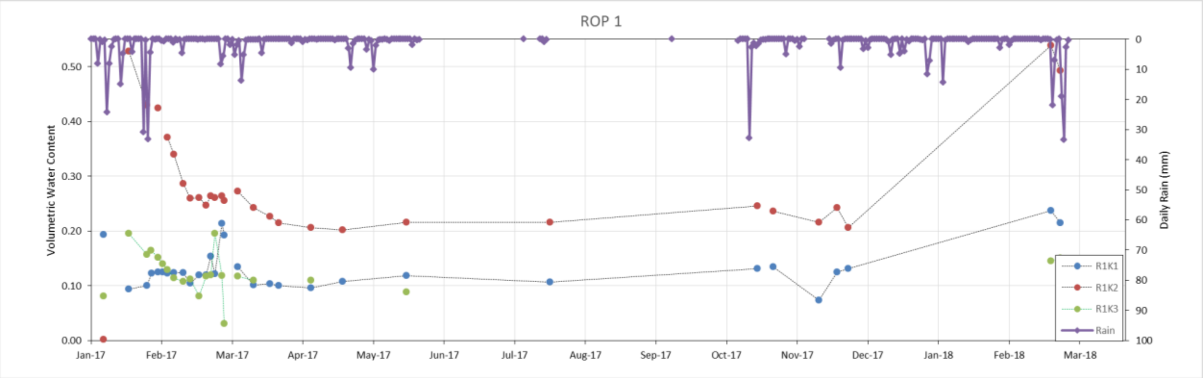
Lysimeter 1



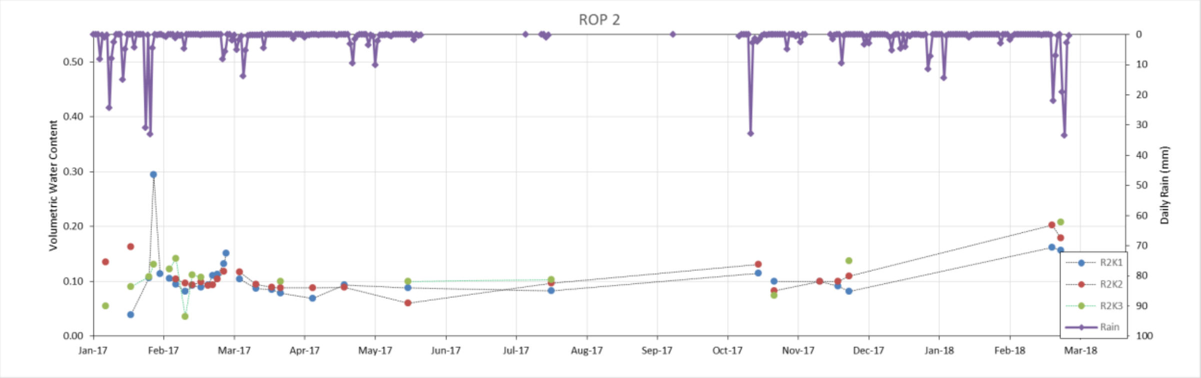
Lysimeter 2



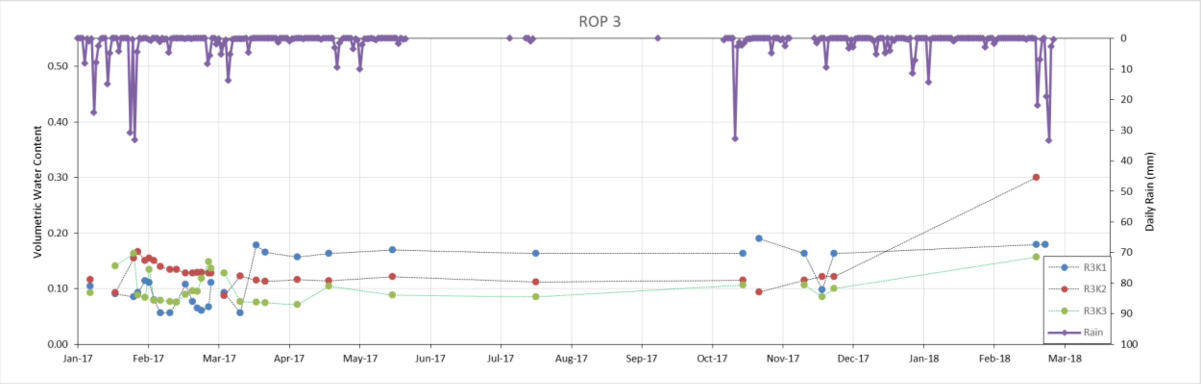
Runoff Plot 1



