Hydraulic properties of the vadose zone at two typical sites in the Western Cape for the assessment of groundwater vulnerability to pollution

Donovan Samuels

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Supervisor
Prof. Nebo Jovanovic

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ABSTRACT

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D.C. Samuels

M.Sc mini-thesis, Applied Geology, Department of Earth Sciences, University of the Western Cape

Aquifer vulnerability assessment is increasingly becoming a very significant basis in order to fulfil the water demands in South Africa. Knowledge of soil hydraulic properties that consists of the soil water retention and hydraulic conductivity functions is a prerequisite for predicting solution transport in soils. The overall objective of the study is to develop a database of hydraulic properties for collected undisturbed samples and to test selected models by making use of this database.

Studies of the vadose zone are generally restricted to the top 1.2 meters; therefore this study aims at essentially improving the lack of measurements and modelling in the vadose zone. There exist several methods to determine hydraulic properties of soil that make use of hydraulic conductivity (K) determination in the vadose zone. The most accurate estimates of hydraulic conductivity are possible through direct measurements or measurements of the water retention curve. For this study, the drilling and sampling of five boreholes (maximum depth 20 m) proceeded during March and April 2005 at two typical sites in the Western Cape, namely the Berg river site (Riebeek West) and Ithemba site (Cape Flats).

In total, 76 undisturbed core samples were collected from which the detailed borehole log descriptions were made. The determination of the soil water retention curves of the collected samples was based on laboratory techniques using Eijkelkamp drying and suction equipment (sand box and clay box).

When modelling groundwater vulnerability, it is essential to look at the soil water retention curves with increased importance, as they provide graphical and mathematical confirmation of porosity, preferential flows, volumetric water content and unsaturated hydraulic conductivity. Therefore, a numerical model called RETC was used to determine soil hydraulic properties. The RETC model uses equations of Van Genuchten (Van Genuchten, 1980) and Brooks-Corey (Brooks and Corey, 1966) to determine parameters for soil water retention and the methods of Mualem (1976) and Burdine (1953) to determine unsaturated hydraulic conductivity functions. Saturated hydraulic conductivity values were estimated by using RETC soil database based on textural descriptions of collected samples. Using the soil hydraulic estimates obtained from RETC, sensitivity analyses were run with a one dimensional transport model, Macro 5.0 for two sites at iThemba and in the Berg river.

DECLARATION

I declare that, *Hydraulic properties of the vadose zone at two typical sites in the Western Cape for the assessment of groundwater vulnerability to pollution* is my own work, that it has not been submitted for any degree or examination in any other university and that all the sources I have used have been acknowledged by complete references.

Donovan Samuels
10 May 2007

Signed: ………………………….

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Chapter One
General Introduction

1.1: Introduction

Water resources in South Africa are limited and randomly distributed. With the rapidly growing population it is generally accepted that the demand for water will increase significantly in the future. Therefore, groundwater represents an important and strategic water resource in South Africa.

The significance of groundwater as a resource grows continuously across the country because of its generally easy accessibility, cost effectiveness and declining surface water sources (Sililo *et al.*, 1999). However, the groundwater resources in South Africa are limited and can easily be polluted particularly as a result of anthropogenic activities. In recognizing the importance of groundwater as a potential source of water supply, both for domestic and industrial uses, every attempt must be made to reduce the deterioration of its quality due to various anthropogenic activities.

Aquifer vulnerability assessment is increasingly becoming a very significant basis in order to fulfill the water demands in South Africa. The vulnerability of an aquifer to pollution is directly related to the hydraulic characteristics of the aquifer overburden and to a significant degree by the characteristics of contaminant attenuation (Sililo *et al.*, 2001). Additionally, all infiltrating surface water must pass through the vadose zone prior to reaching the underlying aquifer. In South Africa, the vadose zone varies in thickness from a few meters to tens of meters and therefore acts as a vital barrier between the ground surface and the aquifer.

Unfortunately, studies of the vadose zone are generally restricted to the top 1,2 meters of the soil profile, with the result that very little is known about the hydrogeological characteristics of the lower parts of the vadose zone (van Schalkwyk and Vermaak, 2000).

With this in mind, the knowledge of hydraulic properties of the vadose zone, which is a key element in hydrologic modeling, will aid in filling the gap in the understanding and assessment of groundwater contamination (Rawls and Pachepsky, 2002).

1.2 Background to the study

This study emerged from two current projects carried out in the Western Cape. These are entitled: “Land Use Impacts on Salinity in Western Cape Waters” (Water Research Commission project No. K5/1503), and “Improved Methods for Aquifer Vulnerability Assessments and Protocols for Producing Vulnerability Maps, Taking into Account Information on Soils” (Water Research Commission project No. K5/1432). In particular, some of the experimental sites of these two projects were used for the determination of hydraulic properties in the vadose zone.

The vadose (unsaturated) zone plays an important role in determining the level of contamination from land surface to the groundwater. In terms of vulnerability assessments, enhanced prognostic transport models through the vadose zone are necessary. Determining the hydraulic properties consisting of soil water retention and hydraulic conductivity is a requirement for predicting the solution transport in soils.

This study focuses mainly on developing a detailed database of hydraulic properties of the vadose zone at two typical sites in Western Cape, and to use this database for modeling. These two sites are typical due to the related type of bedrock consisting of the Malmesbury Group, in particular shales. The study is data-rich and thus it provides adequate information to fulfill the gaps due to the lack of measurements and modeling of the vadose zone. Many process-based models that can be used for predictions of leaching and groundwater contamination make use of water retention and hydraulic properties of the vadose zone (Fetter, 1999; Lindström, 2005).

1.3 Aims and Objectives

There are several aims and objectives that were embarked upon. In order of their priority and how they tied in with the work conducted and the research results obtained, they were set as follows:

1. Identifying various groundwater vulnerability techniques.

2. Assessing the various models for groundwater contamination prediction based upon their background, input parameters and assumptions relevant to groundwater vulnerability.

3. Reviewing the various formulae for the determination of hydraulic properties, based on the water retention curve, relevant to groundwater vulnerability assessment.

4. Determining the soil-water retention curves of selected undisturbed core samples based on laboratory techniques.

5. Developing a database of hydraulic properties for all undisturbed samples collected.

6. Testing selected models by using the above mentioned database through a sensitivity analysis

1.4 OUTLINE OF THESIS

This mini thesis includes seven chapters, with chapter one being the general introduction to the mini thesis providing background information for the research and explaining the nature of the topic as well as the objectives and outline of the mini thesis.

Chapter two provides for the literature review that specifically describes the properties being investigated and the methods for the determination of these properties affecting the description and modeling of groundwater vulnerability.

Chapter three provides a detailed outline of the methodology followed during the research and includes site selection and the materials and methods for the drilling of boreholes, sampling and experimental procedures.

Chapter four provides for the presentation and discussion of the results for the experiments done based on the procedures outlined in chapter three. It includes a database of hydraulic properties of the undisturbed core samples collected.

Chapter five includes the test modeling of data from the database of hydraulic properties given in chapter four using the computer program named, RETC.

Chapter six provides a sensitivity analysis using estimates obtained in chapter five, using a one dimensional transport model, namely Macro 5.0

Chapter seven gives a general conclusions and an overall interpretation of the study with recommendations.

Chapter Two
Literature Review

2.1: Introduction

Available literature, comprising of both local and international literature, is reviewed in this chapter. An evaluation of typical groundwater vulnerability issues and processes occurring in the vadose zone are discussed in this chapter. The main focus of this chapter is essentially the importance of determining hydraulic properties of the vadose zone and the models and methods used to assess groundwater vulnerability to pollution. The literature reviewed here has a significant contribution toward understanding and assessing groundwater vulnerability to pollution.

2.2 Groundwater vulnerability

In recognizing the importance of protecting groundwater resources from pollution, the development of techniques for predicting which areas are more likely to become contaminated as a result of various anthropogenic activities at the land surface, becomes extremely essential. According to Sililo *et al.* (2001) the reality that some areas are more probable than others to become polluted has led to the use of the terminology “groundwater vulnerability to pollution”.

Groundwater vulnerability is the probability that contamination will occur and according to NRC (1993), it is an amorphous concept, not a quantifiable property. The vulnerability of groundwater to pollution depends on the time of travel of infiltrating water, the relative quality of the contaminants that can reach groundwater and the contaminant attenuation capacity of the soil materials through which the water and contaminants travel (Sililo *et al.,* 2001). Additionally, the vulnerability of an aquifer to pollution is determined by the extent of the interactions between soil/aquifer characteristics and the pollutants.

According to Burkart *et al.* (1999), the principles for vulnerability assessment include both intrinsic and specific vulnerability of a site. Vrba and Zaporozec (1994) first distinguished between intrinsic and specific vulnerability where the intrinsic vulnerability characterizes a relative, non-measurable, dimensionless property of the groundwater cover, determined by its thickness, the lithologic properties of the vadose zone, the aquifer properties and the recharge.

Specific vulnerability characterizes the vulnerability of groundwater to certain pollutants and takes into account land use practices. According to definitions from Goldscheider (2002), the intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological and hydrogeological characteristics of an area but is independent of the nature of the contaminants and the contamination situation. The specific vulnerability takes into account the properties of a particular contaminant or group of contaminants in addition to the intrinsic vulnerability of the area (Goldscheider, 2002).

For the purpose of this research, intrinsic vulnerability is considered in particular through the use of water retention measurements of the vadose zone.

2.3 Vadose (Unsaturated) Zone

For any groundwater contamination study, it is essential to have knowledge of the vadose zone as it plays a key role in the transport and fate of pollutants from land surface to the water table. The vadose zone is the section of the geological profile sited between the land surface and the groundwater surface (water table). It is the part of the Earth's layer that contains a three-phase system of solid, liquid and gaseous material. The solid phase (important in this study) of the vadose zone may consist of soil, which is produced by *in situ* weathering; or sediment, transported from the place of weathering; or unweathered bedrock (Fetter, 2001).

The unsaturated zone is subject to weathering, erosion, pedogenic and other processes, often resulting in a complex geological setting comprising of soils and rocks that are very rarely homogeneous and is thus seldom a reflection of the condition in the field. Studies of the vadose zone can thus be complicated considerably due to the range of materials with various physical properties existing in this zone (van Schalkwyk and Vermaak, 2000).

Vadose zone studies differ from saturated zone studies due to the occurrence of air in the pore space. In the pores, there exists a variation in the relative proportion of air and water, and with this variation the hydraulic properties of the porous media can vary (Fetter, 1999). Due to the presence of air in soil, the matric potential becomes negative. In the unsaturated zone the matic potential is negative since it needs energy for the attraction of water onto soil particles whereas in the saturated zone the matric potential is positive due to water (hydrostatic) pressure.

2.4. Preferential Flow

One of the main vadose zone data requirement relate to the evaluation of infiltration rate which is complicated by the presence of preferential flow paths. These pathways can cause rapid transport of water from the surface to aquifers.

Preferential flow is a known process in which contaminants transfer rapidly through the vadose zone, creating a potential risk for the groundwater. According to Fetter (1999), the water and solutes move along preferred pathways through a porous medium and, in the case of flow through the unsaturated zone, solutes by-pass large parts of the soil matrix where shrinkage cracks, animal burrows may operate as flow pathways in which water moves rapidly downwards and by-passes the denser soil matrix.

According to van Schalkwyk and Vermaak (2000), the following types of preferential flow can be identified:

- Fingering which refers to the finger-like flow of water in (typically) sandy soil.
- Funneled flow referring to the funneling of water above a more permeable soil layer or a less permeable layer.
- Macropore channeling referring to the rapid movement of water and solutes along macropores, such as shrinkage cracks and plant root holes.
- Preferential flow in heterogeneous soil which occurs because of the spatial variability in pore size distribution (little is known about this type of flow).

These occurrences of preferential flow in particular and soil heterogeneity in general have disturbing implications for monitoring solute movement in the vadose zone (Fetter, 1999). According to Kung (1990), some studies have recorded seemingly anomalous results, with deeper soil layers having greater concentrations of solute than shallower layers. These anomalies can be explained by preferential flow patterns, with infiltrating solute being directed to certain regions of the unsaturated zone by short circuiting, fingering and funneling (Fetter, 1999). Additional field experiments are still required to determine the significance of preferential flow in different hydrogeological areas in South Africa

2.5 Contaminant Attenuation

The idea of aquifer vulnerability originated from the assumption that the physical environment may give some level of protection against contaminants entering the ground surface (Vrba and Zaprozec, 1994; van Schalkwyk and Vermaak, 2000). Therefore, contaminant attenuation characteristics are essential in aquifer vulnerability assessment studies.

According to Sililo *et al*. (1999), aquifer vulnerability to pollution is directly linked to the hydraulic characteristics of the aquifer overburden and to a large extent determined by the characteristics of contaminant attenuation. Additionally, the vulnerability of soil and groundwater to pollution depends largely on the mobility of the contaminant in the soil.

During the infiltration through soils and transport in aquifer, many contaminants enter the subsurface and are attenuated by a number of processes that are active in the vadose and saturated zones. However, not all subsurface environments are equally effective in this respect. Different physical environments have different capacities for the attenuation of contaminants (van Schalkwyk and Vermaak, 2000). The impact that contamination discharges have on the groundwater environment is extremely dependent on the geological medium through which it moves. It is generally accepted that potentially groundwater degrading activities should be sited on suitable geological formations, thereby enhancing the attenuation processes. During contaminant migration through the subsurface, various physical, chemical and biological processes occur, by which the concentration of different contaminants will be decreased (Sililo *et al.,* 1999).

Fewer biological processes occur at depth in the vadose zone as apposed to near surface, whilst the physical and chemical processes dominate deeper in the vadose zone. Therefore, a major feature of the vadose zone is that it delays the arrival of contaminants to the water table.

2.6 Water Table

The water table is that surface beneath which all interconnected pore space in the rock is water-filled or saturated. The water table exists only in water-bearing formations, which contain openings of sufficient size to permit appreciable movement of water (Soliman *et al.,* 1998).

Groundwater vulnerability can be increased when the water table level is amplified for a long duration allowing the mobilization of the contaminant in the water to be faster. Therefore well drained soils with a shallow water table are much more likely to be more susceptible to pollution than poorly drained soils with a deep water table (Huddleston, 1996).

There exist two types of water tables in soils: apparent and perched water table. An apparent water table lies above a zone of saturation and is open to contamination due to its lack of a confining layer, whereas a perched water table is a saturated area that lies within a zone of aeration, it lies above an apparent water table and is kept there by a soil layer of low permeability such as clay (Fetter, 1999).

An apparent water table is indicated by the level at which water stands in an uncased borehole after sufficient time is permitted for adjustment in the surrounding soil. A perched water table is situated above the apparent water table because of the presence of an impermeable layer. Perched water tables do not increase the risk of groundwater contamination to the same degree of that apparent water tables do, since perched water tables act as a confining layer for contaminants, preventing them from settling into the groundwater. However, the perched water tables put surface waters at risk to contamination, as the interrelation between the surface and perched waters are much greater than that of the ground and surface waters (Huddleston, 1996).

2.7 Hydraulic properties

2.7.1 Overview

The determination of accurate soil hydraulic properties (i.e., the soil water retention and hydraulic conductivity functions) is a prerequisite for predicting water and solute movement in soils (Fujimaki and Inoue, 2003a). Applying mechanistic models to describe water flow in unsaturated media requires knowledge of the soil hydraulic properties represented by relationships between the volumetric soil water content, the soil water pressure head and the hydraulic conductivity (Mermoud and Xu, 2005).

The most frequently considered relationships are the solution of equations describing the flow of water in unsaturated soils that requires the expression of two soil hydraulic properties, the water retention curve and the hydraulic conductivity function (Hwang and Powers, 2003). The water retention curve describes the relationship between the pressure head and the volumetric water content. The hydraulic conductivity function describes the relationship between the unsaturated hydraulic conductivity and volumetric water content or pressure head (Hwang and Powers, 2003). Soil physical properties, such as soil texture, affect hydraulic properties such as hydraulic conductivity. As soil physical properties change, so does the soil water characteristic curve and the hydraulic conductivity.

Hydraulic properties of soils are hysteretic in nature, i.e. diverse relationships between unsaturated hydraulic conductivity and volumetric water content exist depending on the wetting or drying events (van Schalkwyk and Vermaak, 2000). Soil hydraulic properties are highly variable in nature and a large amount of data is necessary to accurately represent the field value of unsaturated hydraulic conductivity (van Schalkwyk and Vermaak, 2000). Numerous methods have been developed to estimate hydraulic properties or determine them directly in the field or laboratory (Kool et al., 1987; Kabat et al., 1989).

Soil water retention curves are frequently determined in the laboratory using tension tables for high pressure head values and standard pressure plate apparatus in the lower pressure head range (Carter, 1993). In the field, hydraulic conductivity functions are determined by different techniques such as the instantaneous profile method, the crust method, various unit-gradient type techniques and sorptivity methods (Klute, 1986). Both field and laboratory procedures are cumbersome, expensive, time-consuming, labour intensive and they give only local scale results. Estimation of hydraulic properties is mostly limited to the water retention function and saturated hydraulic conductivity.

Only a small number of recently developed pedo-transfer functions using basic soil properties (e.g. particle-size distribution, organic matter content and bulk density) are available for the estimation of unsaturated hydraulic conductivity. Pedotransfer functions (PDFs) are an attractive substitute to the direct, costly and often difficult measurement of hydraulic properties of soils. Pedotransfer functions relate hydraulic properties to more easily measured soil data such as soil texture (sand, silt and clay), organic matter content and other data measured regularly by soil surveys (Bouma and Van Laden, 1987). According to Papagiannakis and Fredlund (1984), the indirect determination of unsaturated hydraulic properties has been found adequate for most practical cases and therefore the direct application of methods to determine unsaturated hydraulic conductivity has become satisfactory.

2.7.2 Soil Water Retention

According to Shaw (1994), soil water cannot only be thought of in terms of masses and volumes, but also in terms of the amount of energy needed for water movement or for the retention of water by the soil (potential energy). It is safe to assume that because the movement of water through the voids within the soil is slow, the energy (kinetic energy) needed to move the water is insignificant. The potential energy is thus the prevailing force and can result from gravity, capillary and adsorptive forces. Therefore the soil water potential is the energy needed to overcome the forces acting on the soil water above a reference datum (Shaw, 1994).

The relation between matric potential and volumetric water content for a particular soil is known as a soil water characteristic curve or soil water retention curve (Fetter, 1999). Matric potential is defined as the At atmospheric pressure, the soil is saturated with water (θ_s), where θ_s is the volumetric water content at saturation; the soil will remain saturated as the matric potential is gradually decreased and eventually the matric potential becomes sufficiently negative so that the water can begin to drain from the soil.

Moisture content continues to decline as the matric potential is lowered, until it reaches some irreducible water content or residual water content (θ_r). The soil moisture characteristic curve also shows the pore size distribution of the soil. Well-sorted soils have a narrower range of matric potentials over which water content changes compared to poorly-sorted soils. In well-sorted soils, most of the grains of a specific size are in a narrow range therefore, the pore sizes have a narrow range. The well-sorted soils have a higher bubbling pressure because they have a considerable fraction of large pores. However, once the well-sorted soils begin to de-saturate, they do so rapidly, again because of their balanced pore size distribution.

In Fetter (1999), there are some simple empirical solutions that can be used to relate water content of the soil to matric potential. Brooks and Corey (1966) used the following relationship:

$$\theta = \theta_r + (\theta_s - \theta_r)\,(\psi/h_b)^{-\lambda} \qquad (2.1)$$

where θ is the volumetric water content

θ_s is the volumetric water content at saturation

θ_r is the irreducible minimum water content

ψ is the matric potential

h_b is the bubbling pressure

λ is the experimentaly derived parameter

Brooks and Corey (1966) also defined an effective saturation, S_e, as

$$S_e = \frac{(S_w - \theta_r)}{(1 - \theta_r)} \tag{2.2}$$

Where S_w = the saturation ratio, θ/θ_s (Fetter, 1999)

Van Genuchten (1980) also derived an empirical relationship between matric potential and volumetric water content. He defined the relationship by the following expression:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\Psi|^n]^m} \quad (\theta_r \leq \theta \leq \theta_s) \tag{2.3}$$

$$n = \frac{1}{1-m} \tag{2.4}$$

$$\alpha = 1/h_b \ (2^{1/m} - 1)^{1-m} \tag{2.5}$$

where θ_r and θ_s refer to the residual and saturated volumetric water contents (L^3 L^{-3}), respectively, Ψ (L) is the soil water pressure head (matric potential); and α (L^{-1}), n (dimensionless) and m (dimensionless) are parameters which determine the shape of the θ (Ψ) curve. The residual water content, θ_r, is the water content value where the gradient, $d\theta/d\Psi$, becomes zero, which in theory occurs only as Ψ approaches infinity. In practice, however, θ_r is the water content at some large, but finite, negative value of Ψ. The parameter n determines the rate at which the S-shaped retention curve turns toward the ordinate for large negative values of Ψ, thus reflecting the steepness of the curve, while α equals approximately the inverse of the pressure head at the inflection point where $d\theta/d\Psi$ has its maximum value (Carter, 1993).

In order to find these Van Genuchten soil parameters, a soil water retention curve preferably ranging from a matric potential of 0 to a matric potential of -15 000 cm must be constructed (Fetter, 1999). For the purpose of this study a matric potential range from 1 to 510.9 was calculated and used to ease interpretation of graphical data.

In addition, most of the water and solute fluxes occur in the wet range of the soil water retention curve, along wetting fronts that are close to saturation conditions during infiltration events. The determination of data points for the soil water retention in the dry range is also very time- and labor consuming. The Eijkelkamp apparatus used in this study for the determination of soil water retention would have implied disturbance and re-packing of the core samples to be used in the pressure chamber to obtain the dry range of the water retention curve. It was therefore decided to concentrate on a detailed description of the soil water retention in the wet range only, and on undisturbed core samples

A dimensionless slope S_p is formed from the equation below:

$$S_p = \frac{S}{\theta_s - \theta_r} \qquad (2.6)$$

Where S is the slope of the line (on a logarithmic scale) determined graphically from the soil-water retention curve. The parameter m can be determined from the value of S_p using one of the following equations.

$$m = 1 - \exp(-0.8S_p) \qquad (0 < S_p \leq 1)$$

$$m = 1 - \frac{0.5755}{S_p} + \frac{0.1}{S_p^2} + \frac{0.025}{S_p^3} \qquad (S_p > 1) \qquad (2.7)$$

We can find the values of m and α from equations 2.7 and 2.5, respectively by, using the bubbling pressure from the soil water retention curve (Fetter, 1999).

2.7.3 Hydraulic Conductivity

Hydraulic conductivity is a soil property that describes the ease with which the soil pores permit water (not vapor) movement and it depends on the type of soil, porosity and the configuration of the soil pores. Hydraulic conductivity is a significant soil property when determining the potential for extensive groundwater contamination by a contaminating source. Soils with high hydraulic conductivities and large pore spaces are more likely for isolated attainment of contamination.

Hydraulic conductivity can be determined in a variety of ways. In practice, three common groups of methods are employed: field tests, laboratory tests, and empirical or semi-empirical methods based on grain diameter and grain size distribution, or simple hydraulic models (Domenico and Schwartz, 1998). The hydraulic conductivity of soil or rock depends on various physical factors, including porosity, particle size distribution, shape of particles and arrangement of particles. In general for unconsolidated porous media, hydraulic conductivity varies with particle size; clayey materials exhibit low values of hydraulic conductivity at saturation, whereas sands and gravels display high values (Todd and Mays, 2005).

2.7.3.1 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity represents the factor, other than the hydraulic gradient, which affects the flow of liquid through a porous medium. Properties of fluid, properties of the porous medium and the interaction between the fluid and the porous medium are three important factors affecting this flow (van Schalkwyk and Vermaak, 2000). In saturated soils, the hydraulic conductivity is represented as K_s and in unsaturated soils the hydraulic conductivity is represented as K.

The quantity of water per unit of time, Q, flowing through a column of saturated soil can be expressed by Darcy's Law, as follows:

$$Q = \frac{K_s A \Delta P}{L} \qquad (2.8)$$

Where K_s is the saturated hydraulic conductivity, A is the cross-sectional area of the column through which the water flows, ΔP is the hydrostatic pressure difference from the top of the column to the bottom of the column, and L is the length of the column. Since area A and length L of a given column are fixed, the rate of flow is determined by the hydraulic force ΔP driving the water through the soil (commonly gravity) and the saturated hydraulic conductivity K_s (van Schalkwyk and Vermaak, 2000).

According to van Schalkwyk and Vermaak (2000), saturated hydraulic conductivity can be calculated from soil type descriptions of different soil texture and structure. For this study, RETention Curve Program (RETC) was used to calculate saturated hydraulic conductivity from textural class descriptions based on the Rosetta v.1.0 model (1999). Rosetta v.1.0 is a model built into RETC as a neural network prediction of input and output values for different textural classes of soils. Hydraulic property measurements and techniques for estimating K_{sat} from retention characteristics can be found in Lorentz *et al.,* (2001).

2.7.3.2 Unsaturated Hydraulic Conductivity

In saturated rock or sediment, all the pores are filled with water, and most of them transmit water. However, unsaturated soils have a lower hydraulic conductivity since some of the pore space is filled with air and thus cannot transmit water (Fetter, 1999). Since unsaturated hydraulic conductivity is a very significant feature of the fluid flow analysis in the vadose zone, it is essential to be able to determine this property (van Schalkwyk and Vermaak, 2000).

The unsaturated hydraulic conductivity is a function of the water content of the soil: $K = K_s(\theta)$ and it can also be considered to be a function of the matric potential: $K = K_s(\Psi)$(Fetter, 1999). Unsaturated hydraulic conductivity can be measured in the field or laboratory, but both methods are tedious and time-consuming. Therefore, conductivity can be estimated by soil parameters obtained from water retention curves.

Van Genuchten (1980) combined an empirical S-shaped curve for the soil water retention function with pore size distribution theory of Mualem (1976) to derive a closed-form analytical expression for the unsaturated hydraulic conductivity. Except for saturated hydraulic conductivity, K_s, the resulting conductivity function contains parameters that can be estimated from measures of soil water retention data (Carter, 1993).

Van Genuchten (1980) derived expressions that relate the unsaturated hydraulic conductivity to both water content and pressure head. The relationship between the unsaturated hydraulic conductivity and the water content is

$$K(\theta) = K_s S_e^{1/2} [1 - (1 - S_e^{1/m})^m]^2 \qquad (2.9)$$

where

θ_s = volumetric water content at saturation

θ_r = irreducible minimum water content

S_e = $(\theta - \theta_r) / (\theta_s - \theta_r)$

$K(\theta)$ = unsaturated hydraulic conductivity at water content θ

K_s = saturated hydraulic conductivity

m = Van Genuchten soil parameter estimated from soil water retention curve

The corresponding relationship between the unsaturated hydraulic conductivity and pressure head is

$$K(h) = \frac{K_s \{1 - (\alpha h)^{n-1} [1+ (\alpha h)^n]^{-m}\}}{\{1=(\alpha h)^n\}^{m/2}} \qquad (2.10)$$

K(h) = hydraulic conductivity

h = pressure head

m = van Genuchten soil parameter estimated from soil water retention curve

n = dimensionless van Genuchten soil parameter affecting shape of soil water retention curve

α = van Genuchten soil parameter (inverse of α often referred to as the air entry value,or bubling pressure (Van Genuchten *et al.*, 1991; Fetter, 1999).

Equation 2.3 and 2.10 are analytical functions describing the θ (Ψ) and K(Ψ) relationships, respectively. According to (Van Genuchten *et al.*, 1991, p.30), the Hydaulic Conductivity model of Burdine (1953) can also be used effectively for determining unsaturated hydraulic conductivity.

2.7.4 Soil Porosity (ϵ)

The amount of pores in a soil and their size distribution are useful general indicators of the physical condition of soils. It is calculated from the bulk density and particle density, and can be expressed as a volume percentage. It is equivalent to the volume % water content at saturation as shown in 2.11 below:

$$(\epsilon)= 1 - \frac{\rho_{bulk}}{\rho_{solid}} \quad (X\ 100) \qquad (2.11)$$

Where ρ_{bulk} is the dry bulk density whilst ρ_{solid} is the particle density or density of the soil solid fraction and is approximated by the value of 2.6 g cm^3 (Mathewson, 1981; Bilskie, 2001).