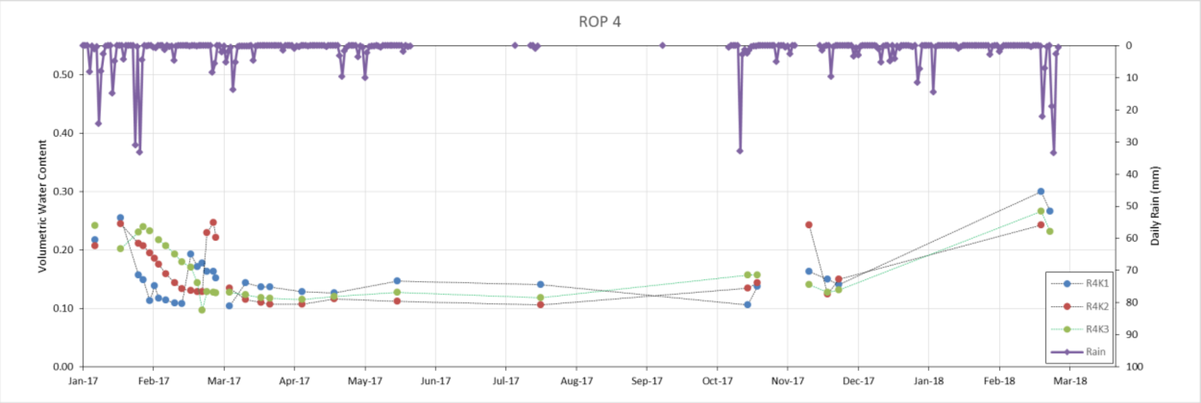
Runoff Plot 2



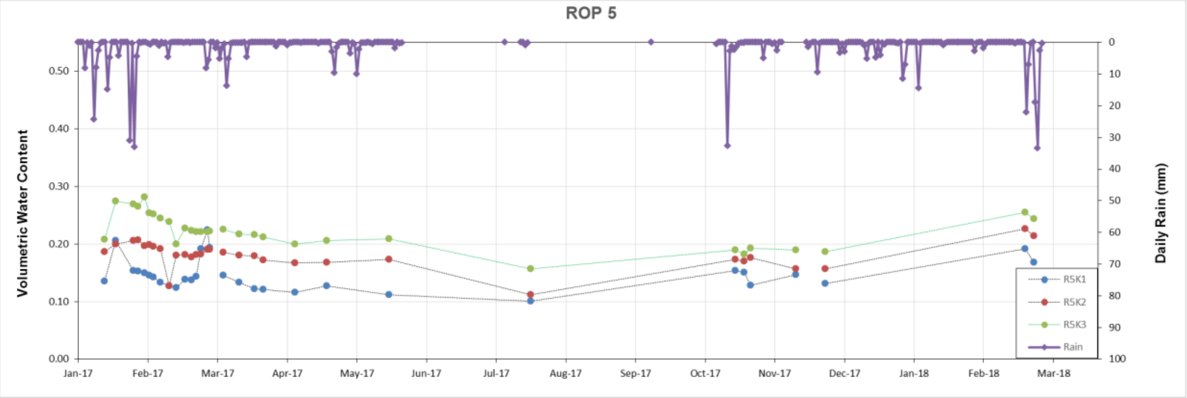
Runoff Plot 3



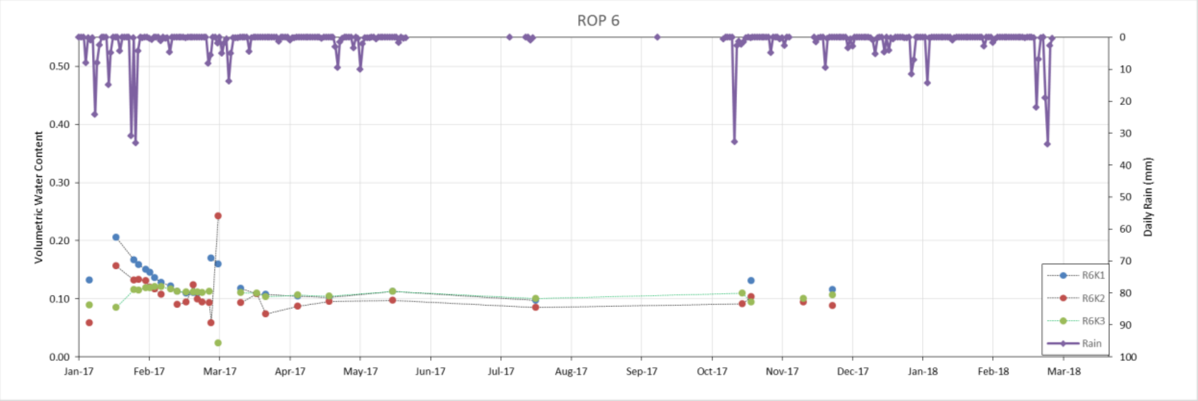
Runoff Plot 4



Runoff Plot 5

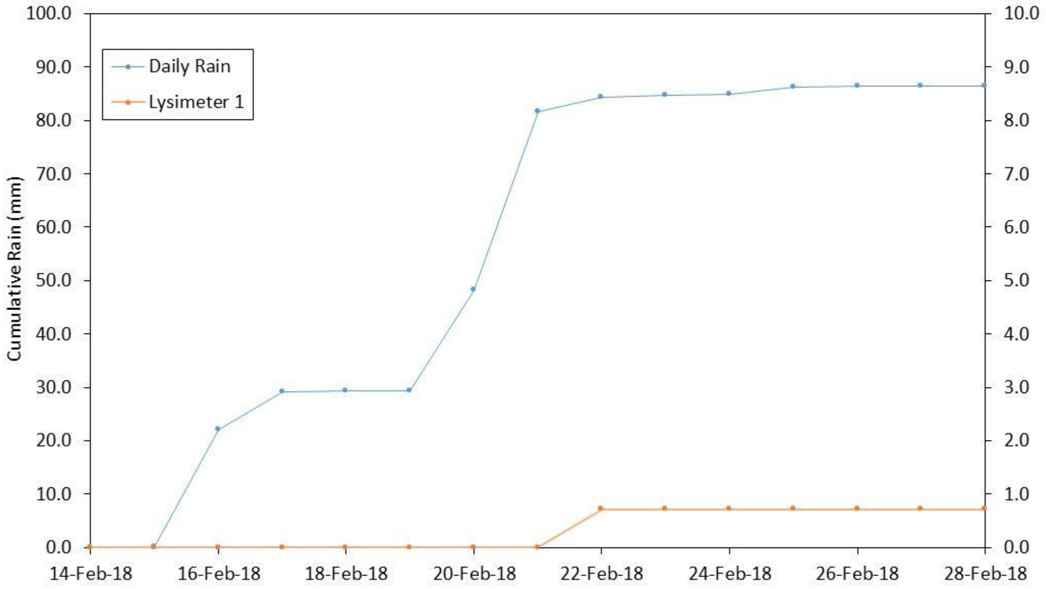


Runoff Plot 6

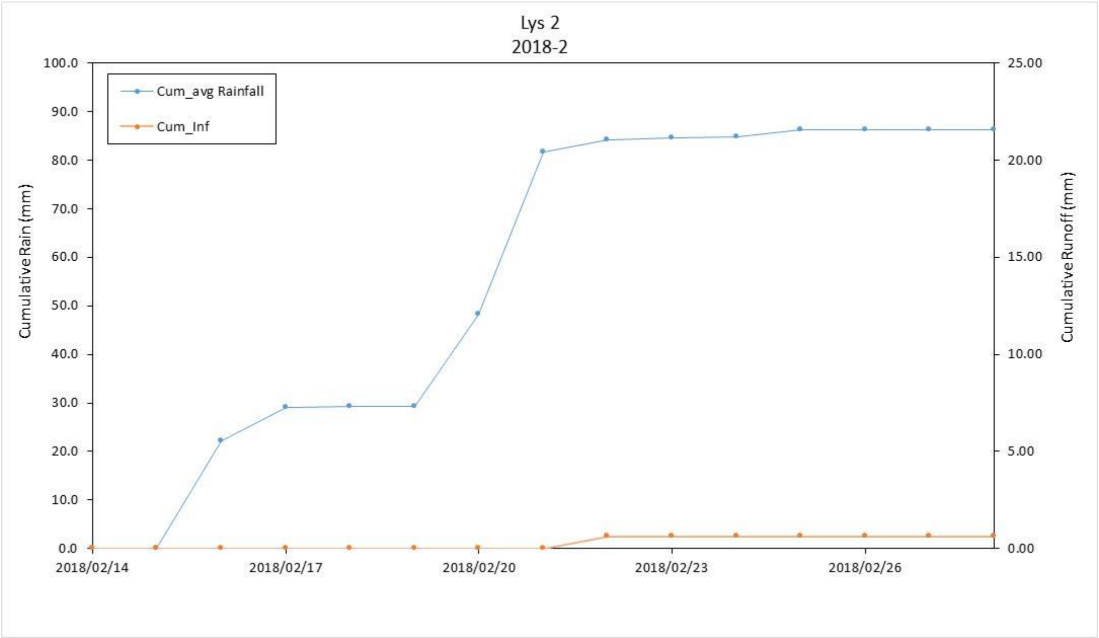


Annexure 3: Precipitation, Infiltration and Runoff