The total soil porosity generally lies between 30% and 70% and may be used as very general indication of the level of compaction in a soil in a similar way as bulk density is used. However, it must be stressed that the values of total porosity should not be used as conclusive evidence for over- compaction problems in soils, but rather as indicators of likely risk. Furthermore, the calculation simply gives the overall volume percentage of the pores space and does not typify the size of the individual pores (Mathewson, 1981).

2.8: Models and Methods

2.8.1 Overview

There is no global methodology for groundwater vulnerability assessment, although numerous diverse approaches exist none of which is considered to be suitable for all situations as they serve different purposes and have different aims. These approaches are discussed in detail by Lindström (2005). For this study, the measurement of water retention data has been determined and the use of a numerical model was applied for assessment of scenarios of groundwater vulnerability to pollution.

2.8.2 Models for the vadose zone:

Numerous models of varying complexity that describe the contaminant transport in the vadose zone have been developed since the 1970s and are applied in a number of contamination studies. Models for the vadose zone are usually one-dimensional, meaning they only consider vertical flow. Several models are based on semi-empirical process descriptions of the lumped functional type, whilst others use more physical descriptions based on Richards's equation of flow through porous media and the advection-dispersion equation for movement of inorganic contaminants (Lindström, 2005). For vulnerability assessments, these models are occasionally applied to assess the travel time through and attenuation capacity within the vadose zone.

A simple numerical model, RETC, was used in this study to determine hydraulic parameters. Using another model, Macro 5.0, a sensitivity analysis was done for these variables.

2.8.3 RETC: model description

RETention Curve Program (RETC) for unsaturated soils, is a computer program which can be used to analyze the soil water retention and hydraulic conductivity functions of unsaturated soils. These hydraulic properties are key parameters in any quantitative description of water flow into and through the unsaturated zone of soils (van Genuchten et al., 1991).

The RETC program uses the parametric models of Brooks-Corey (1966) and Van Genuchten (1980) to represent the soil water retention curve, and the theoretical pore-size distribution models of Mualem (1976) and Burdine (1953) to determine the unsaturated hydraulic conductivity function from experiential soil water retention data. RETC uses equations 2.1 and 2.3 as retention models, and equations 2.9 and 2.10 as hydraulic conductivity models. The RETC program may be used to visualize the hydraulic conductivity from experimental soil water retention data assuming that one observed conductivity value is available. The program also permits the fitting of analytical functions simultaneously to observe water retention and hydraulic conductivity data. RETC uses a non-linear least-squares optimization approach to estimate the unknown model parameters from observed retention and/or conductivity or diffusivity data.

While the models used in RETC are intended to explain the unsaturated soil hydraulic properties for monotonic drying and wetting in homogenous soil, the code can simply be customized to account for more intricate flow processes such as hysteretic two-phase flow or preferential flow (van Genuchten et al., 1991).

2.8.4 MACRO: model description

MACRO is a one-dimensional model of variable- saturated water flow and reactive solute transport in macroporous soils. MACRO is a dual-permeability model, whereby the total soil porosity is partitioned into two flow regions (micropores and macropores), each characterized by a degree of saturation, conductivity, water flow rate, solute concentration, and solute flux density (Larsbo and Jarvis, 2003). It is the most extensively used model of its type, probably because it is physically-based, numerically robust for all hydrological soil types, even for long-term simulations (decades), fairly easy to use, and thrifty with regard to parameter requirements (Larsbo *et al*. 2002).

Despite the extensive adoption of the model in research and for management purposes such as pesticide registration, a number of restrictions in the model have been recognized since it was first introduced more than a decade ago. These restrictions have been enhanced upon by the improved version of the MACRO model (v 5.0) (Larsbo *et al*. 2002).

“Recent features include: (i) fully implicit numerical solutions for water, heat and solute transport in the matrix, for up to 60 numerical layers, (ii) use of a modified Van Genuchten retention function, (iii) new process descriptions and routines for pesticide volatilization at the soil surface and soil tillage and sealing/ consolidation, (iv) built-in pedotransfer functions and inverse capabilities for parameter estimation and model calibration, and (v) a user-friendly Windows interface, with built-in plot routines, linked to databases for archiving, documenting and retrieving simulations” (Larsbo et al. 2002: p.1).

2.8.5 Final considerations

Knowledge of the hydraulic properties of unsaturated soils is essential for most studies involving water flow and solute transport in the vadose zone. Modeling of the vadose zone thus enhances the ability of better understanding of subsurface behavior. The main vadose zone requirements relate to the estimation of infiltration rate which is complicated by the presence of preferential flow paths. The RETC model uses the soil water retention data to estimate soil hydraulic properties essential for modeling flow in the vadose zone. Most frequently used soil hydraulic functions are the functions of van Genuchten-Mualem (Van Genuchten, 1980) and Brooks-Corey-Burdine (Brooks and Corey, 1966), which has limited amount of variable coefficients.

Chapter Three
Materials and Methods

3.1: Introduction

Data for this study were collected and analyzed between March 2005 and April 2006. Field work, laboratory work and desktop work were applied to this research. Core samples were obtained from the drilling of five boreholes (maximum depth = 20m) at two typical sites (Malmesbury Group bedrock) of the Western Cape, namely in the Berg river catchment and at iThemba LABS (Cape Flats). All core samples were analyzed at the Soils lab (for sample preparation) and Hydraulics lab (for Eijkelkamp drying and suction procedures) in the Department of Earth Sciences, University of the Western Cape.

This chapter describes all the methods used in this study to measure the hydraulic properties of the vadose zone at two typical sites in the Western Cape. It includes site selection, drilling, drilling methods, measuring equipment and methods for determining hydraulic properties, and also methods for constructing the water retention curves. These water retention curves provide critical information on water content, matric potential and hydraulic conductivity relationships needed for numerical modeling.

3.2: Field work

3.2.1 Site selection

The selection of two typical locations in the Berg river and at iThemba LABS (Cape Flats) was made to obtain several undisturbed core samples from which the hydraulic properties of the unsaturated zone at these typical sites could be determined to assess groundwater vulnerability to pollution. In total, five boreholes were drilled, two of which were at the iThemba site, (Cape Flats) and another three at the Berg river site (in the vicinity of Riebeek West).

The sites selected formed part of the experiments carried out for two research projects, namely “Land Use Impacts on Salinity in Western Cape Waters” (Water Research Commission project No. K5/1503) and “Improved Methods for Aquifer Vulnerability Assessments and Protocols for Producing Vulnerability Maps, Taking into Account Information on Soils” (Water Research Commission project No. K5/1432).

For the purpose of this study the selected boreholes were named and located (using GPS) in drilling sequence as follows:

Ithemba site 1: S 34.02621°
E 018.71555°
Elevation: 10m

Ithemba site 2: S 34.02346°
E018.71764 °
Elevation: 5m

Bergriver site 1: S 33.18872°
E 018.53822°
Elevation: 129m

Bergriver site 2: S 33.18863°
E 018.53.700°
Elevation: 109m

Bergriver site 3: S 33.23390°
E 019.01142°
Elevation: 78m

The two typical sites of investigation, namely Berg river and iThemba Labs site are shown in figure 3.1

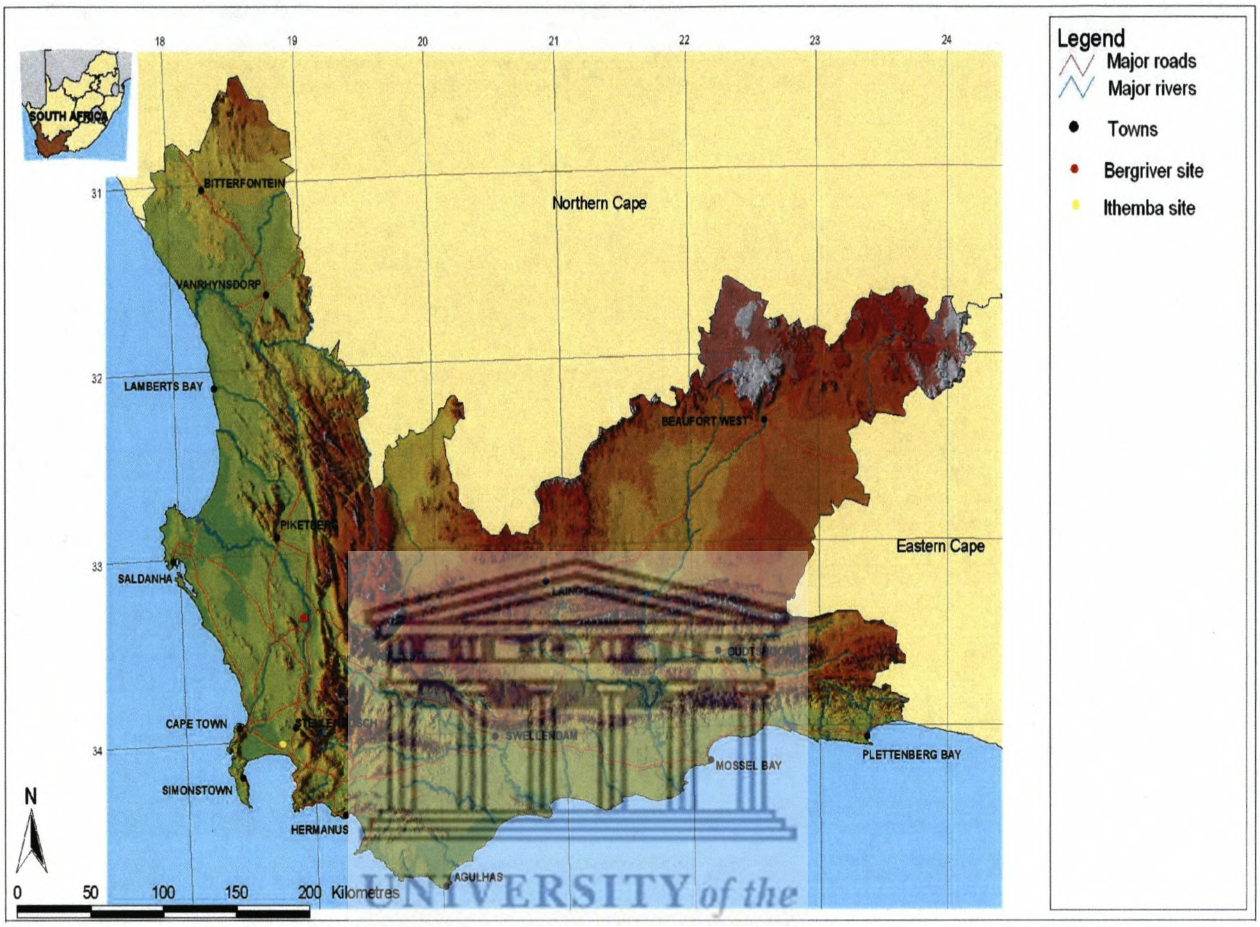

Figure 3.1: Environmental Potential Atlas, DEAT (2000), showing borehole site locations investigated in this study, namely Berg river (Riebeek West) and iThemba LABS (Cape Flats), Western Cape.

3.2.2: Drilling equipment and procedures

3.2.2.1 Drilling equipment:

The following equipment was used for drilling of the five boreholes:

A one gear drilling machine
Auger (volume= 3,535cm^3)
Drill Collars (volume= 5,775cm^3)
Barrel (volume= 17,530cm^3)
Generator + Rubber Pipe (diameter=4cm)
EZEEMIX and Water
5 meter measuring tape
Plastic storage bags (volume= 1L)

3.2.2.2 Drilling Procedures:

Drilling of the five boreholes commenced on 4March 2005 and lasted until the end of April 2005. The first two boreholes were drilled at iThemba LABS (Cape Flats). For these two boreholes namely iThemba site 1 and iThemba site 2, hand augering was done for the first 1.5 meters.

For iThemba site 1, the drill collars (volume=5,775cm^3) were used. For the subsequent four boreholes a barrel (volume= 17,530cm^3) was used upfront to ease the drilling allowing for increase in penetration rate and stability of the drilling machine with increased depth. The rotary drilling was accompanied by the use of a mixture of 0.5% EZEEMIX and water. EZEEMIX is a partially hydrolysed polyacrylamide/ polyacrylate copolymer (PHPA) emulsion that is used to stabilize reactive clay and shale formations and improve lubrication allowing easier penetration through these formations and preventing the borehole walls to collapse. EZEEMIX did not have an effect on the pore spaces of samples since lubricates were only used on the outer part of the core drill (barrel), thus it did not flow into the samples.

Mixing occurred in manually dug 1m^2 hole next to the drilling machine and the mixture was pumped through a rubber pipe from the hole to the drilling machine using a generator (see figure 3.2). This was done for all the boreholes drilled.

For the iThemba site, the initial aim was to drill until bedrock (Malmesbury shale) was entirely reached. However, the drilling of iThemba sites 1 and 2 ceased at 14.5meter and 18.5meter depths respectively due to the instability of the drilling machine with increased depths. For relevance to the project, the maximum drilling depth for Berg river site was restricted to 20meters per borehole. Due to the instability of the drilling machine and slow penetration rate with increase depths, the Berg river sites 1, 2, and 3 were restricted to 18.5, 20 and 14m respectively. Undisturbed core samples were taken for every 0.5m -1.5m and were placed in (1L) plastic storage bags labeled with accurate sample depths. In total, 76 undisturbed core samples where taken at various depths from the five boreholes. The samples were taken for textural description before the experiments proceeded. The fieldwork and laboratory analyses were done intermittently for each borehole.

3.3: Borehole log descriptions:

The descriptions of all five boreholes were prepared to accurately describe the vadose zone lithology of the typical sites selected. These borehole log descriptions were baseline data in this study as they assisted in parametrization for modeling and interpretation of hydraulic properties of the vadose zone.

Due to the presence of water during drilling, small amounts of core were lost and these have been indicated in the borehole logs. Color descriptions were made using the Munsell soil color charts (FAO, 1990). Soil descriptions were made with reference to soil description literature from FAO (1990) and, Gardiner and Dackombe (1983) (see Appendix B for borehole logs). A soil classification triangle was also used for description of soils and can be found at the back of Appendix B.

Figure 3.2: Illustrating the drilling setup (iThemba site 1) which includes: the drilling machine, generator, and $1m^2$ hole (where mixing 0.5%EZEEMIX with water occurred).

3.4: Laboratory work

3.4.1 Measuring Equipment:

The measuring equipment included a balance, elastic bands, a filter cloth ($8cm^2$), oven foil containers (1.71g), soaking tank, sandbox, claybox + manometer, samples rings (PVC and stainless steel), universal oven and vacuum pump.

3.4.2 Sample preparation:

For the determination of the moisture characteristic using the sandbox method undisturbed samples is needed. In total, 76 undisturbed core samples were prepared in the Soils laboratory, Department of Earth Sciences, UWC. Four different sets of sample rings with different volumes were used in this experiment (volumes are included in results: chapter four). The samples were carefully incised into the cores to attain undisturbed samples needed for proper experimental results. The soil-filled samples rings were covered at the bottom with filter cloths using elastic bands. This was done to allow firm contact between core sample and the material used within the Eijkelkamp drying and suction equipment (sandbox and claybox). The samples were also covered with a lid at the top to prevent evaporation of moisture from the sample.

Each sample was numbered according to precise depth obtained from drilling allowing appropriate reference in the borehole descriptions and soil-water retention curves.

3.4.3 pF Determination

3.4.3.1 Introduction

Water is attracted to the soil particles by capillary forces. The combination of these capillary forces is known as moisture pressure. There exists an association between the moisture pressure and amount of moisture for every soil type which is represented by the soil water retention (Fetter, 1999).

The pressure can be expressed as logarithm with base 10 and is referred to as pF. The moisture characteristic, obtained from the pF and moisture percentage is referred to as the pF curve/or water retention curve (Eijkelkamp, User Manual; **www.eijkelkamp.com**). The soil water retention curves in this experiment were determined by using the Eijkelkamp sandbox/ claybox (drying and suction equipment). Four water retention measurement runs were done. The samples of iThemba site 1 and 2 were used in one run. The first water retention run was done for Berg river site 1 during May 2005, whereby the other boreholes' experiment runs followed.

3.4.3.2 Saturating the soil

Saturating the core samples is an important part of the measurements as satisfactory results depend on samples being well saturated. A filter cloth (8 cm^2) was tightened to the bottom part of the sample rings using elastic band. The samples were placed in a soaking tank filled with tap water approximately $^1/_4$ the height of the ring and were left to soak for 7 days until saturation was reached. After saturating the samples, each sample was weighed on a balance to get the saturation weight measurements (Eijkelkamp, User Manual; www.eijkelkamp.com). The saturated samples were then taken to the Hydraulics lab (UWC) for sandbox and claybox methods (pF determination).

3.4.3.3 Drying using Sandbox

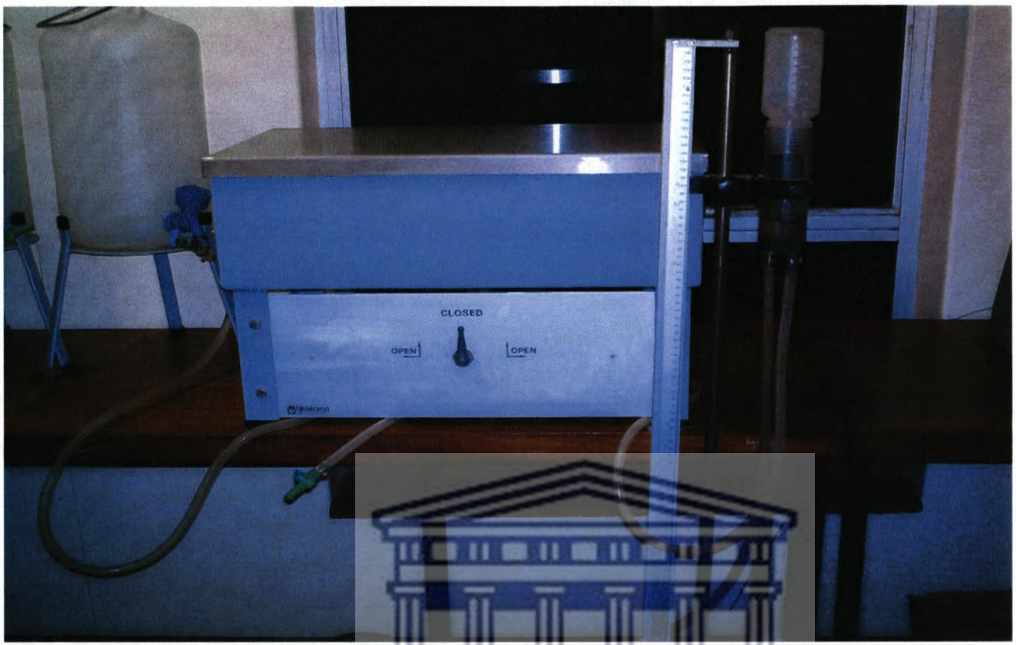

Figure 3.3: Eijkelkamp Sandbox setup in the Hydraulics lab (UWC)

The sandbox method is used to determine the pF of the samples from 0 bar to 0.1 bar. The samples are then moved to the clay/kaolin box, which determines the pF at greater suction pressures (Eijkelkamp, User Manual; www.eijkelkamp.com). One needs to check that all hoses in the sandbox are filled with water and no air bubbles must be present in these hoses. This is to ensure that no air is present as this would prevent water from being drained. The sandbox was filled with water approximately 1 mm above the surface, thereby saturating the sandbox (Eijkelkamp, User Manual; www.eijkelkamp.com).

The sample rings were then placed in the sandbox and pressed lightly downwards to ensure a good contact between the sand and the sample. Cover lids (PVC or stainless steel) were placed on the sample rings to prevent evaporation from the samples. The suction regulator was then returned to approximately 0 bar. The samples were left in the sandbox for three days after which they were weight and then returned to sandbox. When returning the samples to the sandbox, the lid of the sandbox was placed back on the box to prevent evaporation from occurring (Eijkelkamp, User Manual; **www.eijkelkamp.com**).

Water was drained from the sandbox by moving the water bottle (that is attached to a 100cm to 0 cm ruler to the right of the sandbox), downwards (Figure 3.3). The elevation distance of the bottle from the middle of the sample rings can be read on the ruler and it corresponded to the gravitational pressure applied. The water release (drying) levels used in these experiments are shown in table 4.7, chapter 4. The samples were weighed at regular intervals (three days) until a constant reading was achieved (water equilibrium between the sand in the box and the soil in the ring). After four mass readings for each sample in the sandbox, the samples were removed and placed into the clay box where higher suction levels were applied to the samples. This was done for all 76 samples (in experimental sequence). The same 76 samples used in the sandbox were used in the claybox and throughout the experiments.

3.4.3.4 Suction using Clay/Kaolin box

The clay/kaolin box determines the pF between 0.2 and 0.5 bars. This box is filled with the same sand as the sandbox, but is covered with a layer of kaolin clay. The kaolin box was saturated in the same way as the sand box. The samples were weighed and placed on the kaolin surface and were pressed slightly down to form a good contact between the samples and the kaolin. The covers were placed on the samples to prevent evaporation from the samples.

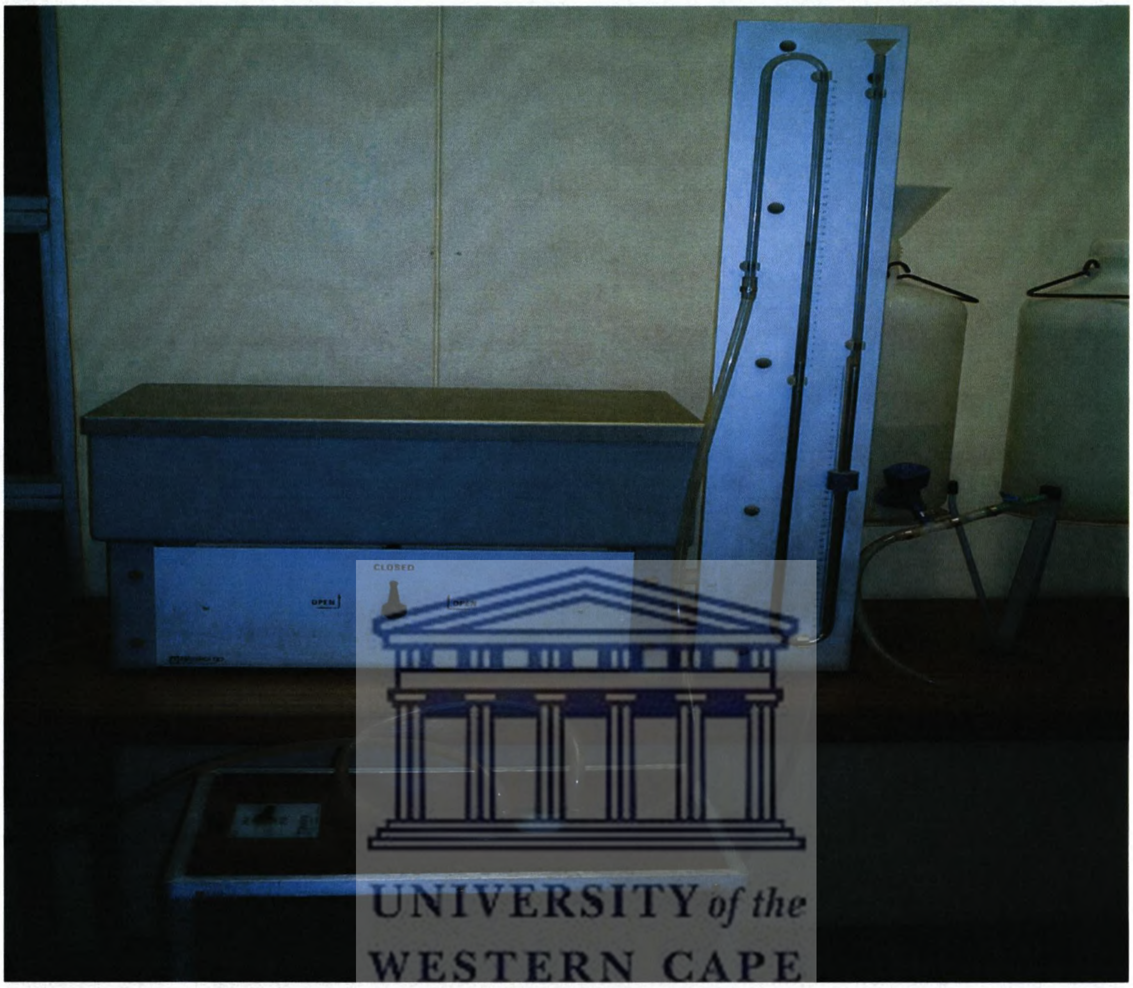

Figure 3.4: Eijkelkamp clay box setup in the Hydraulics lab (UWC)

Water release was done with a vacuum pump (bottom of Figure 3.4). The lid was placed on the clay box to prevent evaporation from occurring (Eijkelkamp, User Manual; www.eijkelkamp.com).

The samples were allowed to stay in the box for 3-4 days. This allowed for water equilibration, and mass readings were taken at regular intervals until the difference was negligible (approximately 0.5g); the mass readings were then recorded at the relevant suction values (Eijkelkamp, User Manual; **www.eijkelkamp.com**). The instructions were repeated for higher suction values (see table 4.7). This was done for all 76 samples.

3.4.3.5 Oven drying

The moisture percentage of a soil sample at pF 7 (104bar) is assumed to be zero. To achieve this, the soil samples need to be dehydrated by means of oven drying (Eijkelkamp, User Manual; www.eijkelkamp.com).

To determine the moisture percentage at pF 7, the soil needs to be removed from the clay box and placed into the oven and dried at approximately 105 degrees Celsius. One needs to note, however, that it is important not to loose any soil particles during this process as this will affect the weight of the sample (Eijkelkamp, User Manual; www.eijkelkamp.com).

Before the samples were placed into the oven, they were removed from the sample ring. The sample rings with cover lids, (8cm^2) filter cloth and elastic bands were weighed. The elastic band and filter cloth were air dried and weighed. It is important to weigh everything that is used to hold the sample when it is in the ring as it contributes significantly to the determination of pF 7, important for calculating the bulk density and volumetric water content from mass readings. The raw samples were placed in foil containers (1.71g) which were then put into the universal oven at 105°C for one day (24 hours). When doing this, it is important to note that no soil particles should be lost as this will affect the weight of the sample. After two days, the samples were taken from the oven and the final weighing was done for the batch of samples. The tabulated measurements can be found in Appendix A.

3.5: Determining points on the soil water retention curve

As mentioned in the literature review, the soil water retention curve is the relationship between the matric potential (or pressure head) and the volumetric water content for a particular soil (Fetter, 1999).