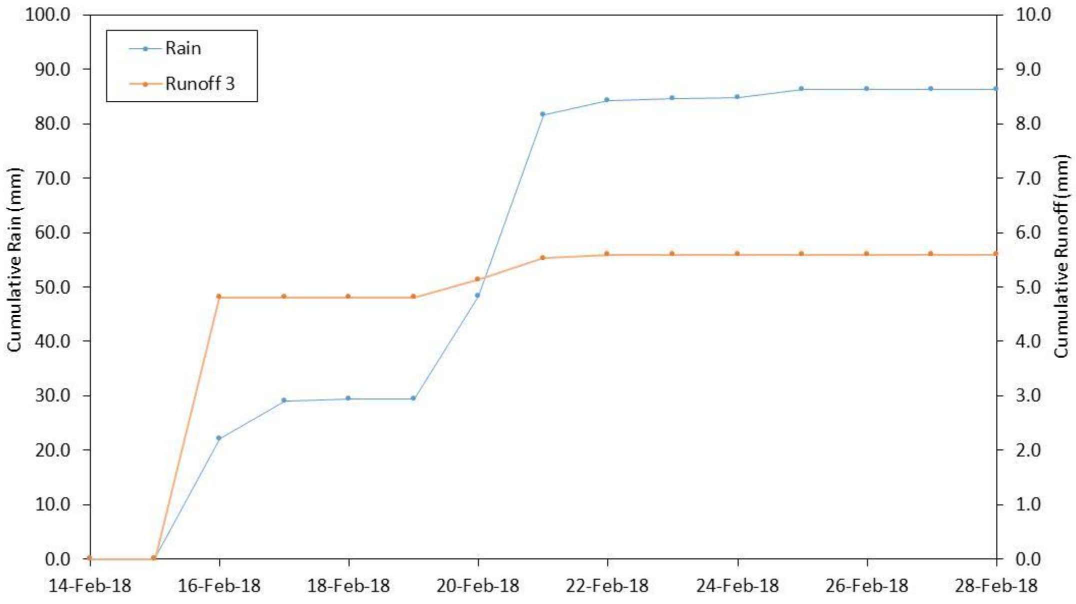
Lysimeter 1 - 2018



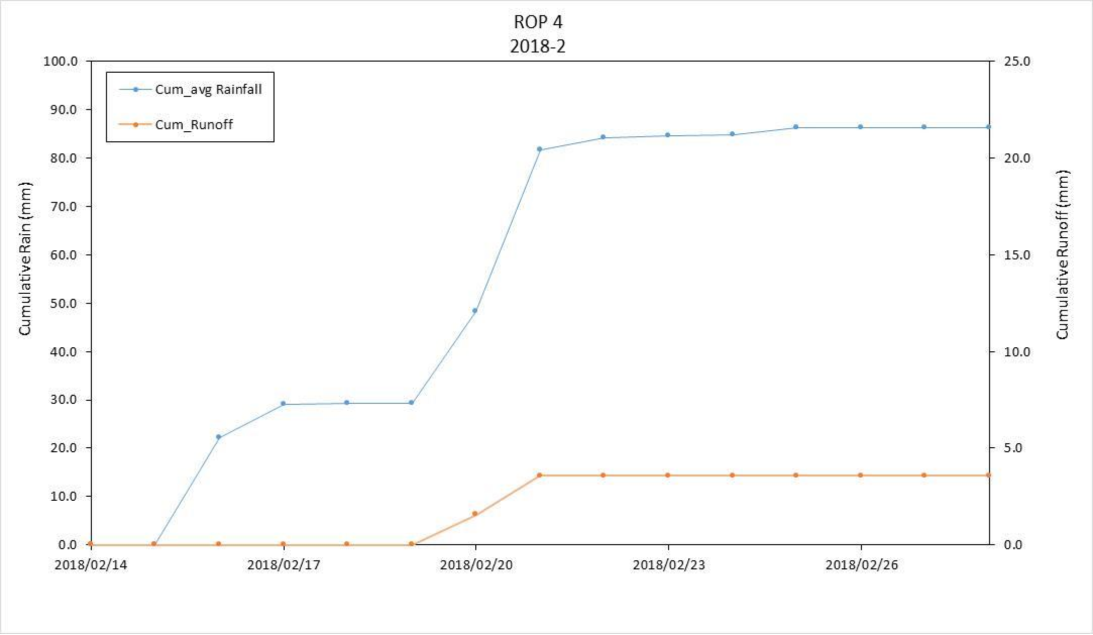
Lysimeter 2 – 2018



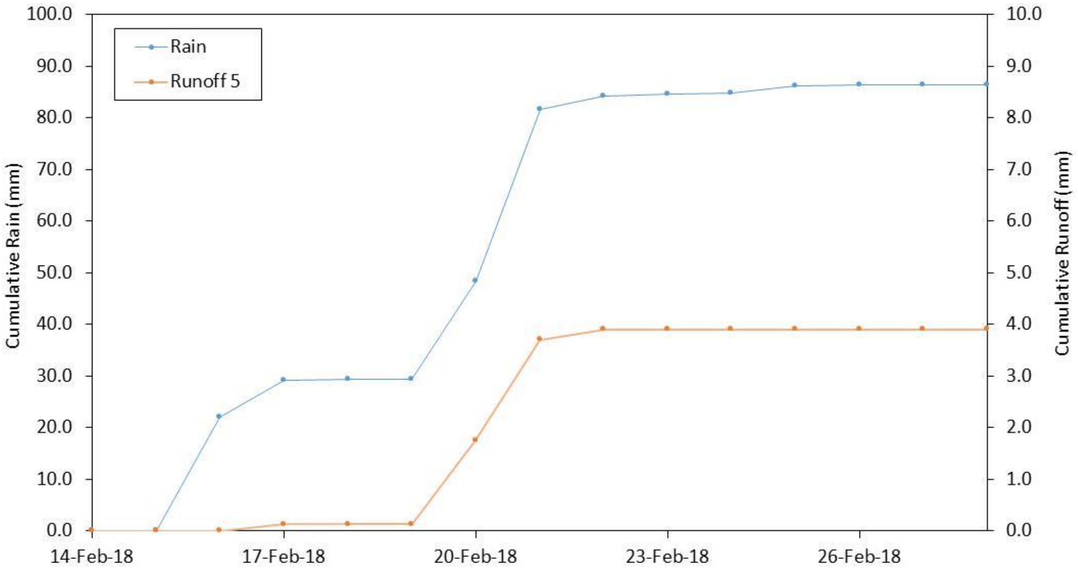
Runoff Plot 3 – 2018