To construct the water retention curves, the tabulated data from the experiments (see chapter 4) were used. These data were used to determine gravimetric and volumetric water content, bulk density and matric potentials. The following calculations were done using raw data obtained from the Eijkelkamp sandbox and claybox:

3.5.1 Gravimetric water content (θ_g)

Gravimetric water content is the mass of water per mass of dry soil. It is measured by weighing a soil sample (m_{wet}), drying the sample to remove the water, then weighing the dried soil (m_{dry}).

$$(\theta_g) = \frac{m_{water}}{m_{soil}} = \frac{m_{wet} - m_{dry}}{m_{dry}} \qquad (3.1)$$

3.5.2 Bulk density (ρ_{bulk})

Bulk density measurements are made primarily as guide to soil compaction and porosity. Bulk density refers to the overall density of a soil (i.e. the mass of mineral soil divided by the overall volume occupied by soil,water and air). The weight of soil solids in bulk density measurements is taken as the oven-dry constant weight at 105°C and is expressed as g cm^{-3}.

$$\rho_{bulk} = \frac{m}{V} \qquad (3.2)$$

Where m= mass of soil (g), and v = volume of sample ring (cm^3)

3.5.3 Volumetric water content (θ)

Volumetric water content is the volume of liquid water per volume of soil. Volume is the ratio of mass to density (ρ) which gives:

$$\boldsymbol{(\theta)} = \frac{V_{water}}{V_{soil}} = \frac{\frac{m_{water}}{\rho_{water}}}{\frac{m_{soil}}{\rho_{soil}}} = \frac{\theta_g * \rho_{soil}}{\rho_{water}} \qquad (3.3)$$

Where θ_g is the gravimetric water content

3.5.4 Matric potential (Ψ)

As mentioned previously in chapter 2, the water retention curve represents the relationship between the matric potential and volumetric water content. To construct the water retention curves, matric potential (Ψ) was determined as follows:

The sandbox water release (drying) levels were calculated by subtracting each drying level from the length of the sandbox ruler (100cm). Note: for the first level at saturation, the matric potential was chosen as 1 to allow for proper construction of water retention curves on a logarithmic scale. Negative values or zero values cannot be plotted correctly on logarithmic charts. The matric potential for drying values are given in table 4.7. The equation 3.4 below is for calculation of matric potential by using claybox suction levels; these calculated suction levels can be found in table 4.7 along with the relevant matric potential measurements are also given in table 4.7.

$$\Psi = H_1 + 13.6\, H_2 \qquad (3.4)$$

Where H_1= height from manometer to vacuum pump (suction path = 45cm) (Figure 3.4)

H_2 = suction level read on the manometer (cm), and

13.6 = conversion factor for mercury manometer

By using the above given equations (3.1 - 3.4), the water retention curves were plotted for all 76 samples with Ψ on the y-axis and θ on the x-axis.

3.6 Final considerations

It is important to notice that the materials and methods used in this study are vital in measuring the water retention of undisturbed soil samples. Therefore, this methodology is an extremely important part of the study as it provided the basis for most accurate estimates of hydraulic conductivity. No pressure plate apparatus was used in the measurements as the samples needed to be undisturbed in order to use them in the pressure chamber. The methodology is somewhat labor-intensive and time-consuming. It also needs high level of care for the prevention of erroneous measurements from occurring, by disturbing or over-or-under saturating the samples. Most of the water movement will occur in the wet range therefore recognizing the wet range (high end) determination of water retention as vital in this study. It is very unlikely that the clayey samples will not reach air entry since we assume that the samples reach air entry at 0.33 bar.

Chapter Four

Experimental Results and Discussion

4.1 Introduction

The results of the water retention experiments are tabulated and discussed in this chapter. They mainly served as a database, which assisted the purposes of modeling in chapter 5.

Water retention curves (WRC) play a crucial role in describing soil hydraulic behavior. These raw measurements are tabulated in Appendix A.

4.2 Experimental Results

4.2.1 Gravimetric water content

Gravimetric water content was calculated according to equation 3.1 given in chapter 3. Gravimetric water content was determined for all five borehole sites and depths whereby significant differences were observed for different layers (see tables A2.1-A2.5 in Appendix A (2)).

4.2.2 Bulk Density

Bulk density measurements for all samples were determined using eq. 3.2 in chapter 3. According to Mathewson (1981), the bulk densities of clay, clay loam and silt loam topsoils may vary between 1.00 and 1.60 g cm^{-3} depending on their condition. Sands and sandy loams typically show variations between about 1.20 and 1.80 g cm^{-3}. There is frequently a tendency for bulk density values to increase with depth, as effects of cultivation and organic matter content decline. Very compact subsoils, of any texture, may have bulk densities exceeding 2 g cm^{-3}. Bulk densities above 1.75 g cm^{-3} for sands, or 1.46 to 1.63 g cm^{-3} for silts and clays, are known to cause interference to root penetration (Mathewson, 1981). Typical bulk density ranges according to Mathewson, (1981) are given below:

Table 4.1: Typical bulk density ranges (after Mathewson, 1981)

Material	**Bulk Density (g cm^{-3})**
Recently cultivated soils	0.9 – 1.2
Surface mineral soils, not recently cultivated, but not compacted	1.1 – 1.4
Soils showing root restriction:	
Sands and Loams	< 1.6 – 1.8
Silts	< 1.4 – 1.6
Clays	Extremely Variable

Bulk density (g cm^{-3}) measurements of all the experimental samples are given and interpreted below:

Table 4.2: Bulk density values for iThemba site 1

Sample depth (m)	Texture/ Lithology	Bulk density (g cm^{-3})
topsoil	loamy sand	1.084
0.5m	sand	1.326
1m	loamy sand	1.429
1.5m	silt	1.394
2.5m	loamy sand	1.277
3m	sand	1.399
4m	sandy clay loam	1.473
6.5m	sandy loam	1.349
7m	silt loam	1.389
8.5m	clay	1.541
10m	clay	1.472
12m	clay	1.648
13m	clay	1.511
14.5m	clay	1.68

Table 4.3: Bulk density values for iThemba site 2

Sample depth (m)	Texture/ Lithology	Bulk density (g cm^{-3})
topsoil	sandy loam	1.106
0.5m	loamy sand	1.219
1m	loamy sand	1.265
2m	clay loam	1.419
3m	sandy loam	1.302
4m	silty clay	1.503
5m	silty clay	1.405
6m	clay	1.566
7m	clay	1.276
8.5m	silty clay	1.49
10m	Malmesbury Shale	1.877
11.5m	Malmesbury Shale	1.607
13m	Malmesbury Shale	1.654
15.5m	Malmesbury Shale	1.531
17m	Malmesbury Shale	1.593
18.5m	Malmesbury Shale	1.648

Table 4.4: Bulk density values for Berg river site 1

Sample Depth (m)	Texture/Lithology	Bulk density (g cm^{-3})
topsoil	sandy clay loam	1.334
1m	clay	1.521
1.8m	clay	1.266
3.3m	clay	1.303
4.8m	clay	1.108
5.8m	clay	1.709
6.3m	clay	1.287
7m	Malmesbury Shale	1.639
8.5m	Malmesbury Shale	1.322
10.5m	Malmesbury Shale	1.439
11.5m	Malmesbury Shale	1.621
13.8m	Malmesbury Shale	1.375
15.3m	Malmesbury Shale	1.729
16.5m	Malmesbury Shale	1.548
17.7m	Malmesbury Shale	1.414
18.5m	Malmesbury Shale	1.507

Table 4.5: Bulk density values for Berg river site 2

Sample depth (m)	Texture/Lithology	Bulk density (g cm^{-3})
Topsoil	clay loam	1.243
0.9	sandy clay	1.64
2.2	silt loam	1.597
3	silt	1.446
4	silt	1.209
5	silt loam	1.576
6.5	clay	1.459
7.5	silty clay	1.53
8.2	clay	1.466
10	Malmesbury Shale	1.388
10.8	Malmesbury Shale	1.496
11.5	Malmesbury Shale	1.426
12.5	Malmesbury Shale	1.677
15	sandy loam	1.291
16.2	Malmesbury Shale	1.65
17.5	Malmesbury Shale	1.605
18.5	Malmesbury Shale	1.643
20	Malmesbury Shale	1.611

Table 4.6: Bulk density values for Berg river site 3

Sample depth (m)	Texture/Lithology	Bulk density (g cm^{-3})
topsoil	sandy loam	1.182
1.4	clay	1.499
2.5	clay	1.381
4	Malmesbury shale	1.402
5.5	Malmesbury shale	1.628
6	Malmesbury shale	1.451
7.5	Malmesbury shale	1.338
9	Malmesbury shale	1.452
10	sandstone	1.551
11	sandstone	1.514
13	sandstone	1.494
14	sandstone	1.477

4.2.2.1 Results and Interpretation:

The topsoil of iThemba site 1 is grassed and manifests recent cultivation, an increase in bulk density values with depth is present, possibly due to effects of cultivation and organic matter content decrease. The sands have a close range between 1.326 to 1.399 g cm^{-3}, loamy sands have a wide range from 1.084 for topsoil to 1.473 g cm^{-3} at increased depth. Clays range between 1.472 and 1.680 g cm^{-3} whereas the one silt sample measured 1.394 g cm^{-3}. No Malmesbury shales were found at iThemba site 1 due to shallow depth of drilling at this site. Therefore, all the above bulk density measurements for iThemba site 1, fall within the bulk density ranges given by Mathewson (1981). An decreasing –increasing undulation in bulk density values with increasing depth exists for the Malmesbury shales at Ithemba site 2. These values range from 1.531 to 1.877 g cm^{-3}, also being the highest bulk density value for all samples determined in this study. Loams range from 1.106 for topsoil to 1.419 g cm^{-3}, clays between 1.276 and 1.566 g cm^{-3} and silty clay between 1.405 and 1.503 g cm^{-3}.

At berg river site 1, bulk densities for clays are extremely variable ranging between 1.108 and 1.709 g cm^{-3}. This can be due to the different structure of clays at this site, which at certain depths were slack material (especially near surface) and firmly structured material at depth. The Malmesbury shales range between 1.321 and 1.729 g cm^{-3}, a much wider range compared to the shales found at iThemba site 2. This can be due to the different geology in the Berg river catchment (more clayey type of environment) compared to the Cape Flats. The bulk densities for samples from Berg river site 2 range from 1.209 t to.677 g cm^{-3}. The loams range between 1.243 to 1.597 g cm^{-3}, whereas the two samples of clay shows small variation ranging from 1.459 to 1.466 g cm^{3}. Silts at this site ranges between 1.209 to 1.446 and silty clay is 1.530 g cm^{-3}, and the Malmesbury shales between 1.388 and 1.677 g cm^{-3}, showing the highest bulk density for this site. Berg river site 3 exhibits also a sandstone layer which bulk density range between 1.477 and 1.551 g cm^{-3}. The Malmesbury shales follow a similar range as at Berg river site 2, ranging from 1.338 to 1.628 g cm^{-3}. Topsoil bears evident of recent cultivation with bulk density of 1.182 g cm^{-3} with clay ranging between 1.381and 1.499 g cm^{-3}.

Overall, the bulk densities of all samples in this study fall within the typical ranges indicated by Mathewson (1981), the topsoils all being loamy with some showing evidence of recent cultivation. Topsoils of Berg river sites 1 and 2 showed their nature of surface mineral soils, not recently cultivated, but not compacted. The bulk densities of clay show a much larger variation for the Berg river site than for the iThemba site.

At these two typical sites, the Malmesbury shales also show a variation between bulk densities, with iThemba having the largest bulk density measurement and the Berg river site showing a similar range of bulk density values between the three sites. This can be due to the geology and origin of soils at the Berg river sites compared to iThemba. The weathered Malmesbury group bedrock at Ithemba site is covered with recent Cenozoic sandy soil and the Malmesbuy group weathered sediments are exposed in most parts of the Berg river site. However, in layers of similar texture found at corresponding depths, there are typically vast differences in the bulk density values depending on organic matter, root penetration and soil structure (Mathewson, 1981)

4.2.3 Volumetric water content

Volumetric water content is a very important measurement in water retention curve determination. It provides values for plotting the water retention curve. It also includes residual water content and water content at saturation, which are two parameters used in chapter 5 in the RETC model. The volumetric water content thus emphasizes the water content which was retained by the soil throughout the experiments. The volumetric water content is calculated using equation 3.3 in chapter 3 and is measured in (cm^3 water/ cm^3 soil). All values of volumetric water content for each borehole were used in RETC for modeling purposes in (chapter 5). These measurements are given in tables A3.1 – A3.5

(see Appendix A(3)). Note: the saturated volumetric water content in this study was related to matric potential equal to1cm, for notational convenience of constructing the water retention curves on a logarithmic scale.

4.2.4 Matric Potential

The matric potential was given by the moisture pressure levels of drying and suction applied to the soils during the experiment. These values were used to construct the water retention curve i.e. matric potential (y-axis) against volumetric water content (x-axis). These measurements were also used in RETC modeling, chapter 5. The following drying (sandbox) and suction (claybox) levels with corresponding matric potential values are given in table 4.7 below:

Table 4.7: Measurements of matric potential from drying and suction values

Drying & suction levels (cm)	Matric Potential (cm)
Drying (sandbox)	
100cm	0
85cm	15
70cm	30
55cm	45
Suction (claybox)	
10cm (5cm + 5cm)	184.5
20cm (10cm + 10cm)	320.5
34cm (17cm + 17cm)	510.9

The water release (drying) levels were read off the ruler of the sandbox (Figure 3.3), whilst the suction levels of the claybox were read off the mercury manometer (Figure 3.4). Note that negative or zero values cannot be plotted on log charts, but only positive values can be used on a logarithmic scale. Due to this, the matric potential value measured at 0cm was set as 1cm on the graphs (Figure 4.1 and in Appendix C). The values for matric potential were plotted against volumetric water content to construct the water retention curves for all samples in this study. Typical retention curves obtained from these measurements (different sites and depths) are shown below:

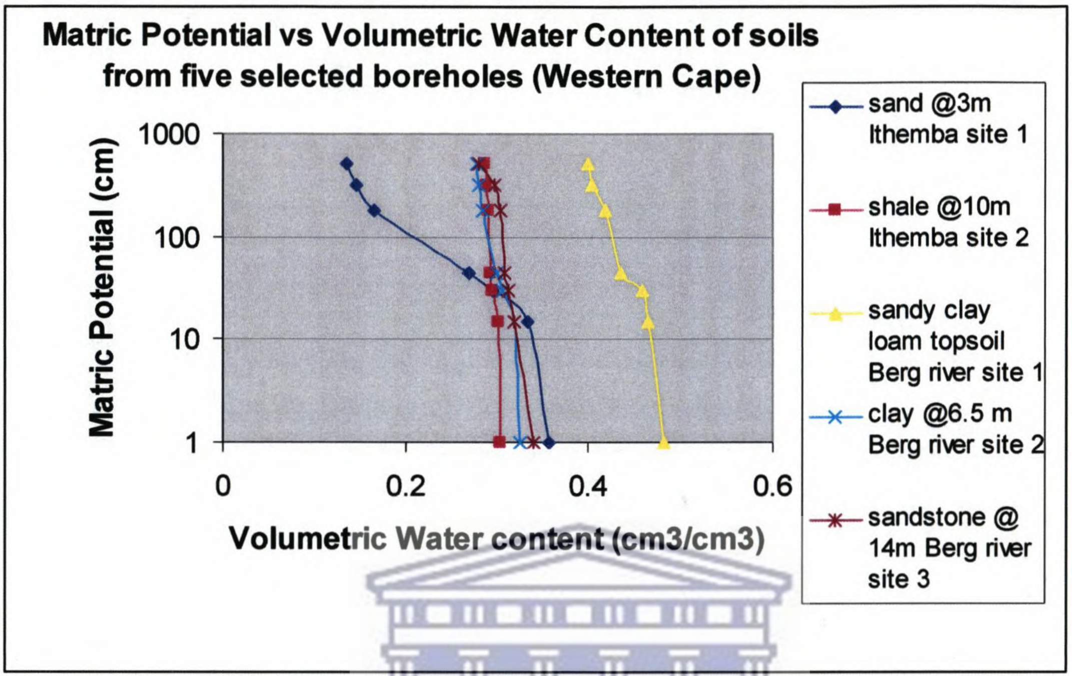

Figure 4: Matric Potential (cm) vs Volumetric Water Content of soils from five selected boreholes in the Western Cape (iThemba LABS and Berg river catchment).

The above superimposed curves give an indication that the volumetric water content for clay, shale and clay loams decreases slowly with increased matric potential in the wet range. This is typical for low permeability materials. For sands, the volumetric water content decreases rapidly with an increase in matric potential in the wet range, thus indicating higher permeability soils. Most of the retention curves follow a similar shape especially for Malmesbury shales, clays and silts. Curves for sands and loamy sands are observed to follow similar shapes. This is due to their textural constituency. The poorly sorted sands and less poorly sorted loamy sands have a narrower range of matric potential over which the water content changes than the well sorted soil. The poorly sorted soils have a higher bubbling pressure because it has slightly larger pores.

However, once the poorly sorted soil begins to desaturate, it does so rapidly, once more because more of the pore spaces are large. Appendix C includes all retention curves with sample photos of the core samples in the sampling rings, showing the colour and texture of the sample material. By using the retention curve data, models, e.g. RETC, can predict various soil hydraulic parameters which are important for modeling the water flow and solute transport in the vadose zone (see chapter 5).

4.2.5 **Soil Porosity**

Soil porosity was also measured in this study by using equation 2.11 given in chapter 2. The results are shown in tables below:

Table 4.8 Soil Porosity, iThemba site 1

Sample depth (m)	Texture/Lithology	Soil Porosity (%)
topsoil	loamy sand	58.3
0.5m	sand	49.0
1m	loamy sand	45.0
1.5m	silt	46.4
2.5m	loamy sand	50.8
3m	sand	46.2
4m	sandy clay loam	43.3
6.5m	sandy loam	48.2
7m	silt loam	46.6
8.5m	clay	40.7
10m	clay	43.4
12m	clay	36.6
13m	clay	41.9
14.5m	clay	35.4

Table 4.9: Soil Porosity, iThemba site 2

Sample depth (m)	Texture/Lithology	Soil Porosity (%)
topsoil	sandy loam	57.5
0.5m	loamy sand	53.1
1m	loamy sand	51.3
2m	clay loam	45.4
3m	sandy loam	49.9
4m	silty clay	42.2
5m	silty clay	46.0
6m	clay	39.8
7m	clay	50.9
8.5m	silty clay	42.7
10m	Malmesbury Shale	27.8
11.5m	Malmesbury Shale	38.2
13m	Malmesbury Shale	36.4
15.5m	Malmesbury Shale	41.1
17m	Malmesbury Shale	38.7
18.5m	Malmesbury Shale	36.6

Table 4.10: Soil Porosity, Berg river site 1

Sample Depth (m)	Texture/Lithology	Soil Porosity (%)
topsoil	sandy clay loam	48.7
1m	clay	41.5
1.8m	clay	51.3
3.3m	clay	49.9
4.8m	clay	57.4
5.8m	clay	34.2
6.3m	clay	50.5
7m	Malmesbury Shale	37.0
8.5m	Malmesbury Shale	49.2
10.5m	Malmesbury Shale	44.6
11.5m	Malmesbury Shale	37.6
13.8m	Malmesbury Shale	47.1
15.3m	Malmesbury Shale	33.5
16.5m	Malmesbury Shale	40.5
17.7m	Malmesbury Shale	45.6
18.5m	Malmesbury Shale	42.0

Table 4.11: Soil Porosity, Berg river site 2

sample depth (m)	Texture/Lithology	Soil Porosity (%)
Topsoil	clay loam	52.2
0.9	sandy clay	36.9
2.2	silt loam	38.6
3	silt	44.4
4	silt	53.5
5	silt loam	39.4
6.5	clay	43.9
7.5	silty clay	41.1
8.2	clay	43.6
10	Malmesbury Shale	46.6
10.8	Malmesbury Shale	42.5
11.5	Malmesbury Shale	45.2
12.5	Malmesbury Shale	35.5
15	sandy loam	50.3
16.2	Malmesbury Shale	36.5
17.5	Malmesbury Shale	38.2
18.5	Malmesbury Shale	36.8
20	Malmesbury Shale	38.0

Table 4.12: Soil Porosity, Berg river site 3

Sample depth (m)	Texture/Lithology	Soil Porosity (%)
topsoil	sandy loam	54.5
1.4	clay	42.3
2.5	clay	46.9
4	Malmesbury shale	46.1
5.5	Malmesbury shale	37.4
6	Malmesbury shale	44.2
7.5	Malmesbury shale	48.5
9	Malmesbury shale	44.2
10	Sandstone	40.3
11	Sandstone	41.8
13	Sandstone	42.5
14	Sandstone	43.2

4.2.5.1 Results and Interpretation:

These calculated soil porosity values lie between 27.8% and 58.3% for all samples measured. The soil porosity for samples at iThemba site 1 ranges from 35.4% to 58.3%, where sands and loams have porosities between 43.3% and 58.3%, clays range between 35.5% and 43.4% with silt at 46.4%. Here, loamy sand (topsoil) has the highest porosity and clays the lowest. At iThemba site 2, soil porosity ranges between 27.8% and 57.5%. The loams range between 45.4% and 57.5%; clays between 39.8% and 50.9%; silty clays between 42.2% to 46%, and Malmesbury shales between 27.8% and 41.1%. Here, the Malmesbury shales have the lowest soil porosity values and the loams the highest. This indicates that cultivation of soils decreases compactness of the soil and thus increases the porosity, as seen in most topsoils being sandy or clay loams. Whereas, for Malmesbury shales which are deeper situated in the subsurface, lower porosity was measured because of higher compaction of the soil. . However, at 7 meter depth at Ithemba site 2, the porosity is high (50.9%) which may be due to the depositional nature of these marine sediments where the clays are weathered and the shales are semi weathered.

The soil porosity at the Berg river site 1 ranges from 33.5% to 57.8%. The clays range between 34.2% and 57.4%. Malmesbury shales from 33.5% to 49.2% and sandy clay loam topsoil have porosity of 48.7%. According to these results, clay tends to have the highest porosity and the Malmesbury shales the lowest, which might be due to the weathered condition of clay as appose to the Malmesbury shales. At the Berg river site 2, soil porosity ranges from 36.5% to 53.5%. Loams have a wide range from 38.6% to 52.2%, whereas the clays range between 36.9 and 43.9%. The silts range between 44.4% and 53.5% showing the highest value for soil porosity at this site with the lowest being that of Malmesbury shale ranging between 36.5% and 46.6%.

The soil porosity at Berg river site 3 shows a range from 37.4% to 54.5%.The Malmesbury shales shows the widest range here which is from 37.4% to 48.5%, clays from 42.3% to 46.9%, sandstone shows the narrowest range of all textural/lithological groups from 40.3% to 43,2%, and sandy loam topsoil showing the highest value for soil porosity equal to 54.5%. Here, it is again evident that the cultivation of soils affects the compactness of soil and thus increases the porosity.

The overall interpretation is that the highest range of soil porosity values exists for topsoils which is from 48.7% to 58.3%. This can be due to the less compact nature of the topsoil. In most instances the compactness of the soil determines the porosity values where less compact soils associates with higher porosity values. Thus the compactness of soil can be deduced from soil porosity. There exists an inverse relationship between the soil porosity and the bulk density, where an increase in bulk density will decrease the soil porosity and vice versa.

4.2.6 Final considerations

The values of porosity calculated with equation 2.11 show a noticeable difference compared to the measured volumetric water content values at saturation (matric potential = 0 cm). This can be as a result of core samples not properly saturated due to air trapped inside the soil samples, compaction under natural conditions and mineralogy. The measured saturation values (volumetric water content at matric potential = 0 cm) were used in RETC for all 76 core samples.

Chapter Five
Modeling: RETC

5.1 Introduction:

Due to the growing evidence that the quality of the subsurface environment is being harmfully affected by anthropogenic activities, computer models are nowadays regularly used to envisage the movement of water and chemicals into and through the unsaturated zone of soils. Such models can be used effectively only if reliable estimates of the flow and transport properties of the medium are accessible (Van Genuchten et al., 1991).

This chapter aids in achieving reliable estimates of flow properties of the vadose zone. The RETC model, which is a numerical model for the determination of soil water retention and hydraulic conductivity functions, was used for this purpose. The results and interpretation of the modeling are discussed in this chapter.

5.2 Soil Hydraulic Estimates:

The RETC model includes the Rosetta Lite v.1.0 (Feb.1999) database of hydraulic properties. These properties can be selected by the user of RETC based on the textural class and they appear by default. The values are summarized in Table 5.1

Table 5.1: Average values for selected soil water retention and hydraulic conductivity parameters for 12 major textural groups (after Rosetta Lite v.1.0, Feb.1999)

Texture	θr	θs	α (1/cm)	n	Ksat (cm/d)
Sand	0.0530	0.3747	0.0353	3.1798	642.98
Loamy sand	0.0485	0.3904	0.0347	1.7466	105.12
Sandy loam	0.0387	0.3870	0.0267	1.4484	38.25
Loam	0.0609	0.3991	0.0111	1.4737	12.04
Silt	0.0501	0.4887	0.0066	1.6769	43.74
Silt loam	0.0645	0.4387	0.0051	1.6626	18.26
Sandy clay loam	0.0633	0.3837	0.0211	1.3298	13.19
Clay loam	0.0792	0.4418	0.0158	1.4145	8.18
Silty clay loam	0.0901	0.4820	0.0084	1.5202	11.11
Sandy clay	0.1169	0.3854	0.0334	1.2067	11.35
Silty clay	0.1108	0.4808	0.0162	1.3207	9.61
clay	0.0982	0.4588	0.0150	1.2529	14.75

In table 5.1, θr = residual water content, θs = saturated water content, alpha (α) and n = shape factors, Ksat = saturated hydraulic conductivity. The RETC model was used to calculate the soil hydraulic parameters from water retention data for all samples in this study. In order to plot water retention and hydraulic conductivity functions, residual soil water content and saturated hydraulic conductivity from the Rosetta database were used (Table 5.1), based on the textural class.

5.3 Results:

The soil hydraulic properties of all samples collected in this study were calculated from six different types of model using RETC. These models are Retention Curve models with associated Conductivity model for each as shown in Table 5.2:

Table 5.2: RETC types models

Retention Curve Model	**Conductivity model**
Van Genuchten variable m, n	(Mualem)
Van Genuchten variable m, n	(Burdine)
Van Genuchten m= 1-1/n	(Mualem)
Van Genuchten m= 1-2/n	(Burdine)
Brooks and Corey	(Mualem)
Brooks and Corey	(Burdine)

The RETC program was run for each of these retention curve models for every sample using the measured retention curve data. This allowed for a data-rich output from which the database of hydraulic properties was constructed. Using the RETC model, the variables n, α, and θ_s were determined, which are essential in the prediction of water flow through the vadose zone. The results are tabulated and sited in Appendix D. A summary table indicating the typical ranges from lowest to highest values for each soil hydraulic parameter obtained from each model and for all five borehole sites is given in Table 5.3.