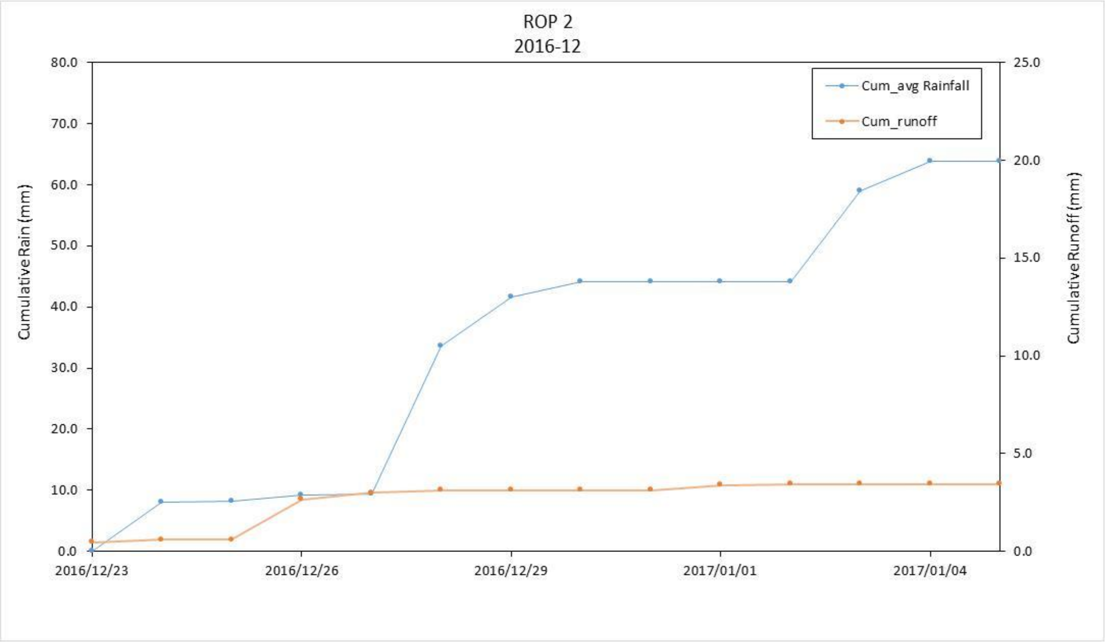
Runoff Plot 4 – 2018



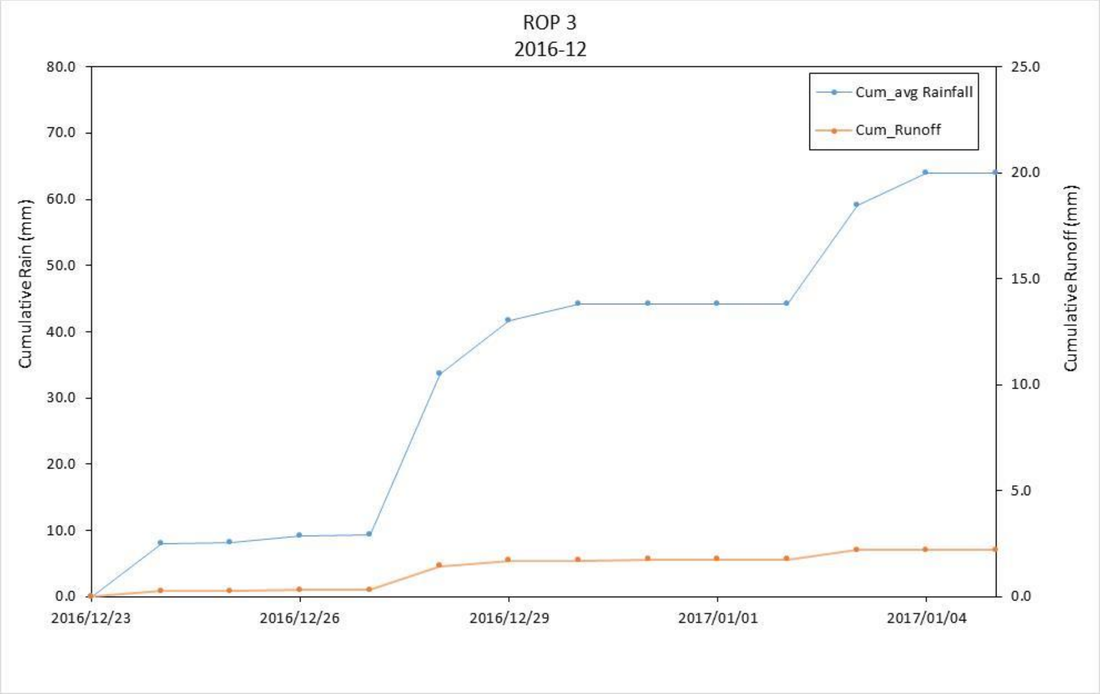
Runoff Plot 5 – 2018



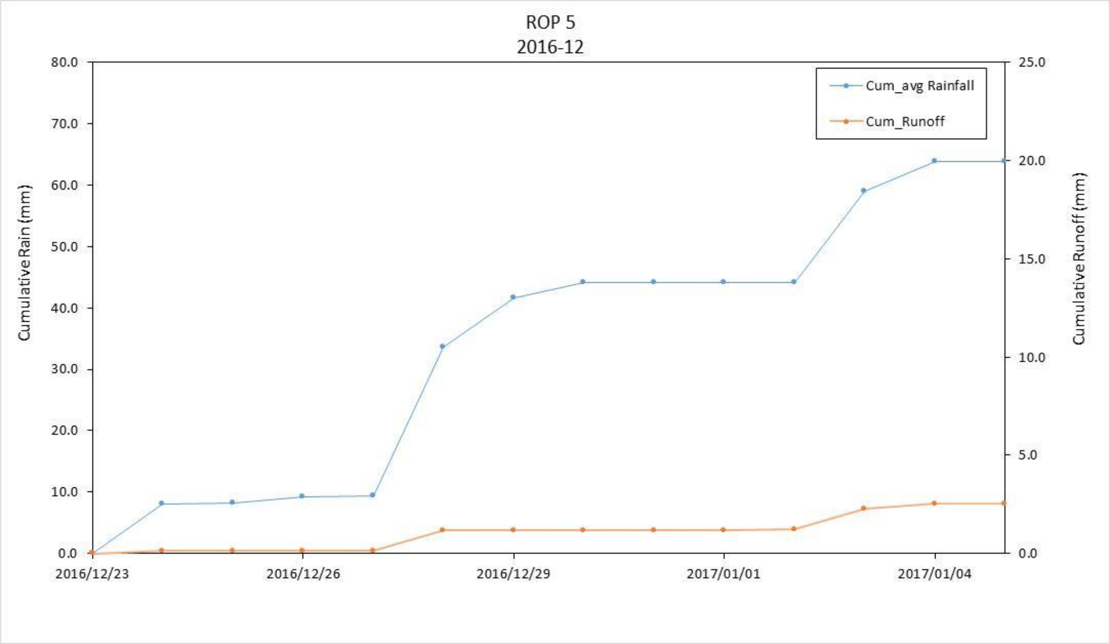