Table 5.3: Typical ranges (from lowest to highest) of soil hydraulic estimates for 5 borehole sites using 6 different RETC types of models

<table>
<tr><th colspan="5">1. Van Genuchten variable m,n (Mualem)</th></tr>
<tr><th>Borehole site</th><th>Theta R (cm3/cm3)</th><th>Theta S (cm3/cm3)</th><th>Alpha (1/cm)</th><th>n</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2960 - 0.4039</td><td>0.0027 - 0.4460</td><td>1.005 - 8.0667</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2752 - 0.5413</td><td>0.0002 - 0.2154</td><td>1.005 - 9.7757</td></tr>
<tr><td>Bergriver site 1</td><td>0.0633 - 0.0982</td><td>0.3036 - 0.4781</td><td>0.0344 - 0.4715</td><td>1.005 - 5.8908</td></tr>
<tr><td>Bergriver site 2</td><td>0.0387 - 0.1169</td><td>0.2295 - 0.3976</td><td>0.0087 - 0.2888</td><td>1.005 - 10.279</td></tr>
<tr><td>Bergriver site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4213</td><td>0.1391 - 9.2057</td><td>1.005 - 6.9055</td></tr>
<tr><th colspan="5">2. Van Genuchten variable m,n (Burdine)</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2959 - 0.3877</td><td>0.0022 - 0.4423</td><td>2.005 - 8.2004</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2745- 0.5406</td><td>0.0012 - 8.0379</td><td>2.005 - 13.9282</td></tr>
<tr><td>Berg river site 1</td><td>0.0633 - 0.0982</td><td>0.3036 - 0.482</td><td>0.0559 - 0.4653</td><td>3.3132 - 10.7041</td></tr>
<tr><td>Berg river site 2</td><td>0.0387 - 0.1169</td><td>0.2221 - 0.3952</td><td>0.0020 - 0.2858</td><td>2.005 - 12.8385</td></tr>
<tr><td>Berg river site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4213</td><td>0.1391 - 9.1925</td><td>2.005 - 7.1095</td></tr>
<tr><th colspan="5">3. Van Genuchten m=1-1/n</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2971 - 0.4047</td><td>0.0087 - 0.7742</td><td>1.0256 - 1.7139</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2768 - 0.5419</td><td>0.0004 - 0.5471</td><td>1.0120 -1.7449</td></tr>
<tr><td>Berg river site 1</td><td>0.0633 - 0.0982</td><td>0.3045 - 0.4848</td><td>0.0334 - 1.1717</td><td>1.0053 - 1.0818</td></tr>
<tr><td>Berg river site 2</td><td>0.0387 - 0.1169</td><td>0.2406 - 0.3991</td><td>0.0472 - 0.4008</td><td>1.0205 - 1.2593</td></tr>
<tr><td>Berg river site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4214</td><td>0.1093 - 9.2209</td><td>1.0523- 1.0100</td></tr>
<tr><th colspan="5">4. Van Genuchten m=1-2/n</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2964 - 0.4032</td><td>0.0207 - 0.4947</td><td>2.0255- 2.5758</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2739 - 0.5412</td><td>0.0017 - 1.1746</td><td>2.0101 - 2.4789</td></tr>
<tr><td>Berg river site 1</td><td>0.0633 - 0.0982</td><td>0.3038 - 0.4823</td><td>0.0534 - 0.5371</td><td>2.0054 - 2.0733</td></tr>
<tr><td>Berg river site 2</td><td>0.0387 - 0.1169</td><td>0.2381 - 0.3974</td><td>0.0725 - 0.3093</td><td>2.0201 - 2.2557</td></tr>
<tr><td>Berg river site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4213</td><td>0.1383 - 9.1533</td><td>2.0101 - 2.0482</td></tr>
<tr><th colspan="5">5. Brooks and Corey (Mualem)</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2959 - 0.3896</td><td>0.0120 - 0.2164</td><td>0.0256 - 0.4320</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2726 - 0.5406</td><td>0.0063 - 1.1654</td><td>0.0155 - 0.4199</td></tr>
<tr><td>Berg river site 1</td><td>0.0633 - 0.0982</td><td>0.3036 - 0.4443</td><td>0.0024 - 0.4569</td><td>0.0054 - 0.5869</td></tr>
<tr><td>Berg river site 2</td><td>0.0387 - 0.1169</td><td>0.2373 - 0.3967</td><td>0.0743 - 0.2853</td><td>0.0204 - 0.2602</td></tr>
<tr><td>Berg river site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4213</td><td>0.1389 - 9.1925</td><td>0.0101 - 0.0482</td></tr>
<tr><th colspan="5">6. Brooks and Corey (Burdine)</th></tr>
<tr><td>iThemba site 1</td><td>0.0387 - 0.0982</td><td>0.2959 - 0.3896</td><td>0.0120 - 0.2164</td><td>0.02564 - 0.4320</td></tr>
<tr><td>iThemba site 2</td><td>0.0387 - 0.1108</td><td>0.2726 - 0.5406</td><td>0.0063 - 1.1654</td><td>0.01559 - 0.4199</td></tr>
<tr><td>Berg river site 1</td><td>0.0633 - 0.0982</td><td>0.3036 - 0.4443</td><td>0.0024 - 0.4569</td><td>0.00547 - 0.5869</td></tr>
<tr><td>Berg river site 2</td><td>0.0387 - 0.1169</td><td>0.2373 - 0.3967</td><td>0.0743 - 0.2853</td><td>0.02041 - 0.2602</td></tr>
<tr><td>Berg river site 3</td><td>0.0387 - 0.1169</td><td>0.3207 - 0.4213</td><td>0.1389 - 9.1925</td><td>0.0101 - 0.0482</td></tr>
</table>

The values for all hydraulic parameters vary significantly from borehole to borehole as well as through layers of similar textural classes. According to the results from the Van Genuchten variable m,n (Mualem), some similar estimates for n = 1.005 were found for all boreholes with different textural classes and at different depths. At iThemba site 2 (van Genuchten variable m,n; Mualem) values for n= 1.005 and 2.005 were found at various depths and correspondingly include textures/lithologies such as sandy loam, clay, Malmesbury shales, silty clay and loamy sand.

iThemba site 1:

The n values are the highest in sand, sandy loam and the lowest in clay and silt. The highest alpha (α) values are in loams and the lowest in clays. The θ_s values at this site are the highest in silt and the lowest in clays, whereas θ_r values are the highest in clay and the lowest in sandy clay loam. The hydraulic parameters vary widely for each model, mainly due to differences in input data and default values at the beginning of iterations.

iThemba site 2:

As mentioned before, some n values are identical at various depths and textures (these values were also the lowest at this site). High values for n were found in clay (according to the Van Genuchten models) and loamy sand (according to the Brooks & Corey models). Alpha (α) values are the highest for Malmesbury shales and the lowest in silty clays. The θ_s is high in clay and low in loamy sand, whereas the θ_r is high in silty clay and low in the topsoil. Data obtained with the Van Genuchten model at this site were used in Macro 5.0 (chapter 6).

Berg river site 1:

The values for n are the highest in shale and the lowest in topsoil according to the Van Genuchten model. The opposite was found with the Brooks & Corey model. The Alpha (α) values are the highest in shale and the lowest in topsoil (Brooks & Corey model) and shale (Van Genuchten model).

The θ_s value is high in topsoil and low in shale, whereas the clay has the highest and topsoil has the lowest θ_r values. At this site, the α and n values are inversely related and thus they determine the shape of the retention curve.

Berg river site 2:

The highest n is found in sandy and clay loams and the lowest in sandy clay (Brooks& Corey) and silt loam (Van Genuchten). The alpha (α) values is the highest in shales and the lowest in silt loam. All models show the lowest and the highest value for θ_s being in silt loam and for θ_r the sandy clay has the highest and sandy loam has the lowest estimates. This site also produced consistent values for estimates of hydraulic properties and it was also used in Macro 5.0 along with iThemba site 2 in chapter 6.

Bergriver site 3:

In Berg river site 3, soil hydraulic estimate results of n have the highest values in sandstone (Van Genuchten) and sandy loam (Brooks & Corey). The lowest values are also found in sandstones (Van Genuchten with variable m,n) and clays (Van Genuchten m=1-1/n and m=1-2/n; Brooks & Corey). The Alpha values here are the highest in shales and the lowest in sandstones. The highest θ_s value is in topsoil and the lowest in shales, whereas the highest value is in sandstone and the lowest in topsoil.

The Brooks & Corey (BC) models give inadequate estimates of less than 1 for n throughout the modeling in this study, since n is limited to values greater than one (van Genuchten, 1980). The values for K_{sat} were taken from the build-in Rosetta v.1. Lite. This was a limitation of the study as measurements of K_{sat} would have been more appropriate. No textural classes for shales and sandstone are included in the model database and their K_{sat} were assumed to be equal to those of clay and sandy clay, respectively. These values are listed along with the RETC soil hydraulic parameter outputs in Appendix D. Most of the K_{sat} estimates have low values as most of the samples consist of clays, shales and silts. Most of iThemba profile tops are sandy and loamy textures as well as the topsoils at the Berg river site, and higher K_{sat} values were therefore selected.

Characteristic graphs of hydraulic properties, log (h) vs log (K), were plotted with the RETC model and examples of different samples using different retention models are shown below (Figures 5.1 – 5.5). The Brooks & Corey and Van Genuchten models show variance in shape of curves mainly due to different model inputs. Appendix E includes the entire log (h) vs K graph database obtained with RETC.

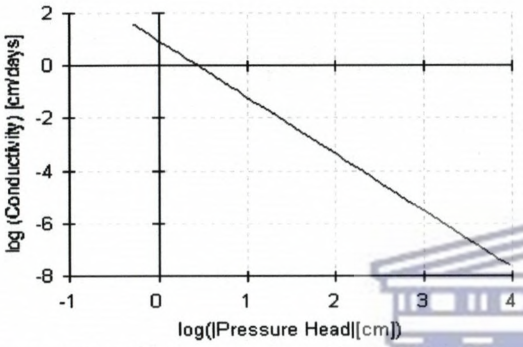

Figure 5.1: RETC graph of log (h) vs log (K) for Berg river site 3, topsoil
(Van Genuchten variable m,n –Mualem)

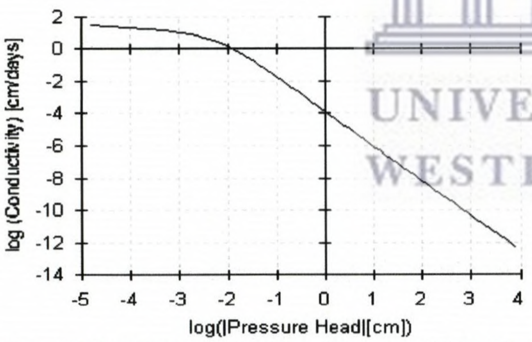

Figure 5.2: RETC graph of log (h) vs log (K) for Berg river site 3, topsoil
(Brooks & Corey –Mualem)

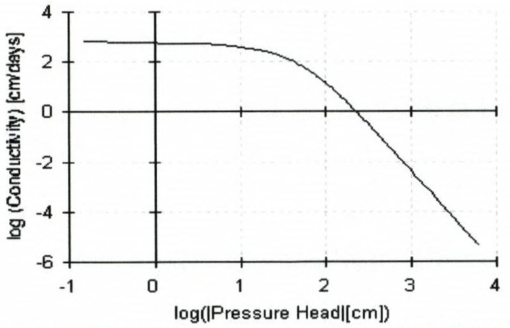

Fig. 5.3: RETC graph of log (h) vs log (K) for iThemba site 1, sand
(Van Genuchten m=1-1/n)

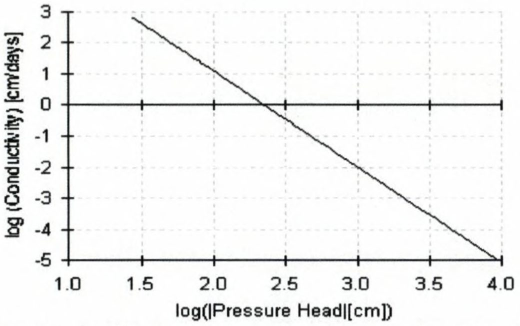

Fig 5.4: RETC graph of log (h) vs log (K) for iThemba site 1, sand (Brooks-Corey-Mualem)

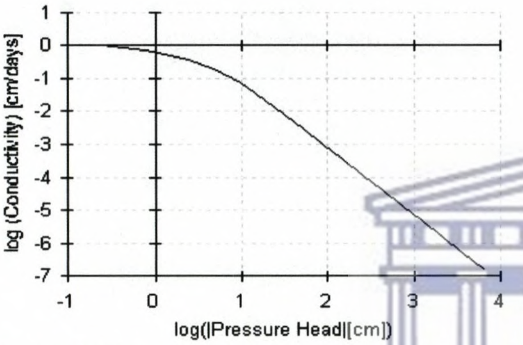

Fig 5.5: RETC graph of log (h) vs log (K) for Berg river site 1, Malmesbury shale (Van Genuchten m=1-2/n)

The above graphs show the graphical relationship between the logarithmic pressures head values and hydraulic conductivity. It can be interpreted that the hydraulic conductivity decreases with increasing log of pressure head. The Brooks & Corey model for sands gives a smoother function over a wider range of pressure head compared to the Van Genuchten model. The Brooks & Corey model applied to topsoil of Bergriver site 3 is also smooth but with a narrower pressure head range and lower values of hydraulic conductivity compared to sandy soils. The graphs follow similar patterns for similar soil textures at different depths. The Malmesbury shales follow an almost similar pattern to the clays, because similar inputs were used. The two typical sites, namely Berg river and iThemba, have different soil textural descriptions in the soil zone, but the clays at depth exhibit characteristic trends of hydraulic properties.

An example of output data file of RETC is shown in Appendix F.

Chapter Six
Sensitivity Analysis: Macro 5.0.

6.1 Introduction:

Macro is a one dimensional Windows-based dual permeability model of water flow and solute transport in structured macroporous soils. It considers non steady state fluxes of water, heat and solute for a variable saturated layered soil profile (Larsbo and Jarvis, 2003).

The complex flow patterns inherent in dual-permeability models represent a difficult numerical problem (Ray et al., 1997). Macro offers a steady and robust solution by decoupling calculations in the computer program with regards to the flow domains (Larsbo and Jarvis, 2003). For the purpose of this study, Macro was used to execute a sensitivity analysis on some data obtained in this study.

6.2 Input and Output data

Two scenarios were run representing each of the two sites. The sensitivity of the output was therefore tested against different inputs of soil properties and climatic conditions for the two sites. The output data analyzed were the volumetric water contents and leaching (groundwater contamination) for the period between 1 January 2003 and 1 January 2005. The input and output data used for both iThemba site 1 and Berg river site 1, are shown in Tables 6.1 to 6.3 and explained below:

Table 6.1: Soil data input for a 1meter soil profile at iThemba site 1

iThemba site 1:	**Textures**	
Soil parameter estimates	**Loamy Sand**	**Sand**
α	0.017	0.014
n	1.370	1.710
Ksat (mm/h)	43.8	267.9
θr (%)	4.8	5.3
θs (%)	40	40
Bulk density gcm^{-3}	1.084	1.326

The data in Table 6.1 were used as soil data input to simulate water content and solute leaching at the iThemba site 1 using Macro 5.0. The soil hydraulic estimates from the Van Genuchten model with m=1-1/n (RETC) were used. Additional selective input data were also used in Macro 5.0 to run the sensitivity analysis. These input data were chosen as follows:

User-defined water contents (initial boundary condition), pressure potential (lower boundary condition), no irrigation with no drainage system installed, perennial crop, pesticide (parent compound) as simulated solute (for leaching) and kinetic sorption with zero degradation in kinetic pool and sorption distribution coefficient equal to 1.1 cm^3/g. At iThemba site 1 the amount of pesticide as initial solute concentration in soil water was set as 1 mg/m^2. The soil at this site is not irrigated and no cultivation is done to change properties such as porosity and bulk density which may affect the water balance.

The soil input data from Table 6.2 were used to simulate water content and solute leaching at the Berg river site 1 using Macro 5.0. Similarly to iThemba site 1, the soil hydraulic estimates from the Van Genuchten m=1-2/n (RETC) were used at Berg river site 1. The additional selective input data at the Berg river site 1 were chosen as follows: user-defined water contents (initial boundary conditions), pressure potential (lower boundary condition), irrigation applied, annual crop rotation, pesticide (parent compound) as solute simulated for leaching, kinetic sorption with zero degradation in kinetic pool sorption distribution coefficient equal to 1.3 cm^3/g. A pesticide concentration in soil water of 2 mg/m^2 was selected at Berg river site 1 due to agricultural activity the site. The initial solute concentration of irrigation water was set at 2 mg/m^2. The pesticide concentration in the irrigation water was applied only once during 2003 and 2004, respectively. The solute leaching and water content was simulated for a one meter soil profile at the Berg river site. This was also done for the iThemba site. The water table at Berg river site is deeper than at iThemba site, therefore leaching at iThemba site did not reach the bottom boundary of the soil profile whereas leaching continued until the bottom boundary of soil profile at Berg river site.

Table 6.2: Soil data input for a 1meter soil profile at Berg river site 1

Berg river site1:	**Textures**	
Soil parameter estimates	**Sandy Clay loam**	**Clay**
α	0.103	0.069
n	1.058	1.053
Ksat (mm/h)	5.4	6.1
θr (%)	6	9
θs (%)	45	40
Bulk density gcm^{-3}	1.334	1.520

Two weather data files (from 1January 1993 to 31October 2005) were used to set up a simulation in Macro 5.0 for each site, the one containing only daily rainfall data, the second containing pre-calculated daily evaporation and transpiration data. These data were obtained from the South African Weather Service and for the purpose of this analysis the period from 1 January 2003 until 1 January 2005 were selected.

In this way, the sensitivity analysis was carried out by comparing two sites with different soil properties, management and climate. At the iThemba site, the soil is typically sandy and the climate characterized by winter rainfall. No irrigation was applied for the iThemba site scenario. At the Berg river site, the soil tends to be clayey. The Berg river site is also located in a winter rainfall area, but the total annual rainfall is lower compared to the iThemba site according to the 1993 to 2005 weather files obtained from the South African weather bureau.

At the Berg river site a pesticide concentration of 2 mg/m^2 was set as the initial solute concentration in irrigation water once for both 2003 and 2004.

The outputs that were considered for these scenario simulations were the same for both the iThemba site 1 and the Bergriver site 1. These are summarized in Table 6.3. Graphs for each of these outputs against time (1 January 2003 to 1 January 2005) were plotted respectively for each site.

Table 6.3: Outputs selected from Macro 5.0 for the scenario simulations for iThemba site 1 and Berg river site 1.

Outputs	**Measuring unit**
Water content (total)	m^3/m^3
Accumulated solute leaching (total)	mg/m^2

6.3 Results and Interpretation:

The sensitivity analysis of outputs is shown graphically for two typical sites, namely iThemba site 1 and Berg river site 1. These graphs indicate the total water content behaviour and solute leaching in the vadose zone at these two sites over a two year period (1January 2003 to 1 January 2005). The graphs were plotted in Microsoft Excel, using the Macro output data file which was converted from bin files to ASCII files. An example of output files of Macro 5.0 can be viewed in Appendix G. The output graphs are shown in Figures 6.1 to 6.6.

iThemba site 1:

Total soil water content

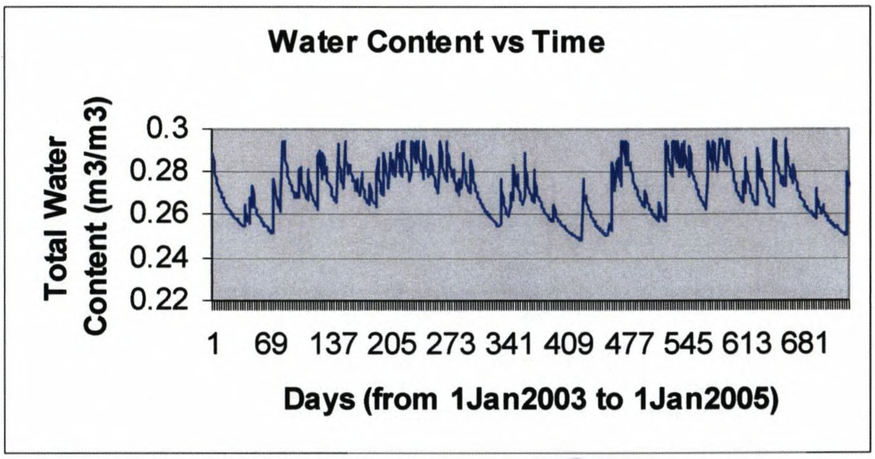

Figure 6.1: Water content vs time for topsoil, iThemba site 1 using Macro 5.0

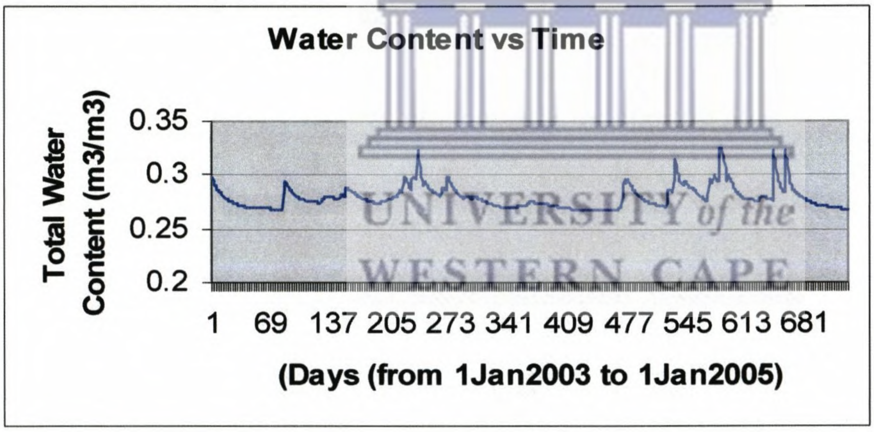

Figure 6.2 Water content vs time at 50cm depth, iThemba site 1 using Macro 5.0

From Figures 6.1 and 6.2, it is clear that the simulated water contents for this soil fluctuate depending on rainfall events and seasons. The data on the x-axis are given in days after the beginning of the simulation. At iThemba site 1, the simulated water contents of the topsoil range between 0.245 m^3/m^3 and 0.31 m^3/m^3, whereas the simulated water contents at 50cm depth range between 0.25 m^3/m^3 to 0.33 m^3/m^3. At iThemba site 1 the water content fluctuation in soil during the period of 1January 2003 and 1January 2005 shows a similar pattern for both the topsoil and at 50cm depth. This is due to the dynamics in infiltration and evaporation from the topsoil and the presence of a shallow perched water table. A rather wet two years can be associated with the small fluctuating values of water contents for the period of 1January 2003 until 1January 2005. This can be as a result of a better and more consistent rainfall period between 1January 2003 and January 2005. However, both Figures 6.1 and 6.2 show increases (peaks) in water content during the rainy months, which are usually June to August in the Western Cape for the period between 1January 2003 and 1January 2005.

Solute leaching

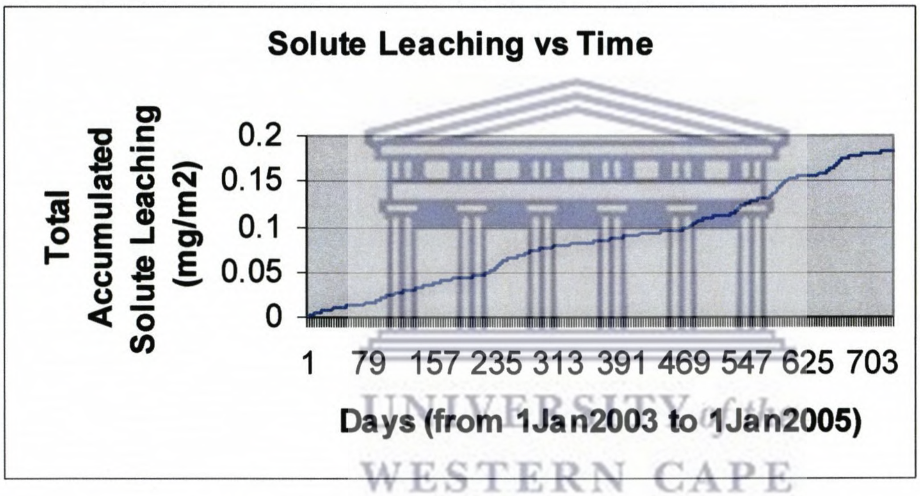

Figure 6.3: Solute leaching vs time for iThemba site 1, using Macro 5.0

From figure 6.3, it is evident that the simulated solute leaching at this site increased slower during the first month and afterwards followed a variable trend until 1 January 2005. From this graph it can also be interpreted that the leaching of solute probably continues after 1 January 2005 as the entire 1 mg/m^2 initial solute concentration in soil water did not leach in two years for this site.

Berg river site 1:
Total soil water content

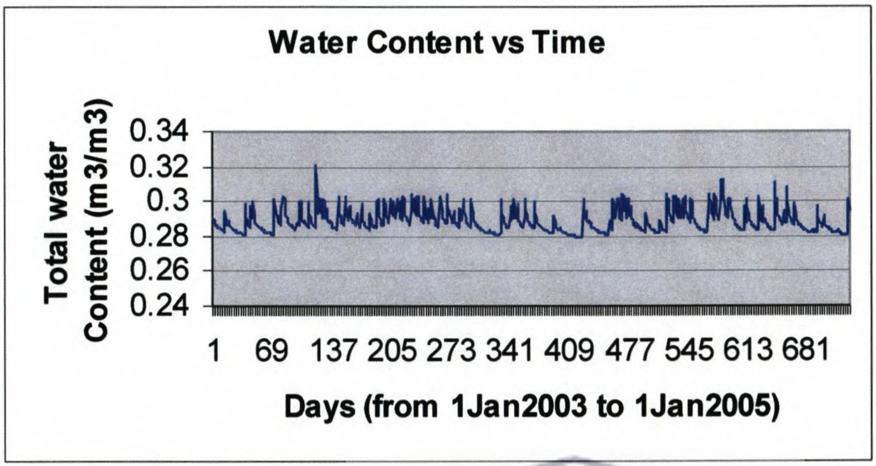

Figure 6.4: Water content vs time for topsoil, Berg river site 1 using Macro 5.0

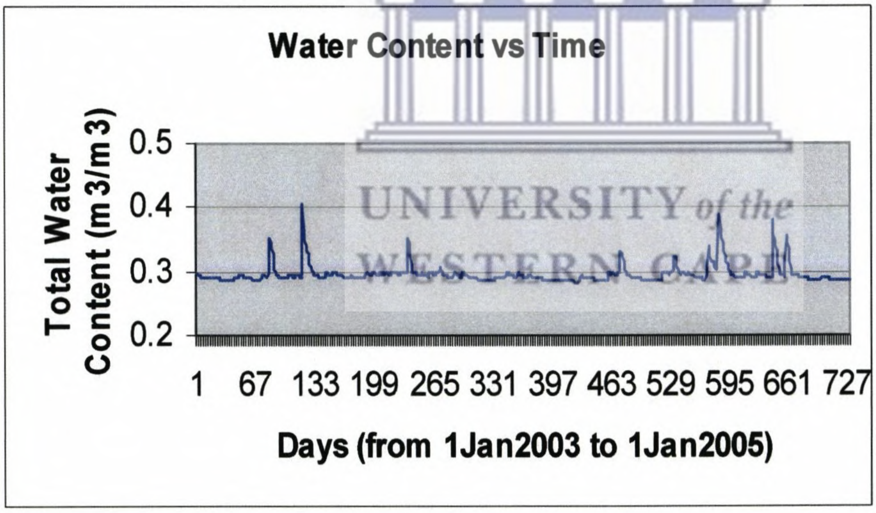

Figure 6.5 Water content vs time at 50cm depth, Berg river site 1 using Macro 5.0

From figure 6.4 and 6.5 a difference in simulated water content variation can be seen for topsoil (0.28 m^3/m^3 to 0.32 m^3/m^3) and 50cm depth (0.27 m^3/m^3 to 0.41 m^3/m^3), respectively. The topsoil water content for the Berg river site follows an almost similar pattern compared to the iThemba site, but a slightly higher water content was found at the Berg river site. However, the soil at 50 cm depth at the Berg river site has higher water contents compared to a similar depth at iThemba. This can be due to the higher soil water retention capacity of the soil at the Berg river site compared to iThemba.

At both sites, small peaks were simulated during certain periods due to exceptional rainfall events. Moreover, at Berg river site this increase in water contents (small peaks) might be due to the irrigation applied to this area having annual crop rotation. The agricultural activities practiced at this site allocate for irrigation only while the crop is growing. When the crop gets harvested the soil is left bare for the rest of the time until a new crop is planted. This can take up to three months thus exposing the soil to direct sunlight which increases the evaporation rate. Soil is also cultivated at this site which might change the soil properties such as porosity and bulk density which may affect the water balance.

Solute leaching

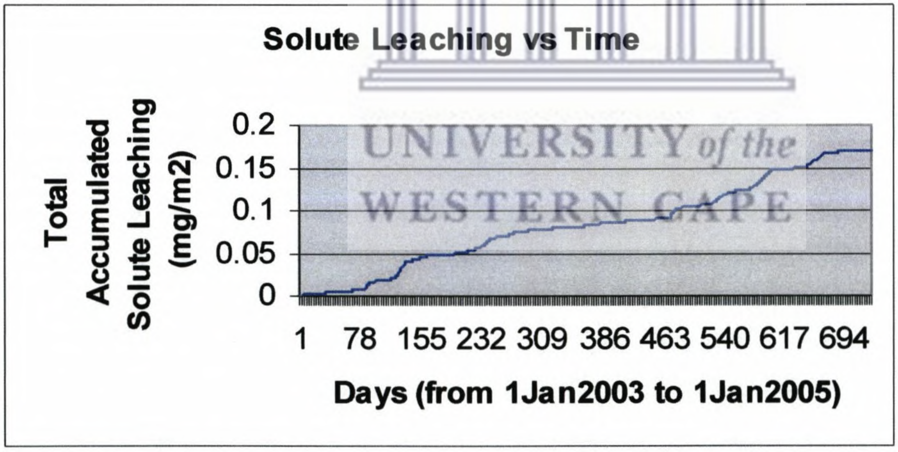

Figure 6.6: Solute leaching vs time at Berg river site 1, using Macro 5.0

Figure 6.6, shows a slow increase in total accumulated solute leaching for the first three months of 2003, at Berg river site 1. Subsequently the graph shows a steady but variable increase until the beginning of 2004 where it slows down for about three months and continues increasing until 1January 2005. The periods of fast solute leaching can in effect be associated with the application of pesticide in irrigation water which occurred once a year for both 2003 and 2004. A time lag between application of pesticide and increase in leaching rate can be observed.