Runoff Plot 2 – 2016



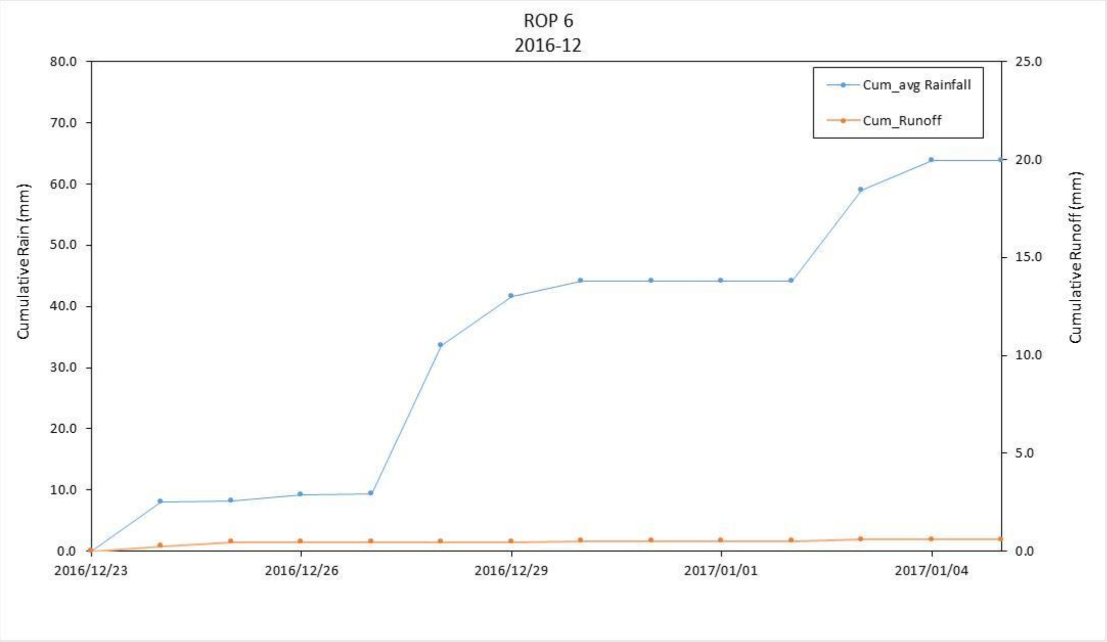
Runoff Plot 3 – 2016



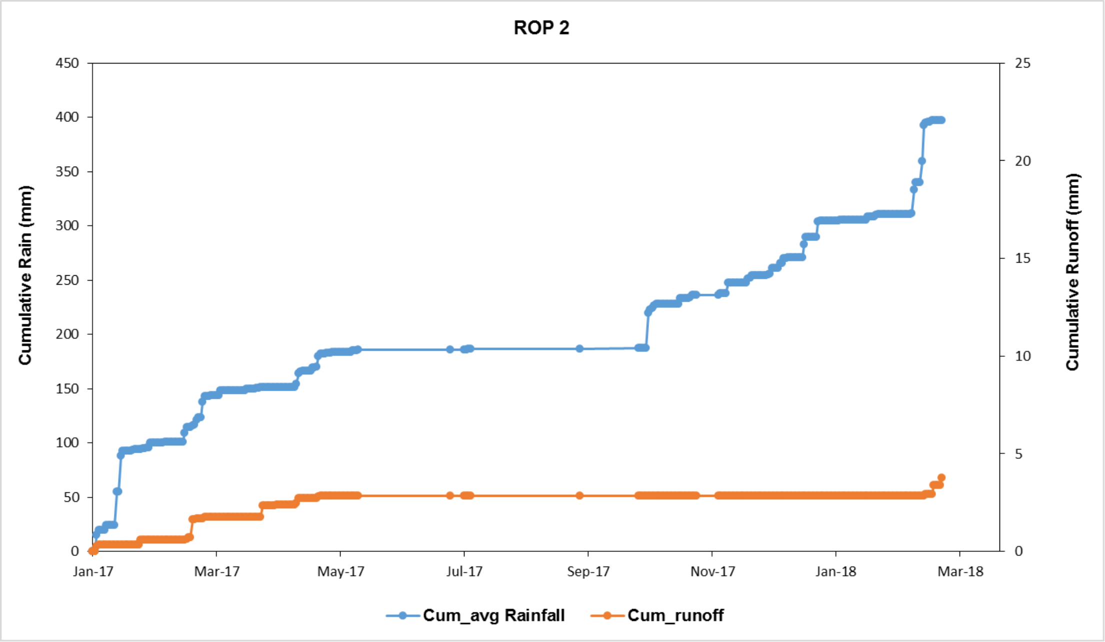
Runoff Plot 5 – 2016



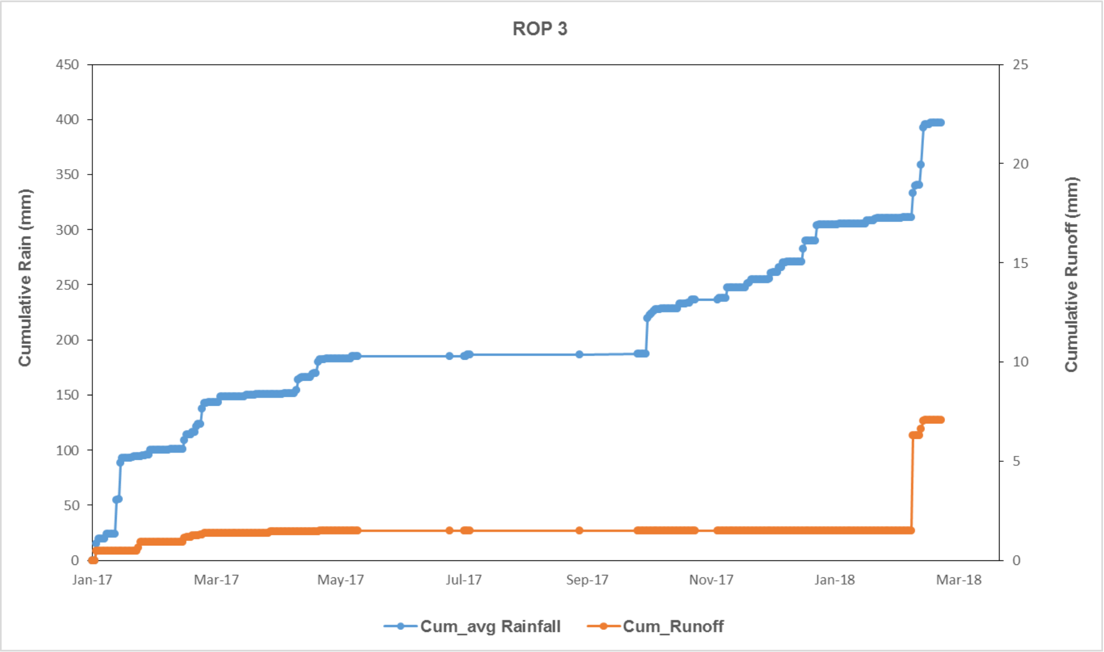
Runoff Plot 6 – 2016



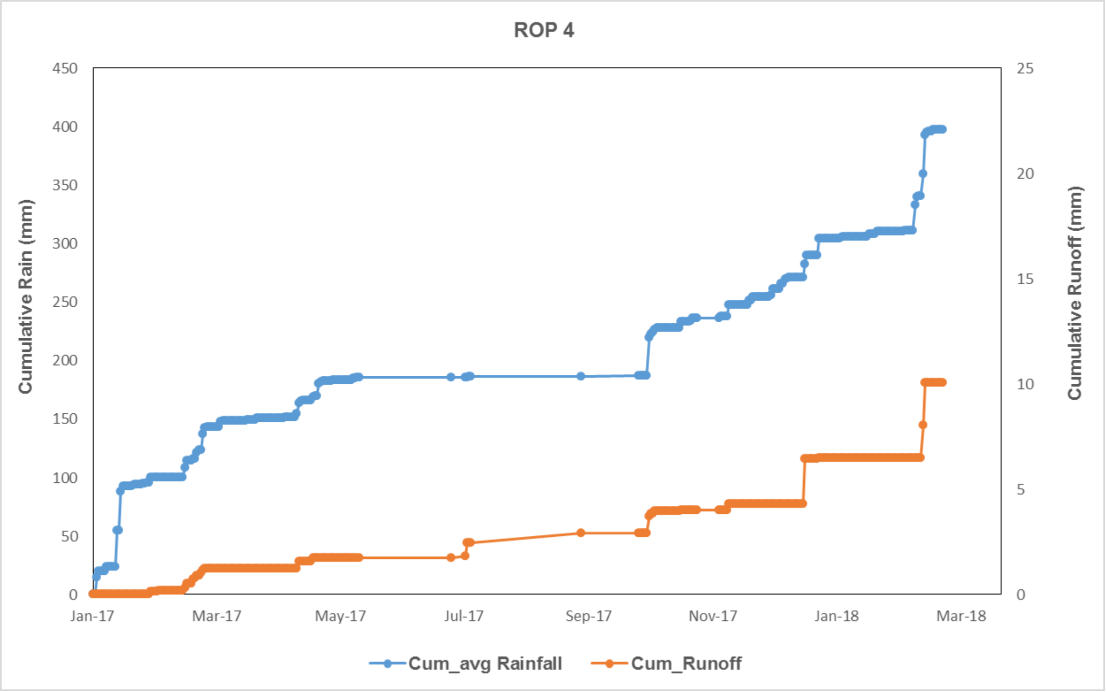
Runoff Plot 2 – 2016 to 2018



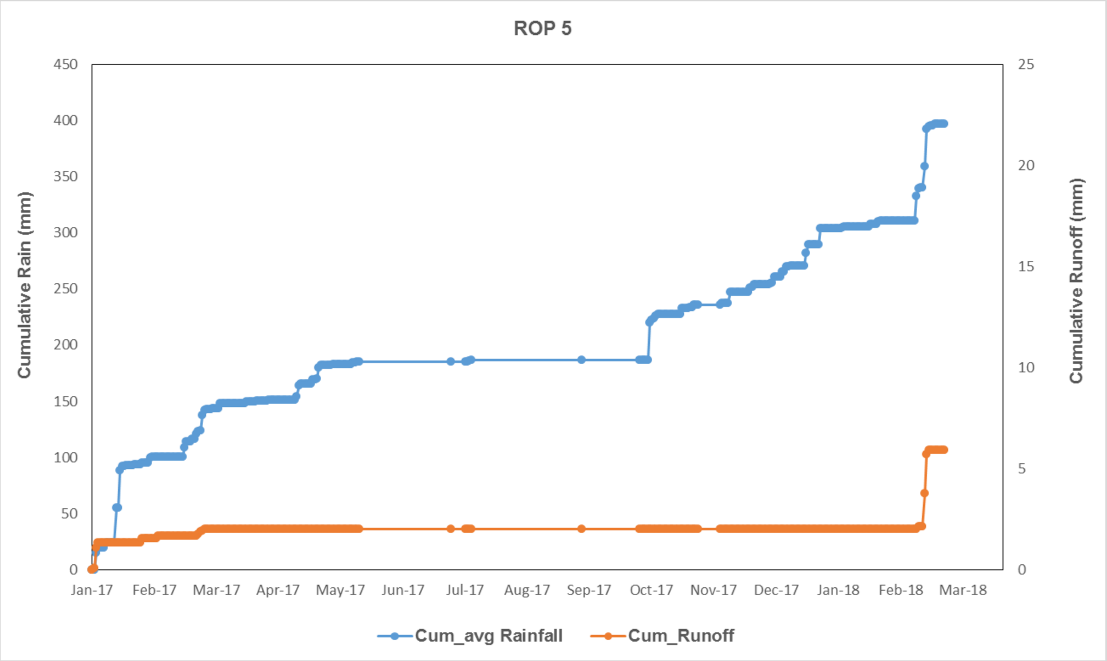