More solute particles are attracted to the clayey soils at Berg river site than to the sandy soils at iThemba.

Therefore, it can be seen from figure 6.6 that the cumulative solute leaching is less at Berg river than at the iThemba site. The solute leaching at Berg river site continues for a longer period than at iThemba site and it is therefore evident that it takes a longer time for pesticides to leach at the Berg river site, but at lower rates, compared to the iThemba site. This indicates that the soils of the Berg river site are of lower permeability compared to the iThemba site, which has more permeable soils (sands and loams). As a result, groundwater vulnerability at iThemba is higher compared to the Berg river site.

6.4 **Final considerations:**

The sensitivity analysis done in Macro 5.0 provides conclusive results for water and solute transport situations in soils. In order to test the reliability of these types of process-based models, validation is required by comparison to measured data. This was, however, beyond the scope of the study. In addition, it is important to realize that the flow and transport of water or/ and solute can be modeled accurately only if data input is of significant quality. The output data of water content and leaching provided us with a better understanding of soil properties (storage and transmission).

Chapter Seven
Conclusions and Recommendations

7.1 **Conclusion:**

Hydraulic properties of the vadose zone can be evaluated using soil water retention data, which aids significantly in the modeling of water flow and solute transport. The soil water retention curve in the RETC program is mathematically fitted using the equations of Brooks & Corey or Van Genuchten, while the unsaturated hydraulic conductivity functions are formulated in terms of the statistical pore-size distribution models of Mualem and Burdine.

This study provides vital information on the vadose zone and serves as a database of hydraulic properties for vadose zone soils in the Cape Flats and also for the Malmesbury weathered bedrock (Western Cape). A natural variability in the hydraulic properties was observed and fairly low conductivities were inferred with depth. The bulk density values are known to have a strong affect on the Van Genuchten parameters and though not heavily examined in previous studies, this study strives to improve the lack of these measurements.

The Malmesbury shales show a similar pattern to clayey soils, with relatively similar low permeability values. Therefore it serves as a good aquiclude in the Riebeek West area (Bergriver) where agricultural activities are prevailing, thus restricting the transfer of pollutants to groundwater. At the iThemba site, a perched aquifer exists at shallow depth of 50cm to 2 meters which is overlain mainly by sandy and loamy material thus making this groundwater vulnerable to pollution. The major aquifer is situated much deeper (±40 meters) into the subsurface (Malmesbury Bedrock), which is again a good confinement for the groundwater from pollution.

In terms of vulnerability assessments, a need still exists for improved models of the vadose zone and thus more studies need to be implemented to enhance the reliability of assessing the groundwater pollution in South Africa.

The methods used in this study generally aim at identifying retention or conductivity properties and because of major advantages in computational techniques and computer power, estimation of the unsaturated soil hydraulic properties by means of these methods can become very attractive in vulnerability assessments. These methods can often be laborious, time-consuming and expensive. However, this is compensated for the output accuracy of process-based models. Computer modeling proposes an economic and efficient way of creating comprehensive predictions of pollutant fate in the vadose zone. Therefore, it presents the opportunity to examine the probable variability in behavior in a broader range of conditions than is expected experimentally.

In this study, the use of the equations of Van Genuchten, (1980) and Brooks and Corey (1966) to estimate soil hydraulic properties, such as soil water retention and hydraulic conductivity, proved invaluable to assess the current state of the vadose zone. A better understanding of the geologic and lithological structure of the vadose zone at two typical sites in Western Cape, namely Bergriver and Cape Flats, and its effect on the storage and flow mechanisms exists thanks to the outcomes of this study. The primary objectives of this study regarding the determination of hydraulic properties in the vadose for the purpose of assessing groundwater vulnerability to pollution were reached. By knowing these hydraulic properties, numerous models can be used to assess groundwater vulnerability to pollution.

7.2 **Recommendations:**

The following recommendations emanated from this study:

- With the advancement of technology, labor-intensive methods need to be improved upon with more advanced equipment and skills.
- The drilling of boreholes with equipment providing more appropriate undisturbed samples is a necessity.
- An increased endeavor into data collection and measurements will result in more reliable input data and therefore accurate output data in models.
- More direct measurements of the water retention curves need to be carried out to improve the lack of knowledge in the vadose zone nationally.
- Vadoze zone modeling. With the knowledge gained in this study, present vadoze zone models can be improved upon to allow methods for estimating solute fate and transport using hydrologic data.
- Unsaturated zone monitoring. The investigations regarding features that may impact negatively on the groundwater [e.g. preferential flow] need to be carried out in order to recognize constituents before they enter the groundwater system. For example, this can be done through monitoring of soil moisture in the vadose zone.
- Hydrogeological models depend principally on applicable data to produce quality output. This will help to increase the accuracy in which the current and future estimates of groundwater as a natural and economic resource are envisaged.

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APPENDIX A

RAW DATA

Appendix A (1)
Sample mass data

iThemba site 1

Note:

Samples in plastic rings with black cap (ring + filter cloth + elastic+ cap = 20.29g)
Samples in stainless steel rings with big caps (ring + filter cloth + elastic+ big cap = 106.80g)
Mass of container for oven drying = 1.71g

Table A1.1: Sample masses(g)

	Sample masses (g)							
sample depth(m)	24-Jun	28-Jun	6-Jul	18-Jul	20-Jul	25-Jul	27-Jul	29-Jul
	saturation	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	257.07	253.53	253.27	250.65	250.16	240.64	236.94	235.97
0.5m	279.70	277.52	277.08	274.23	273.75	259.44	255.08	253.44
1m	281.90	280.68	279.73	276.65	275.64	269.37	267.29	266.05
1.5m	288.55	286.46	286.3	284.20	283.85	280.15	278.28	276.67
2.5m	266.43	264.61	259.49	249.94	248.59	247.70	246.97	245.73
3m	81.83	81.75	80.89	79.58	78.67	75.10	74.44	74.02
4m	83.31	82.86	82.61	82.13	82.11	82.05	81.89	81.64
6.5m	280.05	277.79	277.45	275.44	275.06	271.58	270.33	269.28
7m	79.99	79.73	79.61	79.40	79.24	78.55	78.24	77.88
8.5m	86.42	85.95	85.91	85.86	85.76	85.25	85.07	84.76
10m	84.74	84.63	84.43	84.13	83.81	83.50	83.08	82.93
12m	88.85	88.81	88.78	88.51	88.40	88.03	87.86	87.38
13m	85.29	83.54	83.41	83.12	83.00	82.59	82.46	82.18
14.5m	91.83	91.11	91.00	90.81	90.67	90.47	90.37	90.20

Table A1.2: Oven dried (g)

sample depth (m)	**Oven dried (g)**
topsoil	110.15
0.5m	134.33
1m	144.57
1.5m	141.15
2.5m	129.39
3m	50.67
4m	53.28
6.5m	136.49
7m	50.34
8.5m	55.65
10m	53.24
12m	59.39
13m	54.6
14.5m	60.51

Table A1.3: Sample mass - ring mass

Mass of samples(g) - mass of sample ring(g)								
	24-Jun	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
sample depth(m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	150.27	146.73	146.47	143.85	143.36	133.84	130.14	129.17
0.5m	172.90	170.72	170.28	167.43	166.95	152.64	148.28	146.64
1m	175.10	173.88	172.93	169.85	168.84	162.57	160.49	159.25
1.5m	181.75	179.66	179.50	177.40	177.05	173.35	171.48	169.87
2.5m	159.64	157.81	152.69	143.14	141.79	140.90	140.17	138.93
3m	61.54	61.46	60.60	59.29	58.38	54.81	54.15	53.73
4m	63.02	62.57	62.32	61.84	61.82	61.76	61.60	61.35
6.5m	173.25	170.99	170.65	168.64	168.26	164.78	163.53	162.48
7m	59.70	59.44	59.32	59.11	58.95	58.26	57.95	57.59
8.5m	66.13	65.66	65.62	65.57	65.47	64.96	64.78	64.47
10m	64.45	64.34	64.14	63.84	63.52	63.21	62.79	62.64
12m	68.56	68.52	68.49	68.22	68.11	67.74	67.57	67.09
13m	65.00	63.25	63.12	62.83	62.71	62.30	62.17	61.89
14.5m	71.54	70.82	70.71	70.52	70.38	70.18	70.08	69.91

Table A1.4: Oven dried mass – container mass

sample depth (m)	**oven dried - container (g)**
topsoil	108.44
0.5m	132.62
1m	142.86
1.5m	139.44
2.5m	127.68
3m	48.96
4m	51.57
6.5m	134.78
7m	48.63
8.5m	53.94
10m	51.53
12m	57.68
13m	52.89
14.5m	58.80

iThemba site 2

Note:
Sample in stainless steel ring with small cap (ring + filter cloth + elastic + cap = 103.72g)
Sample in stainless steel ring with big cap (ring + filter cloth + elastic + cap = 106.80g)
Container used for oven drying = 1.71g

Table A1.5: Sample masses (g)

Sample masses (g)								
	24-Jun	28-Jun	6-Jul	18-Jul	20-Jul	25-Jul	27-Jul	29-Jul
sample depth (m)	saturation	100cm	85cm	70cm	55cm	suction=10cm	suction=20cm	suction=34cm
topsoil	249.30	247.14	246.54	245.22	244.90	242.98	241.07	239.02
0.5m	257.63	256.23	255.76	254.31	253.77	248.37	246.24	244.99
1m	265.23	262.07	261.24	258.71	257.33	247.46	246.22	244.67
2m	283.45	280.41	280.13	279.3	279.10	277.83	277.32	276.76
3m	276.35	273.16	272.28	270.52	270.16	266.20	264.83	263.89
4m	302.01	301.37	301.26	301.20	301.18	301.03	300.78	300.11
5m	297.30	296.67	296.6	296.58	296.39	296.27	295.94	295.30
6m	309.74	308.66	308.59	308.19	306.97	305.74	305.21	304.63
7m	288.79	288.42	288.35	287.59	287.43	286.45	286.10	285.67
8.5m	296.53	294.94	294.78	294.50	294.46	294.20	294.03	293.66
10m	322.53	321.75	321.54	320.90	320.75	320.54	320.36	320.01
11.5m	301.91	299.01	298.75	298.24	298.05	297.69	297.45	297.05
13m	306.42	304.71	303.95	303.39	303.27	303.00	302.85	302.56
15.5m	301.04	297.82	297.44	296.32	296.11	295.26	294.89	294.29
17m	301.07	296.29	296.10	295.50	295.38	294.91	294.71	294.29
18.5m	306.72	304.02	303.89	303.46	303.33	303.22	303.11	302.55

Table A1.6: Oven dried mass

sample depth (m)	Oven dried (g)
topsoil	112.3
0.5m	123.64
1m	128.25
2m	143.64
3m	131.89
4m	151.99
5m	142.16
6m	158.32
7m	129.27
8.5m	150.67
10m	189.44
11.5m	162.37
13m	167.13
15.5m	154.83
17m	161.04
18.5m	166.49

Table A1.7 Sample mass - ring mass

Mass of sample- Mass of sample ring (g)								
	24-Jun	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
sample depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	142.50	140.34	139.74	138.42	138.10	136.18	134.27	132.22
0.5m	150.83	149.43	148.96	147.51	146.97	141.57	139.44	138.19
1m	158.43	155.27	154.44	151.91	150.53	140.66	139.42	137.87
2m	176.65	173.61	173.33	172.50	172.30	171.03	170.52	169.96
3m	169.55	166.36	165.48	163.72	163.36	159.40	158.03	157.09
4m	198.29	197.65	197.54	197.48	197.46	197.31	197.06	196.39
5m	190.50	189.87	189.80	189.78	189.59	189.47	189.14	188.50
6m	202.94	201.86	201.79	201.39	200.17	198.94	198.41	197.83
7m	181.99	181.62	181.55	180.79	180.63	179.65	179.30	178.87
8.5m	189.73	188.14	187.98	187.70	187.66	187.40	187.23	186.86
10m	218.81	218.03	217.82	217.18	217.03	216.82	216.64	216.29
11.5m	198.19	195.29	195.03	194.52	194.33	193.97	193.73	193.33
13m	199.62	197.91	197.15	196.59	196.47	196.20	196.05	195.76
15.5m	194.24	191.02	190.64	189.52	189.31	188.46	188.09	187.49
17m	194.27	189.49	189.30	188.70	188.58	188.11	187.91	187.49
18.5m	199.92	197.22	197.09	196.66	196.53	196.42	196.31	195.75

TableA1.8: Oven dried mass – container mass

sample depth (m)	**Oven dried-container (g)**
topsoil	110.59
0.5m	121.93
1m	126.54
2m	141.93
3m	130.18
4m	150.28
5m	140.45
6m	156.61
7m	127.56
8.5m	148.96
10m	187.73
11.5m	160.66
13m	165.42
15.5m	153.12
17m	159.33
18.5m	164.78

Berg river site 1

Note:
Sample in stainless steel ring with small cap (ring + filter cloth + elastic + cap = 103.72g)
Container used for oven drying = 1.71g

Table A1.9: Sample masses (g)

Sample masses (g)								
	25-May	30May	2-Jun	6-Jun	13-Jun	28-Jun	1-Jul	7-Jul
Sample Depth (m)	saturation	100cm	85cm	70cm	55cm	suction= 10cm	suction=20cm	suction=34cm
topsoil	286.20	285.33	283.65	282.98	280.79	279.06	277.55	277.13
1m	297.06	296.44	296.33	296.15	295.82	295.22	295.14	295.11
1.8m	268.23	266.70	266.43	266.10	265.65	265.15	264.93	264.86
3.3m	273.92	272.77	272.44	271.85	270.89	269.18	268.74	268.52
4.8m	249.94	248.92	248.64	248.27	247.83	247.01	246.82	246.75
5.8m	312.74	312.57	312.50	312.31	311.97	311.34	311.22	311.19
6.3m	272.98	271.80	271.51	270.99	269.71	268.06	267.67	267.51
7m	307.50	307.12	307.12	306.92	306.57	305.69	305.52	305.41
8.5m	275.96	275.26	275.03	274.53	273.52	271.75	271.21	270.97
10.5m	278.91	277.96	277.75	277.42	277.06	276.58	276.40	276.32
11.5m	305.41	305.16	305.01	304.75	304.50	304.34	304.26	304.16
13.8m	279.78	277.99	277.68	276.99	275.99	274.85	274.61	274.50
15.3m	308.36	308.09	308.01	307.95	307.86	307.52	307.55	307.53
16.5m	295.00	294.33	294.13	293.69	293.01	292.10	291.92	291.83
17.7m	280.51	280.07	279.75	278.91	277.32	275.23	274.81	274.62
18.5m	289.53	288.37	288.12	287.45	286.38	284.95	284.66	284.51

Table A1.10: Oven dried mass (g)

Sample Depth (m)	Oven dried (g)
topsoil	135.12
1m	153.76
1.8m	128.32
3.3m	131.99
4.8m	112.49
5.8m	172.65
6.3m	130.41
7m	165.61
8.5m	133.86
10.5m	145.59
11.5m	163.81
13.8m	139.23
15.3m	174.61
16.5m	156.53
17.7m	143.15
18.5m	152.44

Table A1.11: Sample mass - ring mass

			Mass of sample - Mass of sample ring(g)					
	25-May	**30-May**	**2-Jun**	**6-Jun**	**13 Jun**	**28-Jun**	**1-Jul**	**7-Jul**
Sample Depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	182.48	181.61	179.93	179.26	177.07	175.34	173.83	173.41
1m	193.34	192.72	192.61	192.43	192.10	191.50	191.42	191.39
1.8m	164.51	162.98	162.71	162.38	161.93	161.43	161.21	161.14
3.3m	170.20	169.05	168.72	168.13	167.17	165.46	165.02	164.80
4.8m	146.22	145.20	144.92	144.55	144.11	143.29	143.10	143.03
5.8m	209.02	208.85	208.78	208.59	208.25	207.62	207.50	207.47
6.3m	169.26	168.08	167.79	167.27	165.99	164.34	163.95	163.79
7m	203.78	203.40	203.40	203.20	202.85	201.97	201.80	201.69
8.5m	172.24	171.54	171.31	170.81	169.80	168.03	167.49	167.25
10.5m	175.19	174.24	174.03	173.70	173.34	172.86	172.68	172.60
11.5m	201.69	201.44	201.29	201.03	200.78	200.62	200.54	200.44
13.8m	176.06	174.27	173.96	173.27	172.27	171.13	170.89	170.78
15.3m	204.64	204.37	204.29	204.23	204.14	203.80	203.83	203.81
16.5m	191.28	190.61	190.41	189.97	189.29	188.38	188.20	188.11
17.7m	176.79	176.35	176.03	175.19	173.60	171.51	171.09	170.90
18.5m	185.81	184.65	184.40	183.73	182.66	181.23	180.94	180.79

Table A1.12: Oven dried mass – container mass

Sample Depth (m)	Oven dried-container (g)
topsoil	133.41
1m	152.05
1.8m	126.61
3.3m	130.28
4.8m	110.78
5.8m	170.94
6.3m	128.70
7m	163.90
8.5m	132.15
10.5m	143.88
11.5m	162.10
13.8m	137.52
15.3m	172.90
16.5m	154.82
17.7m	141.44
18.5m	150.73

Berg river site 2

Note:
Sample in stainless steel ring with big cap (ring + filter cloth + elastic + cap = 106.80g)
Container used for oven drying = 1.71g

Table A1.13: Sample masses (g)

Sample masses (g)								
	22Aug05	29Aug05	2Sep05	6Sep05	13Sep05	21-Sep-05	24-Sep-05	26-Sep-05
Sample depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	268.78	266.82	266.21	263.91	260.97	256.87	256.14	255.73
0.9	308.89	308.80	308.75	307.68	307.41	307.09	306.74	306.66
2.2	306.74	302.24	301.35	299.69	298.68	297.08	296.79	296.74
3	288.05	287.22	286.67	284.33	282.81	280.27	279.77	279.53
4	262.25	259.31	258.31	256.78	255.46	253.18	252.67	252.41
5	304.09	304.05	304.02	303.26	302.53	301.24	300.66	300.40
6.5	286.29	285.12	284.57	283.27	282.56	281.05	280.65	280.49
7.5	299.85	299.29	299.09	298.26	297.55	296.08	295.57	295.39
8.2	289.71	288.46	287.86	286.78	285.96	284.66	284.47	284.34
10	282.62	281.16	280.73	277.51	276.11	274.12	273.81	273.74
10.8	292.94	292.44	291.97	290.32	289.54	288.31	288.00	287.83
11.5	284.47	282.48	281.92	280.49	279.80	278.03	277.66	277.49
12.5	305.65	303.11	302.83	301.40	300.65	299.29	298.90	298.68
15	269.09	264.18	261.85	255.05	252.47	249.81	249.47	249.34
16.2	309.06	307.58	306.96	305.13	304.30	303.06	302.76	302.65
17.5	301.58	300.01	299.20	297.60	296.90	296.30	295.98	295.56
18.5	307.20	305.73	304.68	303.71	302.90	301.97	301.58	301.12
20	306.22	304.77	304.59	303.75	303.00	301.54	301.12	300.87

Table A1.14: Oven dried mass(g)

Sample depth (m)	Oven Dried (g)
topsoil	126.01
0.9	165.70
2.2	161.42
3	146.34
4	122.66
5	159.29
6.5	147.62
7.5	154.68
8.2	148.29
10	140.49
10.8	151.27
11.5	144.26
12.5	169.40
15	130.85
16.2	166.67
17.5	162.20
18.5	165.97
20	162.79

Table A1.15: Sample mass - ring mass

Mass of sample-Mass of sample ring (g)								
	22-Aug-05	29-Aug-05	2-Sep-05	6-Sep-05	13-Sep-05	21-Sep-05	24-Sep-05	26-Sep-05
Sample depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
Topsoil	161.98	160.02	159.41	157.11	154.17	150.07	149.34	148.93
0.9	202.09	202.00	201.95	200.88	200.61	200.29	199.94	199.86
2.2	199.94	195.44	194.55	192.89	191.88	190.28	189.99	189.94
3	181.25	180.42	179.87	177.53	176.01	173.47	172.97	172.73
4	155.45	152.51	151.51	149.98	148.66	146.38	145.87	145.61
5	197.29	197.25	197.22	196.46	195.73	194.44	193.86	193.60
6.5	179.49	178.32	177.77	176.47	175.76	174.25	173.85	173.69
7.5	193.05	192.49	192.29	191.46	190.75	189.28	188.77	188.59
8.2	182.91	181.66	181.06	179.98	179.16	177.86	177.67	177.54
10	175.82	174.36	173.93	170.71	169.31	167.32	167.01	166.94
10.8	186.14	185.64	185.17	183.52	182.74	181.51	181.20	181.03
11.5	177.67	175.68	175.12	173.69	173.00	171.23	170.86	170.69
12.5	198.85	196.31	196.03	194.60	193.85	192.49	192.10	191.88
15	162.29	157.38	155.05	148.25	145.67	143.01	142.67	142.54
16.2	202.26	200.78	200.16	198.33	197.50	196.26	195.96	195.85
17.5	194.78	193.21	192.40	190.80	190.10	189.50	189.18	188.76
18.5	200.40	198.93	197.88	196.91	196.10	195.17	194.78	194.32
20	199.42	197.97	197.79	196.95	196.20	194.74	194.32	194.07

Table A1.16: Oven dried mass – container mass

Sample depth (m)	**Oven dried - container(g)**
Topsoil	124.30
0.9	163.99
2.2	159.71
3	144.63
4	120.95
5	157.58
6.5	145.91
7.5	152.97
8.2	146.58
10	138.78
10.8	149.56
11.5	142.55
12.5	167.69
15	129.14
16.2	164.96
17.5	160.49
18.5	164.26
20	161.08

Berg river site 3

Note:
PVC rings with cap+ filter cloth + elastic = 51.30g
Foil container for oven drying = 1.71g

Table A1.17: Sample masses (g)

sample masses (g)								
	3Jan06	6Jan06	10Jan06	13Jan06	16Jan06	18-Jan-06	23-Jan-06	25-Jan-06
sample depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	187.17	179.57	174.43	172.60	171.21	170.79	170.32	170.05
1.4	204.33	202.16	201.75	201.50	201.18	201.03	200.96	200.91
2.5	196.79	193.61	191.48	190.73	190.04	189.70	189.53	189.41
4	197.10	192.99	191.46	190.93	190.42	190.19	190.11	190.02
5.5	214.34	211.82	210.36	209.84	209.33	209.11	208.84	208.71
6	197.95	194.00	192.20	191.53	190.93	190.84	190.68	190.43
7.5	189.08	183.98	181.91	181.16	180.55	180.30	180.20	180.02
9	200.11	194.97	192.81	192.05	191.39	191.21	191.09	190.96
10	208.79	203.13	201.82	201.36	200.98	200.34	199.96	199.67
11	203.98	200.22	199.75	198.92	198.42	197.88	197.18	196.72
13	202.69	198.38	197.72	196.79	196.23	195.88	195.52	195.18
14	199.92	196.60	194.86	194.42	194.03	193.75	193.19	191.78

Table A1.18: Oven dried mass

sample depth (m)	Oven dried(g)
topsoil	96.27
1.4	121.63
2.5	112.22
4	113.89
5.5	131.91
6	117.76
7.5	108.73
9	117.88
10	125.78
11	122.84
13	121.25
14	119.85

Table A1.19: Sample mass - ring mass

Mass of sample (g) - Mass of container (g)								
	3Jan06	6Jan06	10Jan06	13Jan06	16Jan06	18-Jan-06	23-Jan-06	25-Jan-06
Sample depth (m)	**saturation**	**100cm**	**85cm**	**70cm**	**55cm**	**suction=10cm**	**suction=20cm**	**suction=34cm**
topsoil	135.87	128.27	123.13	121.30	119.91	119.49	119.02	118.75
1.4	153.03	150.86	150.45	150.20	149.88	149.73	149.66	149.61
2.5	145.49	142.31	140.18	139.43	138.74	138.40	138.23	138.11
4	145.80	141.69	140.16	139.63	139.12	138.89	138.81	138.72
5.5	163.04	160.52	159.06	158.54	158.03	157.81	157.54	157.41
6	146.65	142.70	140.90	140.23	139.63	139.54	139.38	139.13
7.5	137.78	132.68	130.61	129.86	129.25	129.00	128.90	128.72
9	148.81	143.67	141.51	140.75	140.09	139.91	139.79	139.66
10	157.49	151.83	150.52	150.06	149.68	149.04	148.66	148.37
11	152.68	148.92	148.45	147.62	147.12	146.58	145.88	145.42
13	151.39	147.08	146.42	145.49	144.93	144.58	144.22	143.88
14	148.62	145.30	143.56	143.12	142.73	142.45	141.89	140.48

Table A1.20: Oven dried mass – container mass

Sample depth (m)	Oven dried - container (g)
topsoil	94.56
1.4	119.92
2.5	110.51
4	112.18
5.5	130.2
6	116.05
7.5	107.02
9	116.17
10	124.07
11	121.13
13	119.54
14	118.14

Appendix A (2)

Water Retention Data (i)

Gravimetric Water Content

iThemba site 1

Table A2.1: Gravimetric water content of iThemba site 1 samples

Gravimetric water Content							
Sample Depth (m)	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
topsoil	0.353098	0.350701	0.32654	0.322021394	0.234231	0.200111	0.191166
0.5m	0.287287	0.283969	0.262479	0.2588599	0.150958	0.118082	0.105716
1m	0.217136	0.210486	0.188926	0.181856363	0.137967	0.123408	0.114728
1.5m	0.288439	0.287292	0.272232	0.269721744	0.243187	0.229776	0.21823
2.5m	0.235981	0.19588	0.121084	0.110510652	0.10354	0.097823	0.088111
3m	0.25531	0.237745	0.210989	0.192401961	0.119485	0.106005	0.097426
4m	0.213302	0.208455	0.199147	0.198758968	0.197596	0.194493	0.189645
6.5m	0.26866	0.266137	0.251224	0.248404808	0.222585	0.213311	0.20552
7m	0.222291	0.219823	0.215505	0.212214682	0.198026	0.191651	0.184248
8.5m	0.217278	0.216537	0.21561	0.213756025	0.204301	0.200964	0.195217
10m	0.248593	0.244712	0.23889	0.232679992	0.226664	0.218513	0.215603
12m	0.187933	0.187413	0.182732	0.180825243	0.174411	0.171463	0.163141
13m	0.195878	0.19342	0.187937	0.185668368	0.177916	0.175458	0.170164
14.5m	0.204422	0.202551	0.19932	0.196938776	0.193537	0.191837	0.188946

iThemba site 2

Table A2.2: Gravimetric water content of iThemba site 2 samples

Gravimetric water Content							
Sample Depth (m)	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
topsoil	0.269012	0.263586	0.25165024	0.248757	0.231395	0.214124	0.195587
0.5m	0.225539	0.221685	0.209792504	0.205364	0.161076	0.143607	0.133355
1m	0.227043	0.220484	0.200489964	0.189584	0.111585	0.101786	0.089537
2m	0.223209	0.221236	0.215387867	0.213979	0.205031	0.201437	0.197492
3m	0.277923	0.271163	0.257643263	0.254878	0.224458	0.213935	0.206714
4m	0.315212	0.31448	0.314080383	0.313947	0.312949	0.311286	0.306827
5m	0.351869	0.351371	0.351228195	0.349875	0.349021	0.346671	0.342115
6m	0.288934	0.288487	0.28593321	0.278143	0.270289	0.266905	0.263202
7m	0.423801	0.423252	0.417293823	0.41604	0.408357	0.405613	0.402242
8.5m	0.263024	0.26195	0.260069817	0.259801	0.258056	0.256915	0.254431
10m	0.161402	0.160283	0.156874234	0.156075	0.154957	0.153998	0.152133
11.5m	0.215548	0.21393	0.210755633	0.209573	0.207332	0.205838	0.203349
13m	0.196409	0.191815	0.188429452	0.187704	0.186072	0.185165	0.183412
15.5m	0.247518	0.245037	0.237722048	0.236351	0.230799	0.228383	0.224464
17m	0.189293	0.1881	0.1843344	0.183581	0.180631	0.179376	0.17674
18.5m	0.196869	0.19608	0.193470081	0.192681	0.192014	0.191346	0.187948