Runoff Plot 3 – 2016 to 2018



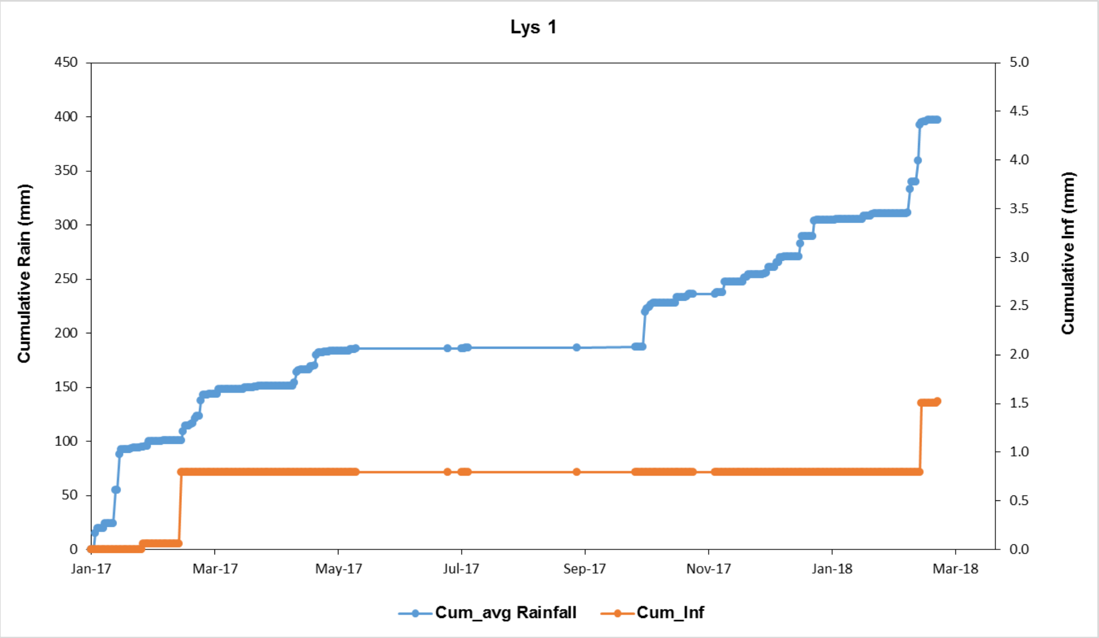
Runoff Plot 4 – 2016 to 2018



Runoff Plot 5 – 2016 to 2018



Lysimeter 1 2016 to 2018



Lysimeter 2 2016 to 2018