Berg river site 1

Table A2.3: Gravimetric Water Content for Berg river site 1 samples

	Gravimetric water content						
Sample Depth (m)	**30-May**	**2-Jun**	**6-Jun**	**13-Jun**	**28-Jun**	**1-Jul**	**7-Jul**
topsoil	0.361292	0.3486995	0.3436774	0.3272618	0.314294	0.30297579	0.299828
1m	0.267477	0.2667544	0.2655705	0.2634002	0.259454	0.25892798	0.258731
1.8m	0.287260	0.2851276	0.2825211	0.2789669	0.275018	0.27328015	0.272727
3.3m	0.297589	0.2950568	0.2905281	0.2831593	0.270034	0.26665643	0.264968
4.8m	0.310705	0.3081784	0.3048384	0.3008666	0.293465	0.29174941	0.291118
5.8m	0.221773	0.2213642	0.2202527	0.2182637	0.214578	0.21387621	0.213701
6.3m	0.305982	0.3037296	0.2996892	0.2897436	0.276923	0.27389277	0.27265
7m	0.241000	0.2410006	0.2397804	0.2376449	0.232276	0.23123856	0.230567
8.5m	0.298070	0.2963299	0.2925463	0.2849035	0.27151	0.26742338	0.265607
10.5m	0.211009	0.2095496	0.207256	0.204754	0.201418	0.20016681	0.199611
11.5m	0.242689	0.2417643	0.2401604	0.2386181	0.237631	0.23713757	0.236521
13.8m	0.267233	0.2649796	0.2599622	0.2526905	0.244401	0.24265561	0.241856
15.3m	0.182012	0.18155	0.181203	0.1806825	0.178716	0.17888953	0.178774
16.5m	0.231171	0.2298799	0.2270379	0.2226457	0.216768	0.21560522	0.215024
17.7m	0.246818	0.244556	0.2386171	0.2273756	0.212599	0.20962952	0.208286
18.5m	0.225038	0.2233796	0.2189345	0.2118357	0.202349	0.2004246	0.199429

Berg river site 2

Table A2.4: Gravimetric Water Content for Berg river site 2 samples

	Gravimetric water content						
Sample depth (m)	29Aug05	2-Sep-05	6-Sep-05	13Sep05	21Sep05	24Sep05	26Se-05
Topsoil	0.287369	0.282462	0.263958	0.240306	0.207321	0.201448	0.19815
0.9	0.231782	0.231478	0.224953	0.223306	0.221355	0.219221	0.218733
2.2	0.223718	0.218145	0.207752	0.201428	0.191409	0.189594	0.189281
3	0.247459	0.243656	0.227477	0.216967	0.199405	0.195948	0.194289
4	0.260934	0.252666	0.240017	0.229103	0.210252	0.206036	0.203886
5	0.251745	0.251555	0.246732	0.242099	0.233913	0.230232	0.228582
6.5	0.222123	0.218354	0.209444	0.204578	0.194229	0.191488	0.190391
7.5	0.258351	0.257044	0.251618	0.246977	0.237367	0.234033	0.232856
8.2	0.239323	0.23523	0.227862	0.222268	0.213399	0.212103	0.211216
10	0.256377	0.253279	0.230076	0.219988	0.205649	0.203415	0.202911
10.8	0.241241	0.238098	0.227066	0.221851	0.213627	0.211554	0.210417
11.5	0.23241	0.228481	0.21845	0.213609	0.201193	0.198597	0.197404
12.5	0.170672	0.169002	0.160475	0.156002	0.147892	0.145566	0.144254
15	0.218677	0.200635	0.147979	0.128001	0.107403	0.10477	0.103763
16.2	0.217144	0.213385	0.202291	0.19726	0.189743	0.187924	0.187258
17.5	0.203876	0.198829	0.188859	0.184497	0.180759	0.178765	0.176148
18.5	0.211068	0.204676	0.19877	0.193839	0.188177	0.185803	0.183003
20	0.229017	0.227899	0.222684	0.218028	0.208964	0.206357	0.204805

Berg river site 3

Table A2.5: Gravimetric Water Content for Berg river site 3 samples

Gravimetric water content							
Sample depth (m)	6-Jan-06	10Jan-06	13Jan-06	16Jan-06	18Jan-06	23Jan-06	25Jan-06
topsoil	0.356493	0.302136	0.282783	0.268084	0.263642	0.258672	0.255816
1.4	0.258005	0.254586	0.252502	0.249833	0.248582	0.247999	0.247582
2.5	0.287757	0.268482	0.261696	0.255452	0.252375	0.250837	0.249751
4	0.263059	0.249421	0.244696	0.24015	0.238099	0.237386	0.236584
5.5	0.232873	0.221659	0.217665	0.213748	0.212058	0.209985	0.208986
6	0.229642	0.214132	0.208358	0.203188	0.202413	0.201034	0.19888
7.5	0.239768	0.220426	0.213418	0.207718	0.205382	0.204448	0.202766
9	0.236722	0.218129	0.211586	0.205905	0.204356	0.203323	0.202204
10	0.223745	0.213186	0.209479	0.206416	0.201257	0.198195	0.195857
11	0.229423	0.225543	0.218691	0.214563	0.210105	0.204326	0.200528
13	0.230383	0.224862	0.217082	0.212398	0.20947	0.206458	0.203614
14	0.229897	0.215168	0.211444	0.208143	0.205773	0.201033	0.189098

Appendix A (3)

Water Retention Data (ii)

Volumetric Water Content

iThemba site 1

Table A3.1: Volumetric water content of iThemba site 1 samples

	Volumetric Water Content **(cm^{3}water/cm^{3}soil)**						
sample depth (m)	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
topsoil	0.3829	0.3803	0.3541	0.3492	0.2540	0.2170	0.2073
0.5m	0.3810	0.3766	0.3481	0.3433	0.2002	0.1566	0.1402
1m	0.3102	0.3007	0.2699	0.2598	0.1971	0.1763	0.1639
1.5m	0.4022	0.4006	0.3796	0.3761	0.3391	0.3204	0.3043
2.5m	0.3013	0.2501	0.1546	0.1411	0.1322	0.1249	0.1125
3m	0.3571	0.3325	0.2951	0.2691	0.1671	0.1482	0.1362
4m	0.3142	0.3071	0.2934	0.2928	0.2911	0.2865	0.2794
6.5m	0.3621	0.3587	0.3386	0.3348	0.3000	0.2875	0.2770
7m	0.3088	0.3054	0.2994	0.2948	0.2751	0.2662	0.2559
8.5m	0.3348	0.3337	0.3322	0.3294	0.3148	0.3097	0.3008
10m	0.3659	0.3602	0.3516	0.3425	0.3336	0.3216	0.3173
12m	0.3097	0.3088	0.3011	0.2980	0.2874	0.2825	0.2688
13m	0.2959	0.2922	0.2839	0.2805	0.2688	0.2651	0.2571
14.5m	0.3434	0.3402	0.3348	0.3308	0.3251	0.3222	0.3174

iThemba site 2

Table A3.2: Volumetric water content of iThemba site 2 samples

Volumetric water content(cm^{3}water/cm^{3}soil)							
Sample depth (m)	**28-Jun**	**6-Jul**	**18-Jul**	**20-Jul**	**25-Jul**	**27-Jul**	**29-Jul**
topsoil	0.2975	0.2915	0.2783	0.2751	0.2559	0.2368	0.2163
0.5m	0.2750	0.2703	0.2558	0.2504	0.1964	0.1751	0.1626
1m	0.2873	0.2790	0.2537	0.2399	0.1412	0.1288	0.1133
2m	0.3168	0.3140	0.3057	0.3037	0.2910	0.2859	0.2803
3m	0.3618	0.3530	0.3354	0.3318	0.2922	0.2785	0.2691
4m	0.4737	0.4726	0.4720	0.4718	0.4703	0.4678	0.4611
5m	0.4942	0.4935	0.4933	0.4914	0.4902	0.4869	0.4805
6m	0.4525	0.4518	0.4478	0.4356	0.4233	0.4180	0.4122
7m	0.5406	0.5399	0.5323	0.5307	0.5209	0.5174	0.5131
8.5m	0.3918	0.3902	0.3874	0.3870	0.3844	0.3827	0.3790
10m	0.3030	0.3009	0.2945	0.2930	0.2909	0.2891	0.2856
11.5m	0.3463	0.3437	0.3386	0.3367	0.3331	0.3307	0.3267
13m	0.3249	0.3173	0.3117	0.3105	0.3078	0.3063	0.3034
15.5m	0.3790	0.3752	0.3640	0.3619	0.3534	0.3497	0.3437
17m	0.3016	0.2997	0.2937	0.2925	0.2878	0.2858	0.2816
18.5m	0.3244	0.3231	0.3188	0.3175	0.3164	0.3153	0.3097

Berg river site 1

Table A3.3: Volumetric water content for Berg river site 1 samples

Volumetric water content(cm^3water/cm^3soil)							
Sample Depth (m)	**30-May**	**2-Jun**	**6-Jun**	**13-Jun**	**28-Jun**	**1-Jul**	**7-Jul**
topsoil	0.4820	0.4652	0.4585	0.4366	0.4193	0.4042	0.4000
1m	0.4067	0.4056	0.4038	0.4005	0.3945	0.3937	0.3934
1.8m	0.3637	0.3610	0.3577	0.3532	0.3482	0.3460	0.3453
3.3m	0.3877	0.3844	0.3785	0.3689	0.3518	0.3474	0.3452
4.8m	0.3442	0.3414	0.3377	0.3333	0.3251	0.3232	0.3225
5.8m	0.3791	0.3784	0.3765	0.3731	0.3668	0.3656	0.3653
6.3m	0.3938	0.3909	0.3857	0.3729	0.3564	0.3525	0.3509
7m	0.3950	0.3947	0.3930	0.3895	0.3807	0.3790	0.3779
8.5m	0.3939	0.3916	0.3866	0.3765	0.3588	0.3534	0.3510
10.5m	0.3036	0.3015	0.2982	0.2946	0.2898	0.2880	0.2872
11.5m	0.3934	0.3919	0.3893	0.3868	0.3852	0.3844	0.3870
13.8m	0.3675	0.3644	0.3575	0.3475	0.3361	0.3337	0.3326
15.3m	0.3147	0.3139	0.3133	0.3124	0.3090	0.3093	0.3091
16.5m	0.3579	0.3559	0.3515	0.3447	0.3356	0.3338	0.3329
17.7m	0.3491	0.3459	0.3375	0.3216	0.3007	0.2965	0.2946
18.5m	0.3392	0.3367	0.3300	0.3193	0.3050	0.3021	0.3006

Berg river site 2

Table A3.4: Volumetric water content for Berg river site 2 samples

Volumetric water content(cm^3water/cm^3soil)							
Sample depth (m)	29Aug05	2Sep05	6Sep05	13Sep05	21Sep05	24Sep05	26Sep05
Topsoil	0.3572	0.3511	0.3281	0.2987	0.2577	0.2504	0.2463
0.9	0.3801	0.3796	0.3689	0.3662	0.3630	0.3595	0.3587
2.2	0.3573	0.3484	0.3318	0.3217	0.3057	0.3028	0.3023
3	0.3579	0.3524	0.3290	0.3138	0.2884	0.2834	0.2810
4	0.3156	0.3056	0.2903	0.2771	0.2543	0.2492	0.2466
5	0.3967	0.3964	0.3888	0.3815	0.3686	0.3628	0.3602
6.5	0.3241	0.3186	0.3056	0.2985	0.2834	0.2794	0.2778
7.5	0.3952	0.3932	0.3849	0.3778	0.3631	0.3580	0.3562
8.2	0.3508	0.3448	0.3340	0.3258	0.3128	0.3109	0.3096
10	0.3558	0.3515	0.3193	0.3053	0.2854	0.2823	0.2816
10.8	0.3608	0.3561	0.3396	0.3318	0.3195	0.3164	0.3147
11.5	0.3313	0.3257	0.3114	0.3045	0.2868	0.2831	0.2814
12.5	0.2862	0.2834	0.2691	0.2616	0.2480	0.2441	0.2419
15	0.2824	0.2591	0.1911	0.1653	0.1387	0.1353	0.1340
16.2	0.3582	0.3520	0.3337	0.3254	0.3130	0.3100	0.3089
17.5	0.3272	0.3191	0.3031	0.2961	0.2901	0.2869	0.2827
18.5	0.3467	0.3362	0.3265	0.3184	0.3091	0.3052	0.3006
20	0.3689	0.3671	0.3587	0.3512	0.3366	0.3324	0.3299

Berg river site 3

Table A3.5: Volumetric Water Content for Berg river site 3 samples

Volumetric water content(cm^3water/cm^3soil)							
Sample depth(m)	6-Jan-06	10Jan-06	13Jan-06	16Jan-06	18Jan-06	23Jan-06	25Jan-06
topsoil	0.4213	0.3571	0.3342	0.3168	0.3116	0.3057	0.3023
1.4	0.3867	0.3816	0.3785	0.3745	0.3726	0.3717	0.3711
2.5	0.3973	0.3707	0.3614	0.3527	0.3485	0.3464	0.3449
4	0.3688	0.3497	0.3431	0.3367	0.3338	0.3328	0.3317
5.5	0.3790	0.3607	0.3542	0.3478	0.3451	0.3417	0.3401
6	0.3331	0.3106	0.3022	0.2947	0.2930	0.2916	0.2884
7.5	0.3207	0.2948	0.2854	0.2778	0.2747	0.2734	0.2712
9	0.3437	0.3167	0.3072	0.2989	0.2967	0.2952	0.2936
10	0.3469	0.3306	0.3248	0.3201	0.3121	0.3073	0.3037
11	0.3473	0.3415	0.3311	0.3248	0.3181	0.3093	0.3036
13	0.3441	0.3359	0.3243	0.3173	0.3129	0.3084	0.3041
14	0.3395	0.3177	0.3122	0.3073	0.3038	0.2968	0.2792

APPENDIX B

Borehole Logs

Ithemba site 1

Ithemba site 2

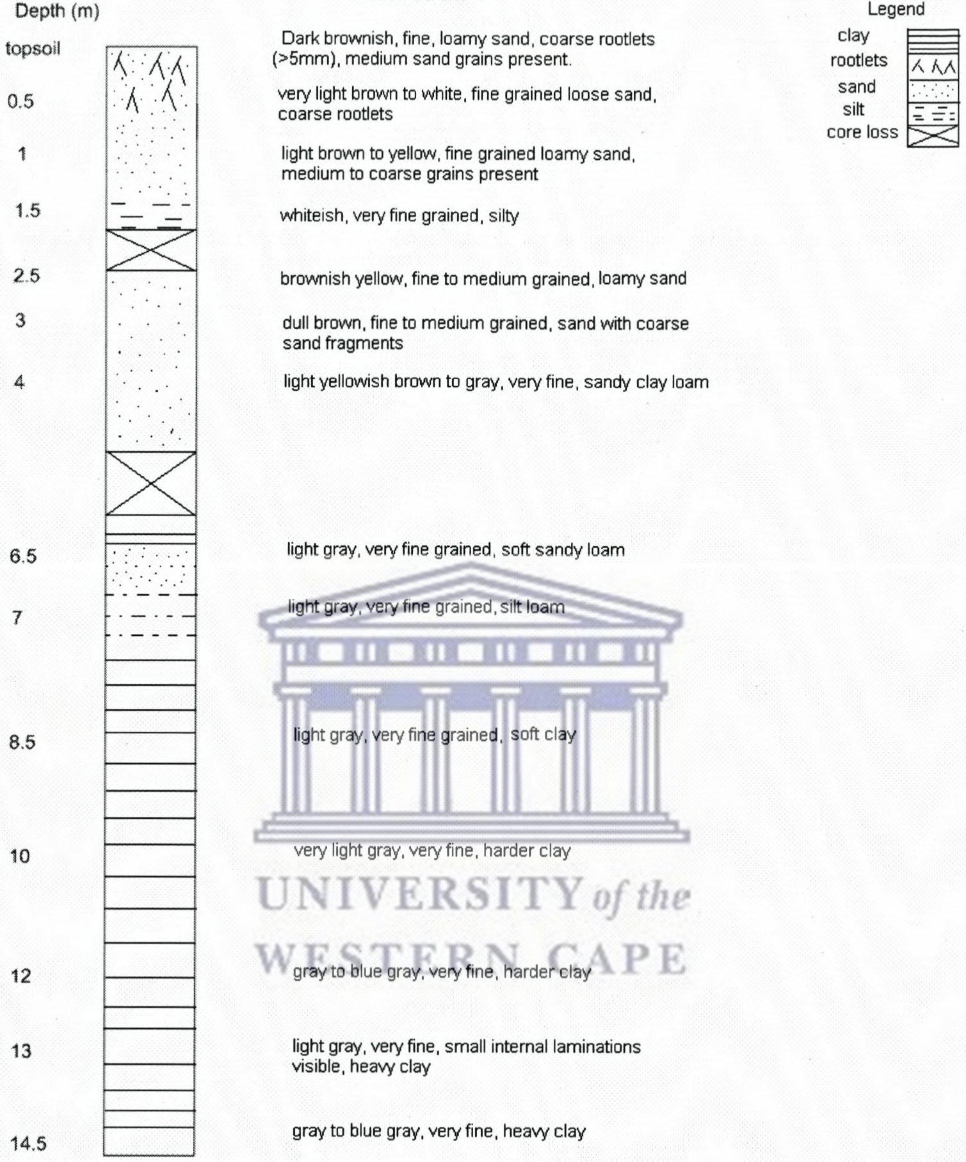
Bergriver site 1

Bergriver site 2

Bergriver site 3

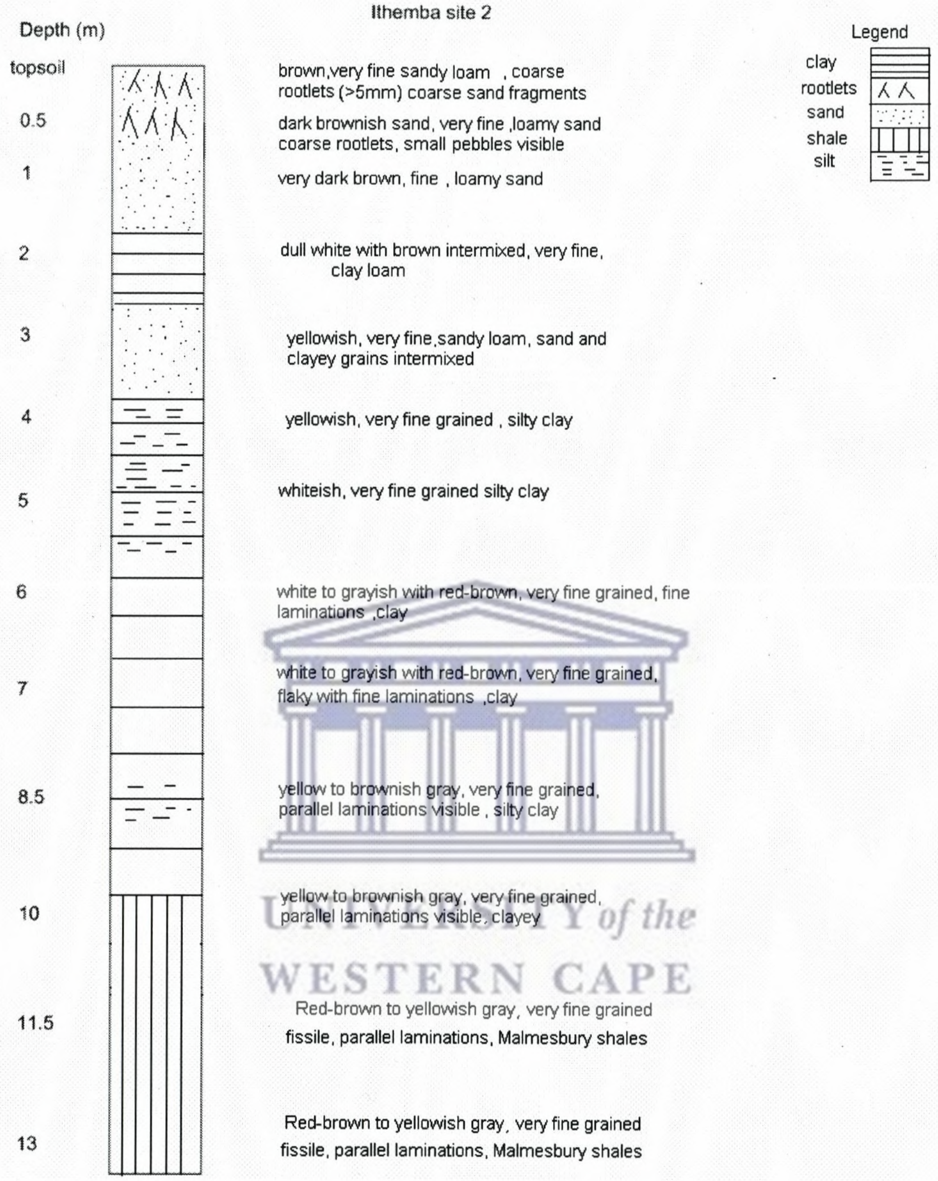
Included a soil classification triangle

Ithemba site 1

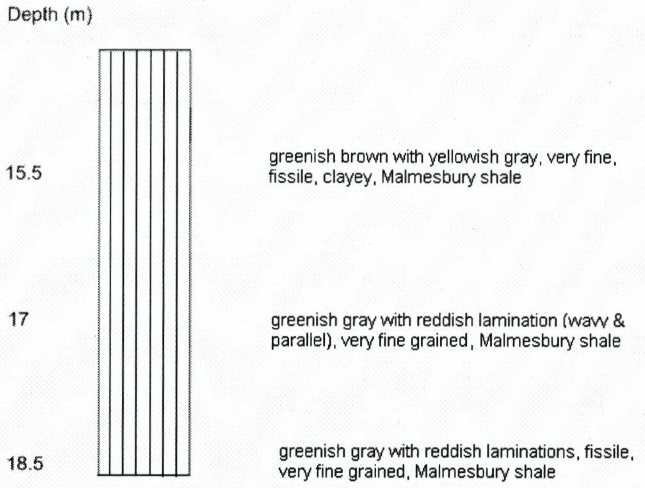


Depth (m)	
topsoil	Dark brownish, fine, loamy sand, coarse rootlets (>5mm), medium sand grains present.
0.5	very light brown to white, fine grained loose sand, coarse rootlets
1	light brown to yellow, fine grained loamy sand, medium to coarse grains present
1.5	whiteish, very fine grained, silty
2.5	brownish yellow, fine to medium grained, loamy sand
3	dull brown, fine to medium grained, sand with coarse sand fragments
4	light yellowish brown to gray, very fine, sandy clay loam
6.5	light gray, very fine grained, soft sandy loam
7	light gray, very fine grained, silt loam
8.5	light gray, very fine grained, soft clay
10	very light gray, very fine, harder clay
12	gray to blue gray, very fine, harder clay
13	light gray, very fine, small internal laminations visible, heavy clay
14.5	gray to blue gray, very fine, heavy clay

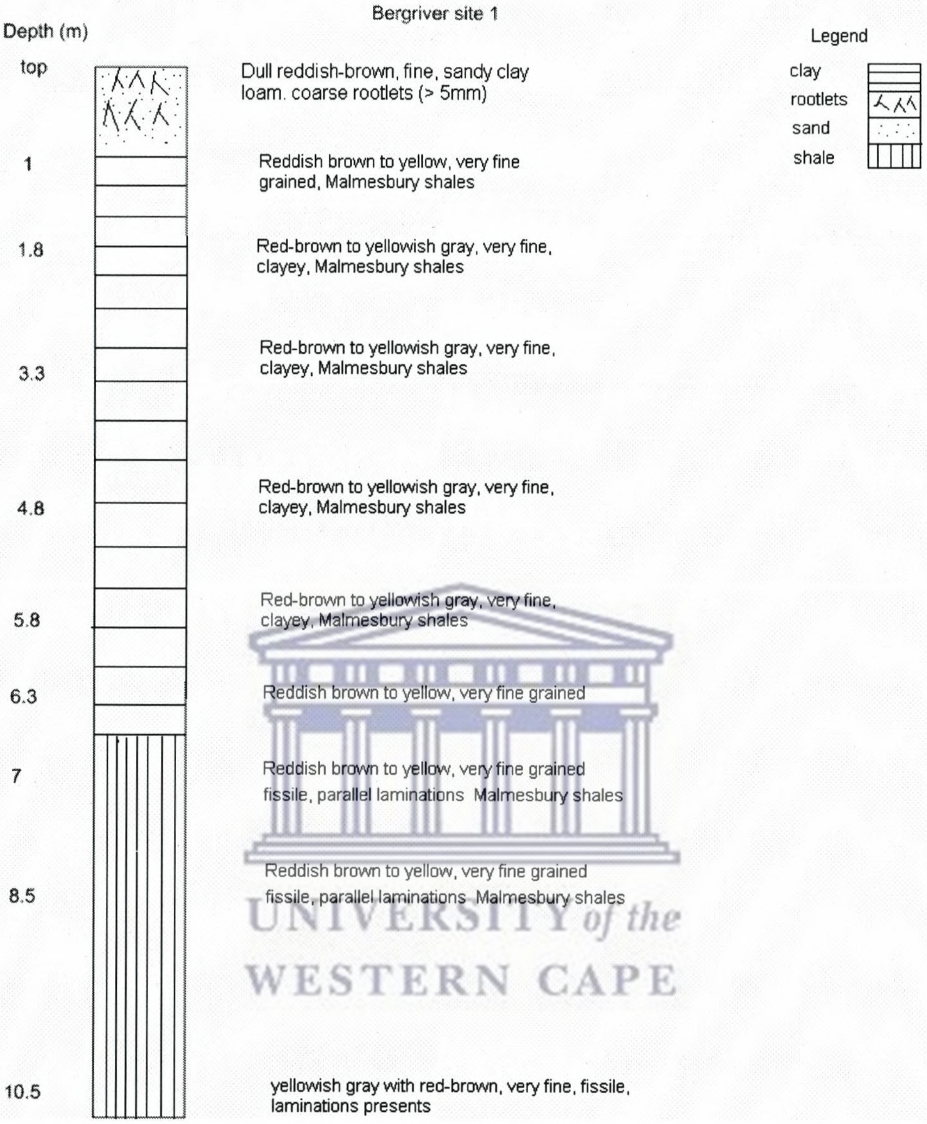
Ithemba site 2



Depth (m)	
topsoil	brown,very fine sandy loam , coarse rootlets (>5mm) coarse sand fragments
0.5	dark brownish sand, very fine ,loamy sand coarse rootlets, small pebbles visible
1	very dark brown, fine , loamy sand
2	dull white with brown intermixed, very fine, clay loam
3	yellowish, very fine,sandy loam, sand and clayey grains intermixed
4	yellowish, very fine grained , silty clay
5	whiteish, very fine grained silty clay
6	white to grayish with red-brown, very fine grained, fine laminations ,clay
7	white to grayish with red-brown, very fine grained, flaky with fine laminations ,clay
8.5	yellow to brownish gray, very fine grained, parallel laminations visible , silty clay
10	yellow to brownish gray, very fine grained, parallel laminations visible, clayey
11.5	Red-brown to yellowish gray, very fine grained fissile, parallel laminations, Malmesbury shales
13	Red-brown to yellowish gray, very fine grained fissile, parallel laminations, Malmesbury shales



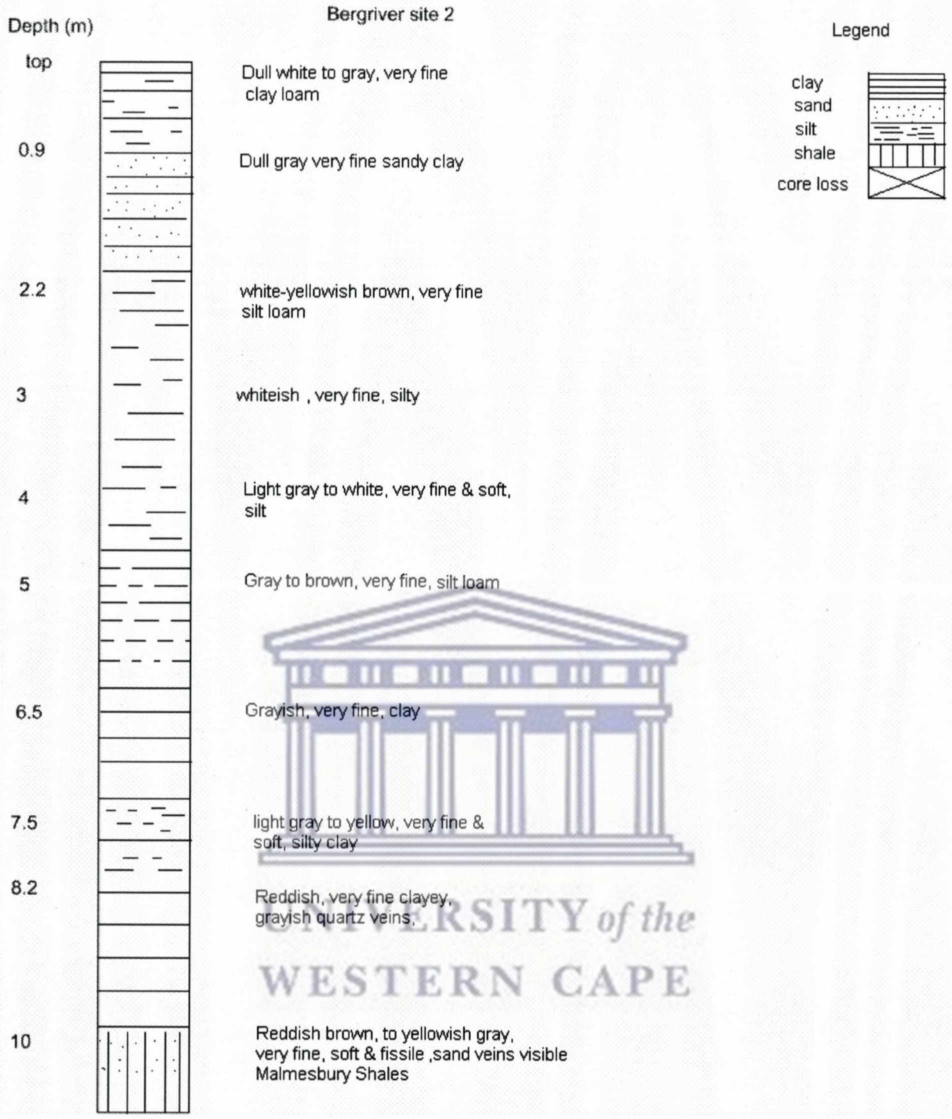
Depth (m)	
15.5	greenish brown with yellowish gray, very fine, fissile, clayey, Malmesbury shale
17	greenish gray with reddish lamination (wavy & parallel), very fine grained, Malmesbury shale
18.5	greenish gray with reddish laminations, fissile, very fine grained, Malmesbury shale

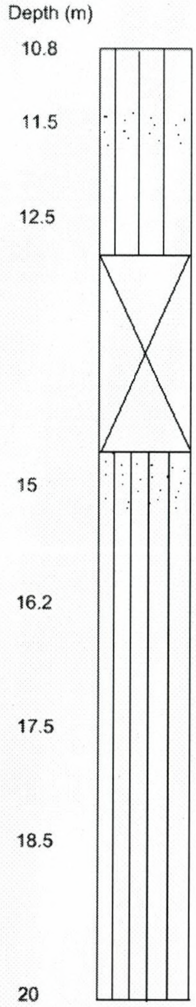


Bergriver site 1

Depth (m)	
top	Dull reddish-brown, fine, sandy clay loam. coarse rootlets (> 5mm)
1	Reddish brown to yellow, very fine grained, Malmesbury shales
1.8	Red-brown to yellowish gray, very fine, clayey, Malmesbury shales
3.3	Red-brown to yellowish gray, very fine, clayey, Malmesbury shales
4.8	Red-brown to yellowish gray, very fine, clayey, Malmesbury shales
5.8	Red-brown to yellowish gray, very fine, clayey, Malmesbury shales
6.3	Reddish brown to yellow, very fine grained
7	Reddish brown to yellow, very fine grained fissile, parallel laminations Malmesbury shales
8.5	Reddish brown to yellow, very fine grained fissile, parallel laminations Malmesbury shales
10.5	yellowish gray with red-brown, very fine, fissile, laminations presents

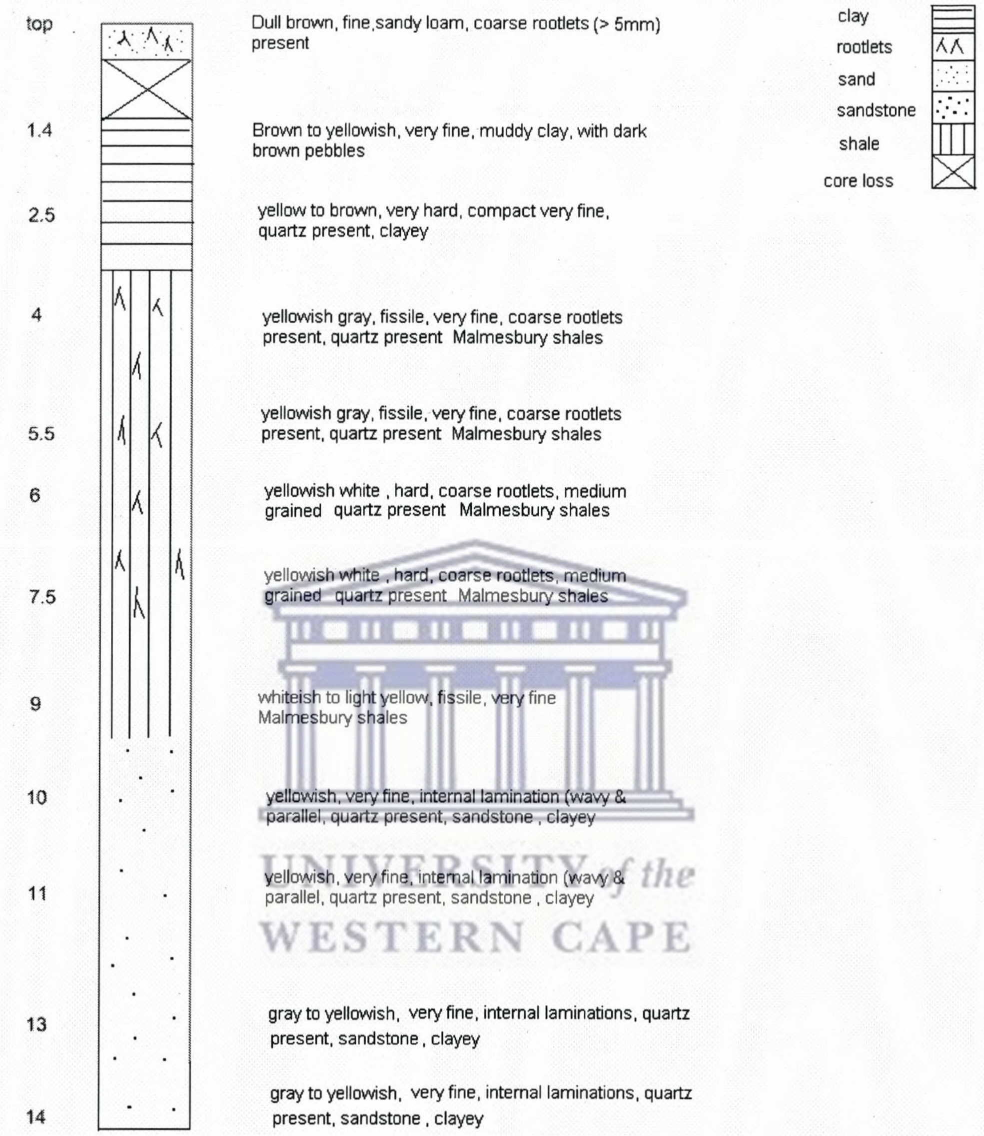
Depth (m)	
11.5	yellowish gray to red-brown, very fine grained, fissile, Malmesbury shales
13.8	yellowish to red-brown, with blackish internal parallel laminations, very fine grained
15.3	yellowish to red-brown, with blackish internal parallel laminations, very fine grained, fissile
16.5	yellowish brown, with blackish internal parallel laminations, very fine grained, fissile
17.7	yellowish brown, very fine grained , cross & parallel laminations, quartz veins present, fissile
18.5	yellowish brown to gray, very fine & fissile, Malmesbury shales


Bergriver site 2
Depth (m)
top
Dull white to gray, very fine clay loam
0.9
Dull gray very fine sandy clay
2.2
white-yellowish brown, very fine silt loam
3
whiteish , very fine, silty
4
Light gray to white, very fine & soft, silt
5
Gray to brown, very fine, silt loam
6.5
Grayish, very fine, clay
7.5
light gray to yellow, very fine & soft, silty clay
8.2
Reddish, very fine clayey, grayish quartz veins,
10
Reddish brown, to yellowish gray, very fine, soft & fissile ,sand veins visible Malmesbury Shales
Legend
clay
sand
silt
shale
core loss

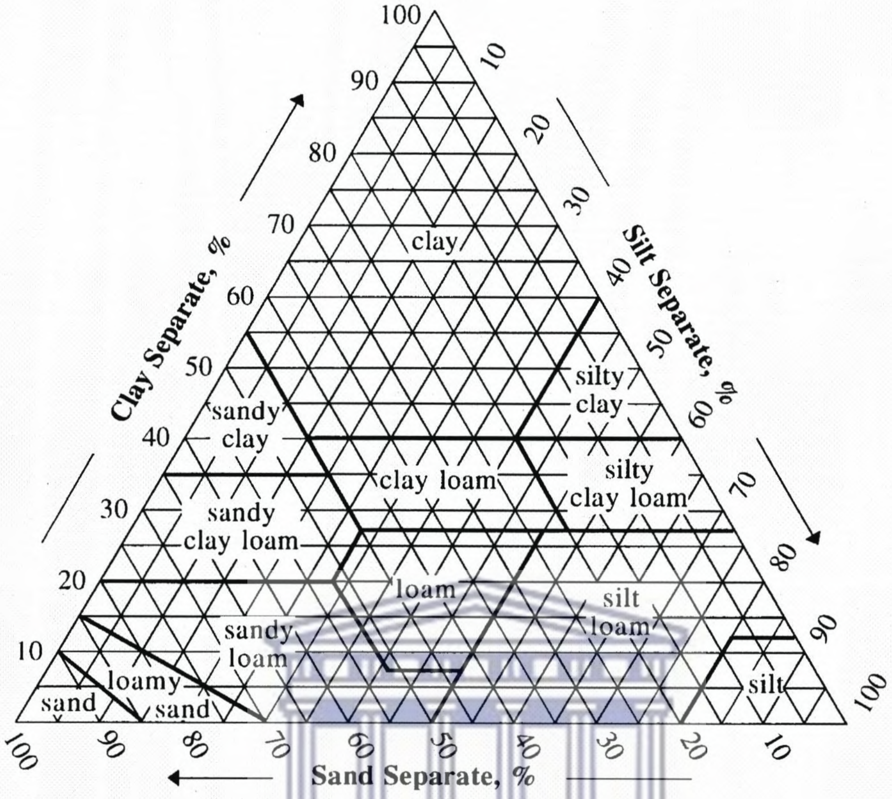


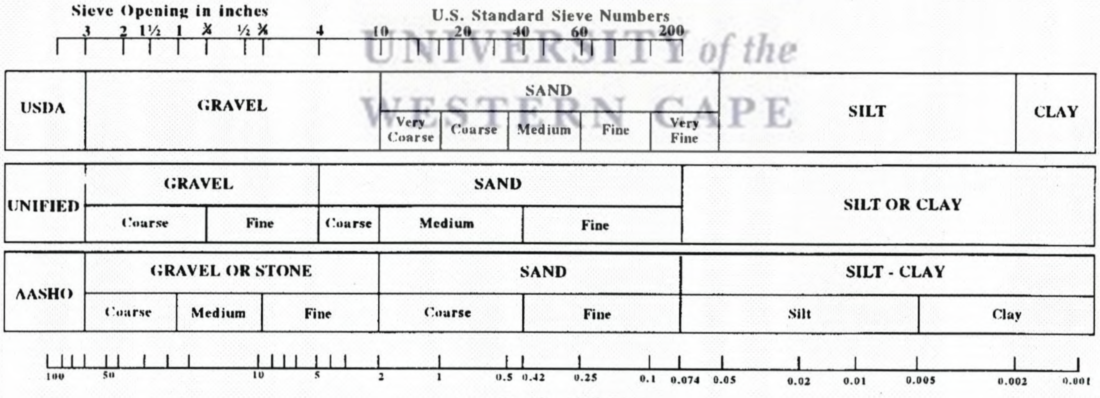
Depth (m)	
10.8	Reddish brown to yellowish gray, very fine & soft, small fissilty, easy breakable
11.5	Reddish brown, very fine, laminations visible, thin sandy vein visible Malmesbury shale
12.5	Light brown to red with yellow, fissile, hard, quartzy fragments visible, very fine grained
15	Dull brown, very fine, sandy material with quartz present sandy loam
16.2	Brownish to gray, fissile, very fine, Malmesbury Shale
17.5	yellowish gray, fissile, very fine, shale hard and compact, light black veins visible
18.5	yellowish gray, fissile, very fine, shale hard and compact,dark black vein visible
20	yellowish brown, very fine Malmesbury shales with small quartz fragments visible

Bergriver site 3



Depth (m)	
top	Dull brown, fine,sandy loam, coarse rootlets (> 5mm) present
1.4	Brown to yellowish, very fine, muddy clay, with dark brown pebbles
2.5	yellow to brown, very hard, compact very fine, quartz present, clayey
4	yellowish gray, fissile, very fine, coarse rootlets present, quartz present Malmesbury shales
5.5	yellowish gray, fissile, very fine, coarse rootlets present, quartz present Malmesbury shales
6	yellowish white , hard, coarse rootlets, medium grained quartz present Malmesbury shales
7.5	yellowish white , hard, coarse rootlets, medium grained quartz present Malmesbury shales
9	whiteish to light yellow, fissile, very fine Malmesbury shales
10	yellowish, very fine, internal lamination (wavy & parallel, quartz present, sandstone , clayey
11	yellowish, very fine, internal lamination (wavy & parallel, quartz present, sandstone , clayey
13	gray to yellowish, very fine, internal laminations, quartz present, sandstone , clayey
14	gray to yellowish, very fine, internal laminations, quartz present, sandstone , clayey





COMPARISON OF PARTICLE SIZE SCALES

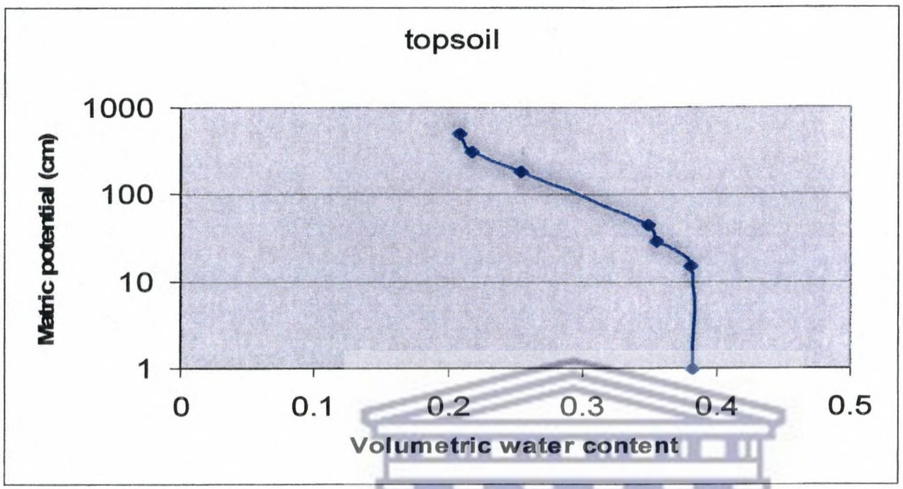
http://soils.usda.gov/technical/handbook/images/Part618Exhibit8_hi.jpg

APPENDIX C

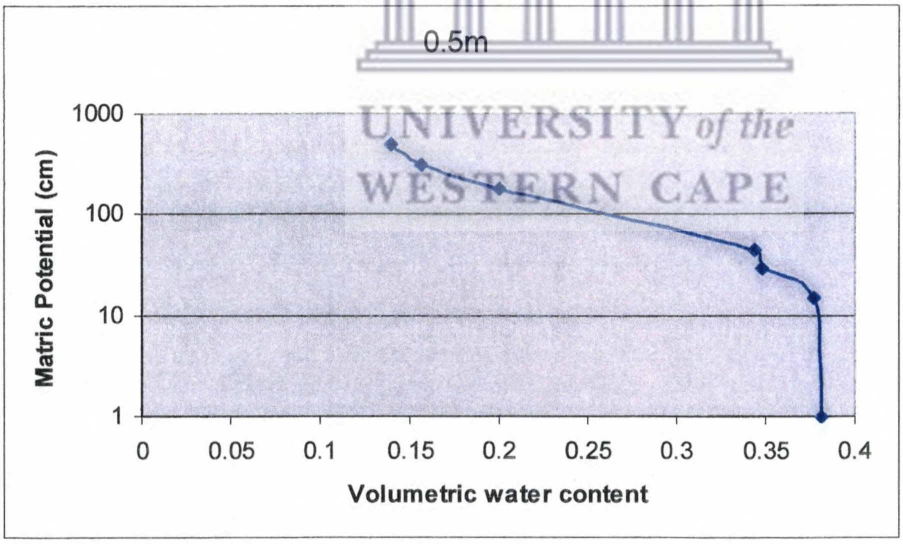
SOIL WATER RETENTION CURVES
+
SAMPLE PHOTOS

iThemba site 1

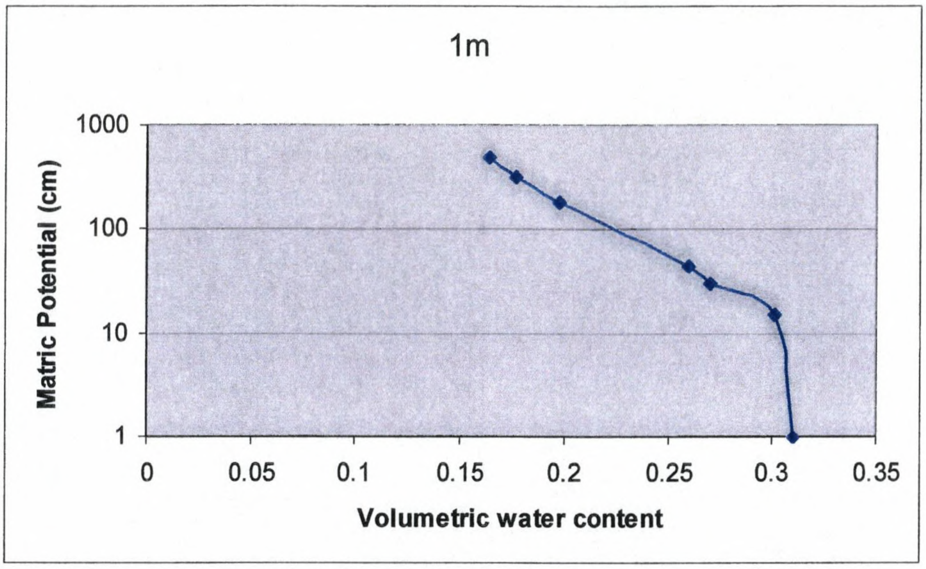
Note: the photos for iThemba site 1 have been omitted.
Also, due to the differences in the decreasing volumetric water content values of the 76 undisturbed soil samples, the scale of the XY plots could not be fitted consistently for all undisturbed samples.



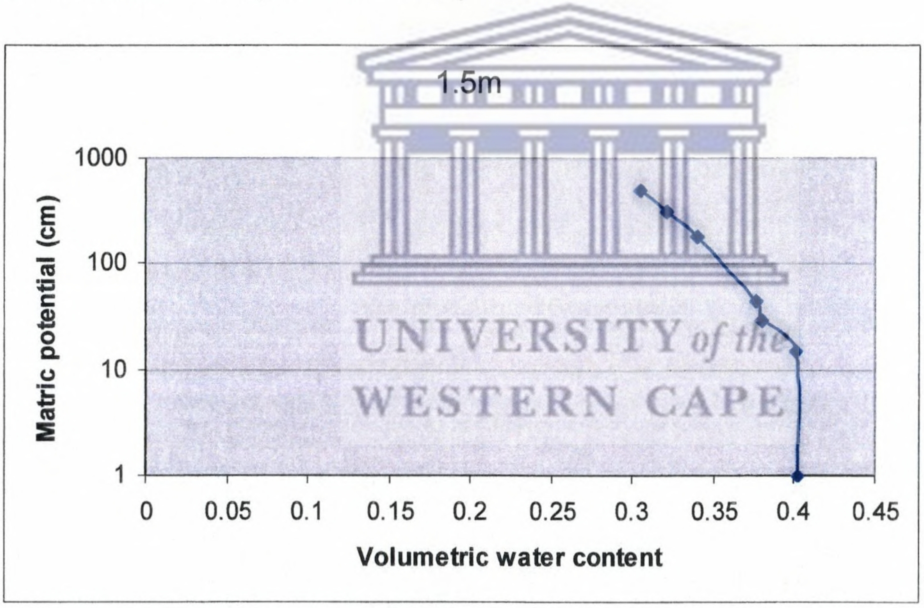
iThemba site 1: Topsoil: Loamy sand



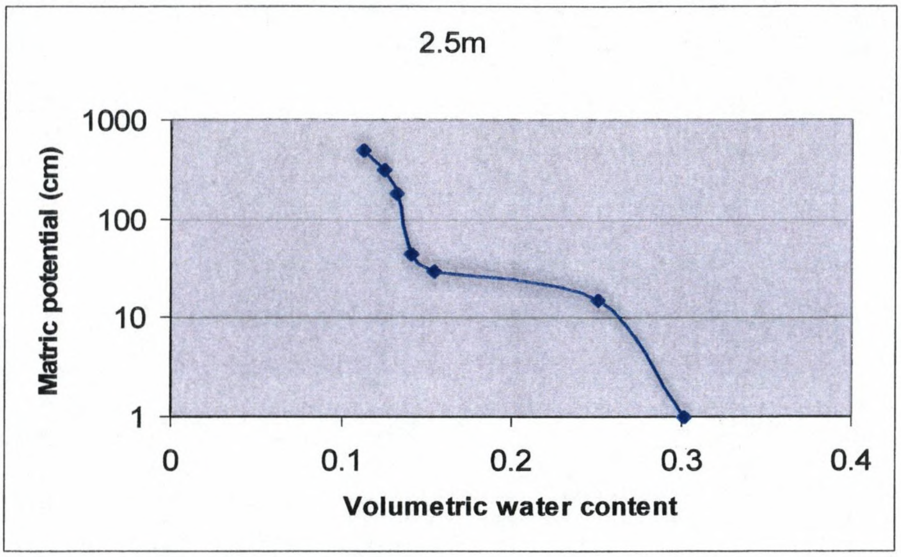
iThemba site 1: Depth= 0,5m: Sand



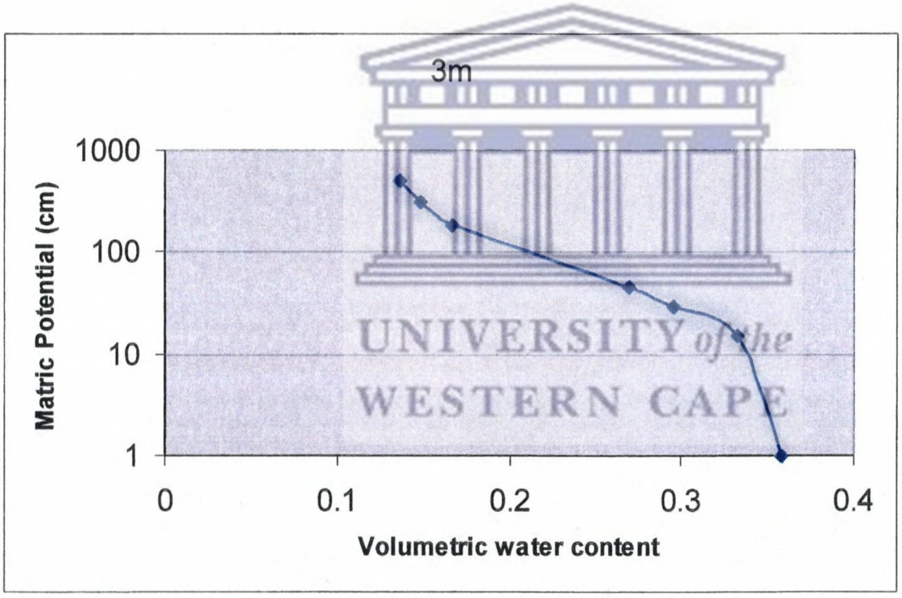
iThemba site 1: Depth= 1m: loamy sand



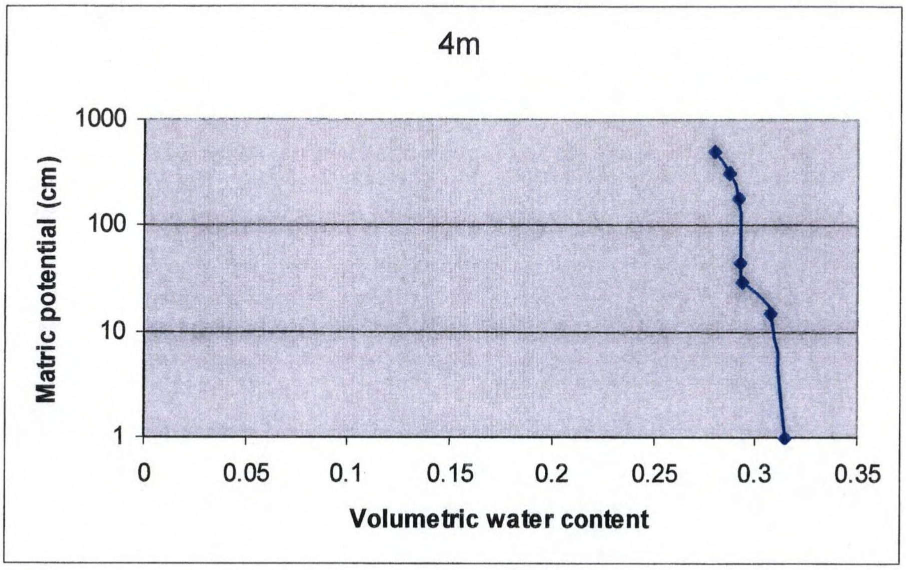
iThemba site 1: Depth= 1.5m: silt



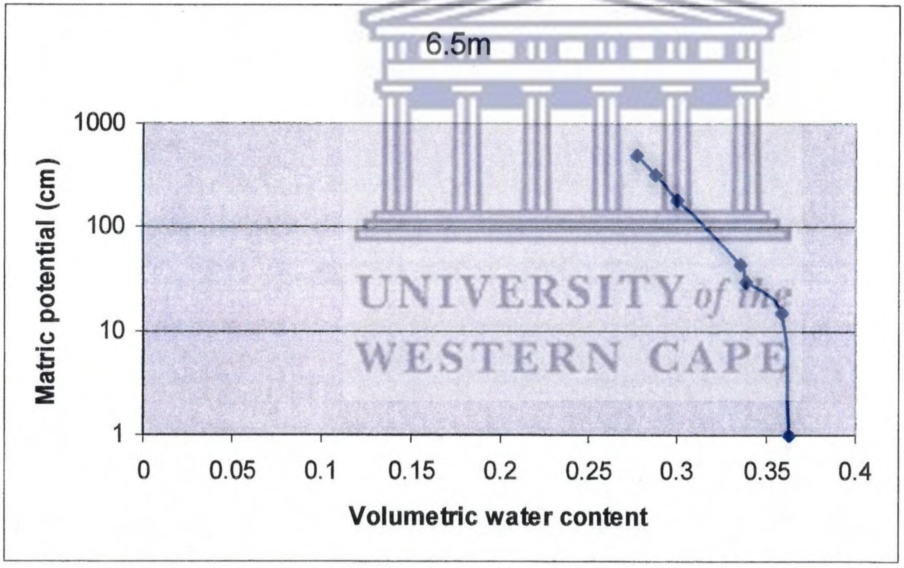
iThemba site 1: Depth= 2.5m: Loamy sand



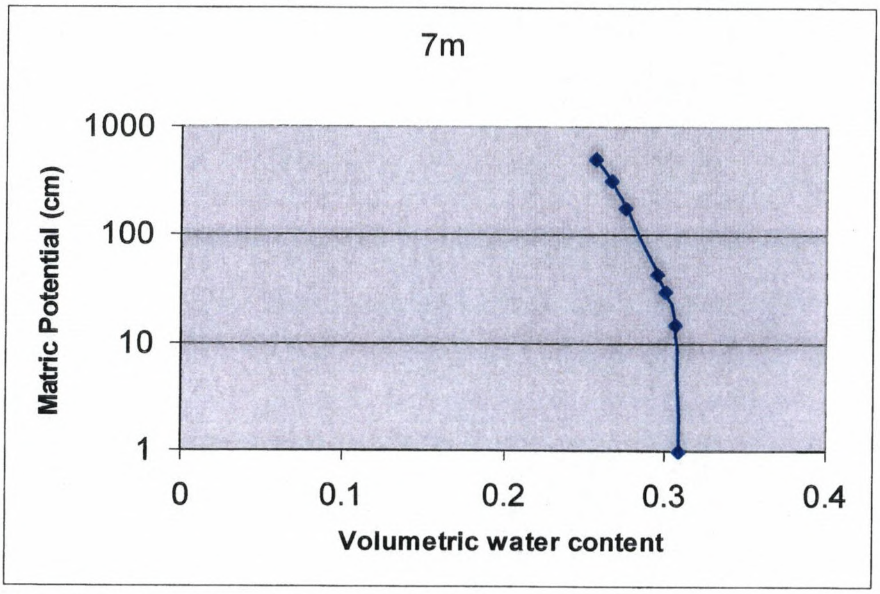
iThemba site 1: Depth= 3m: sand



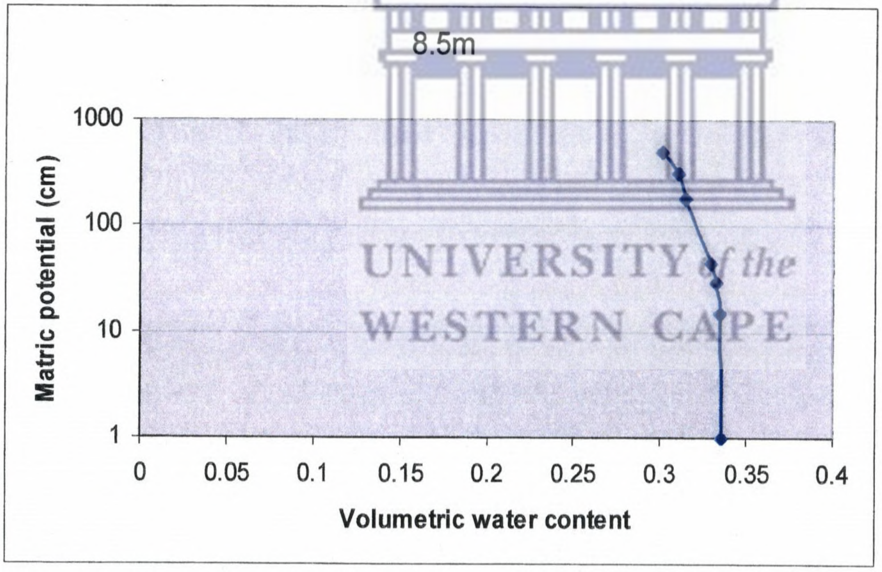
iThemba site 1: Depth= 4m: Sandy Clay Loam



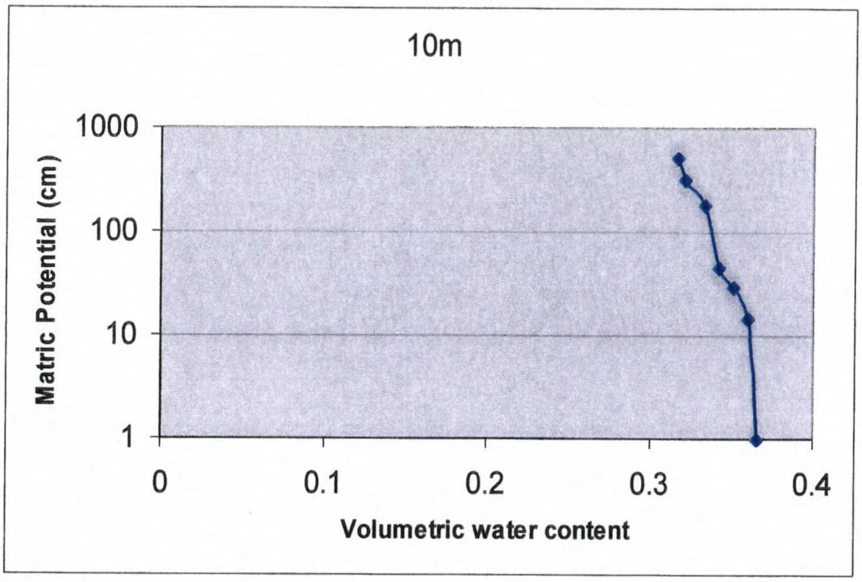
iThemba site 1: Depth= 6.5m: Sandy Loam



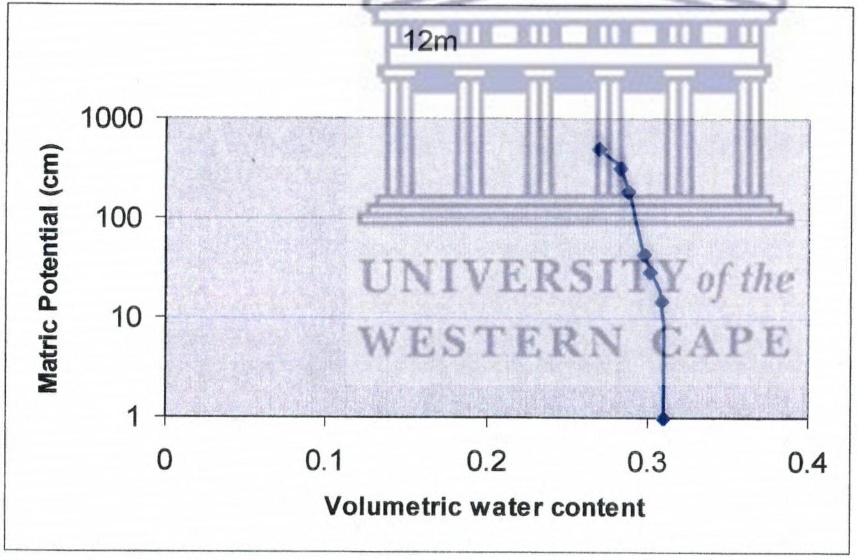
iThemba site 1: Depth= 7m: Silt loam



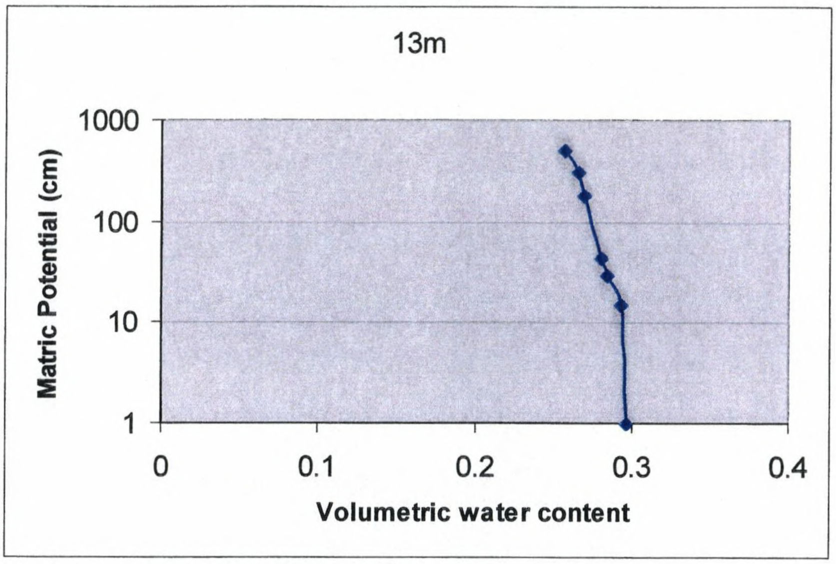
iThemba site 1: Depth= 8.5m: Clay



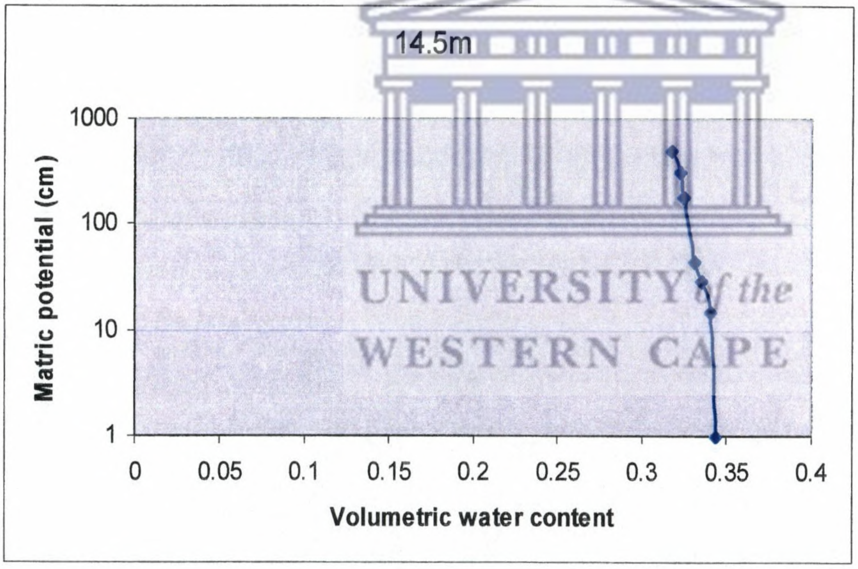
iThemba site 1: Depth= 10m: Clay



iThemba site 1: Depth= 12m: Clay

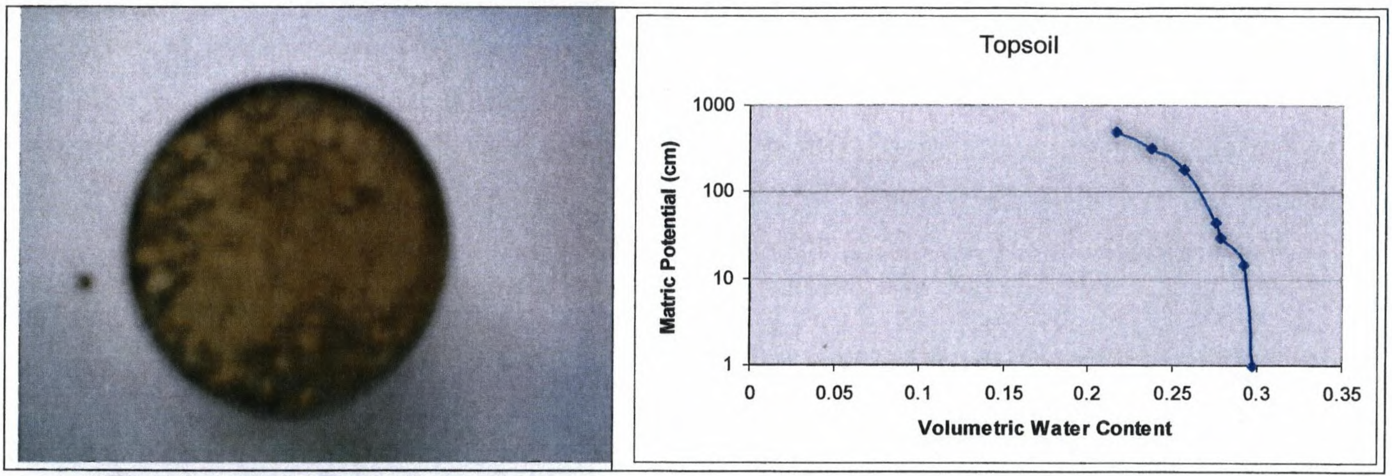


iThemba site 1: Depth= 13m: Clay

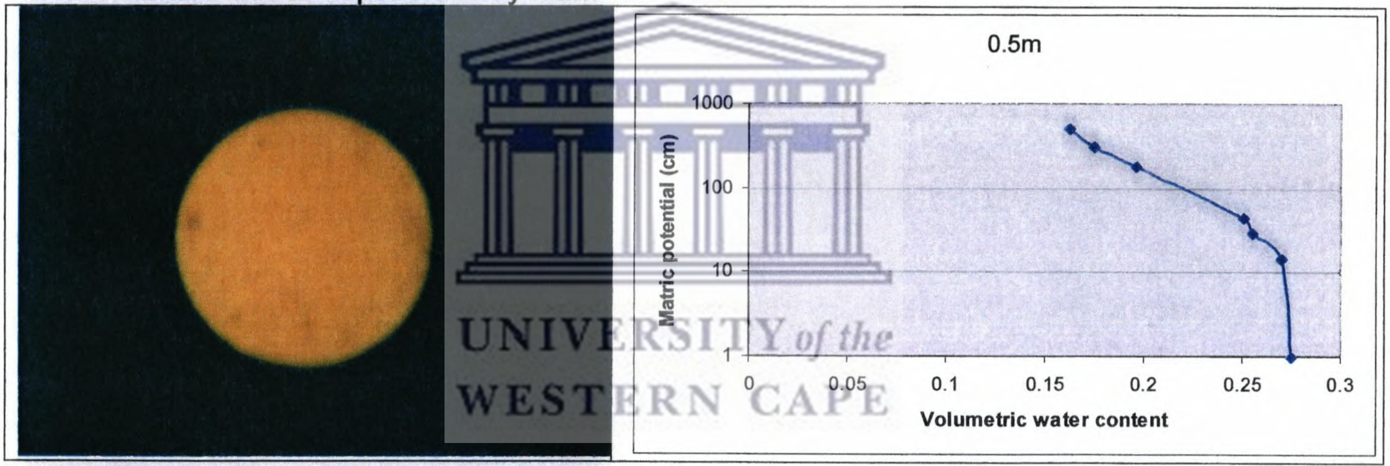


iThemba site 1: Depth= 14.5m: Clay

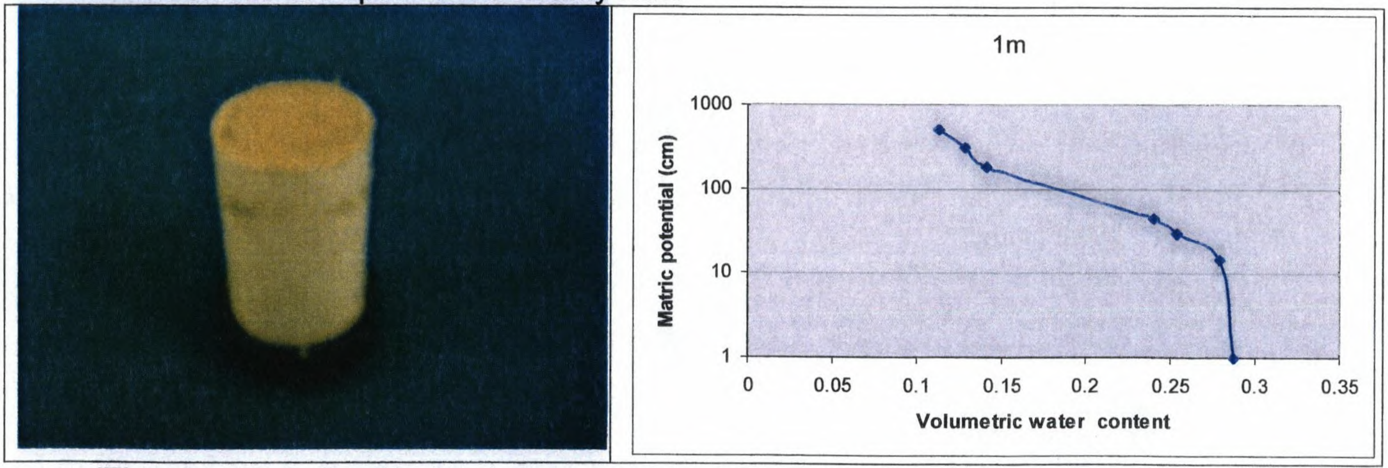
iThemba site 2



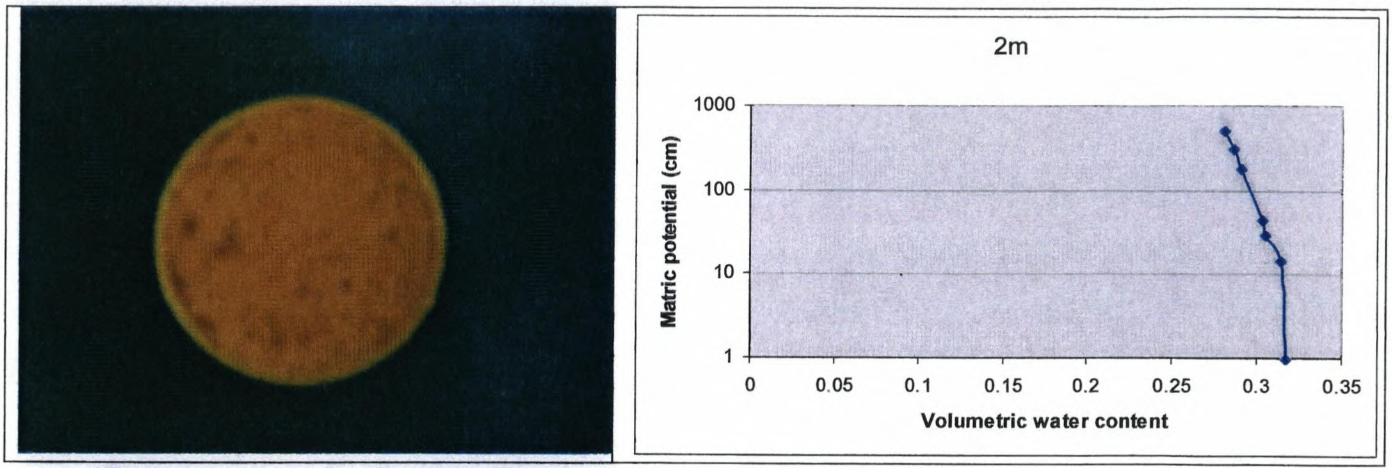
iThemba site 2: Topsoil: sandy loam



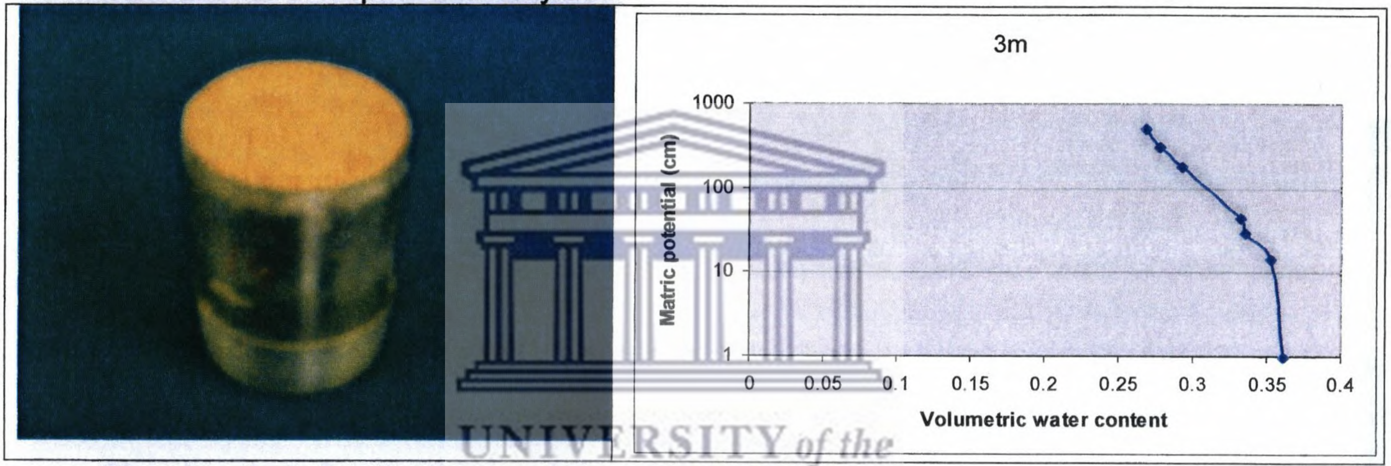
iThemba site 2: Depth= 0.5m: Loamy sand



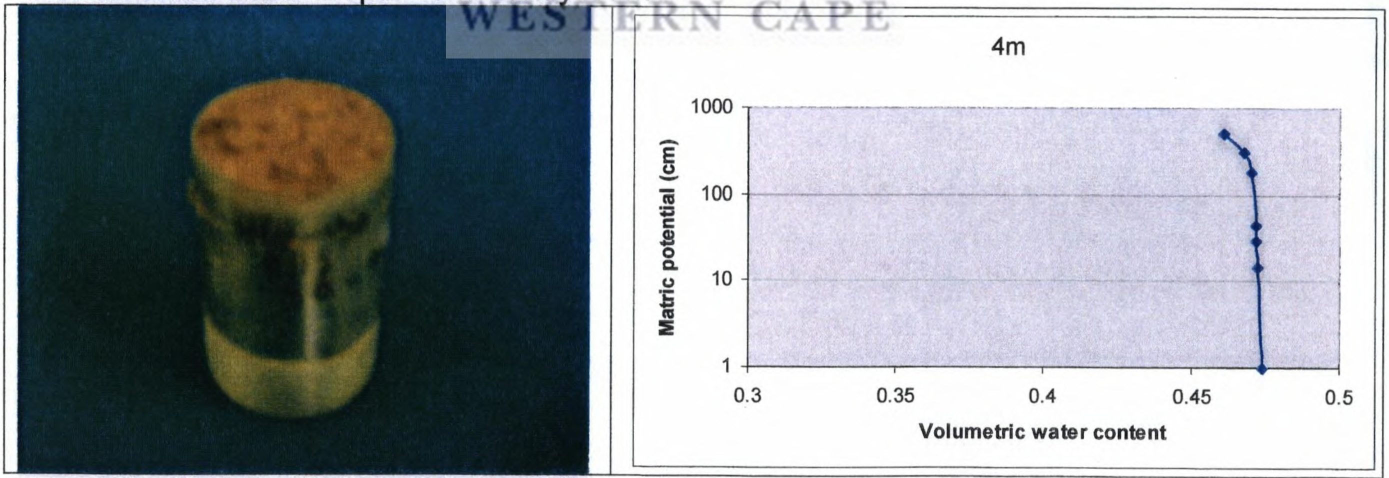
iThemba site 2: Depth= 1m: Loamy sand



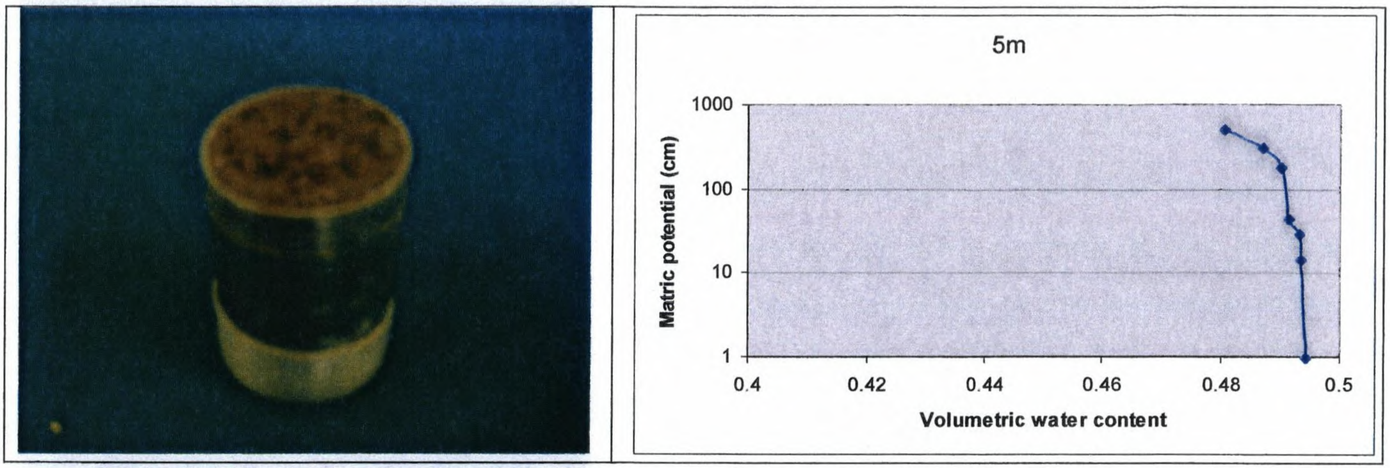
iThemba site 2: Depth= 2m: Clay Loam



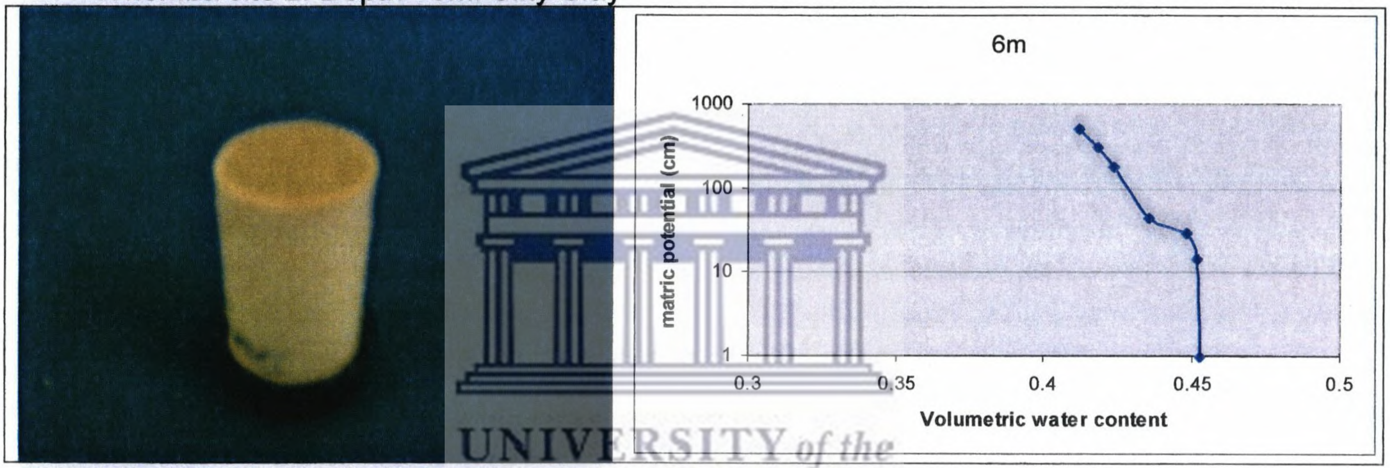
iThemba site 2: Depth= 3m: sandy loam



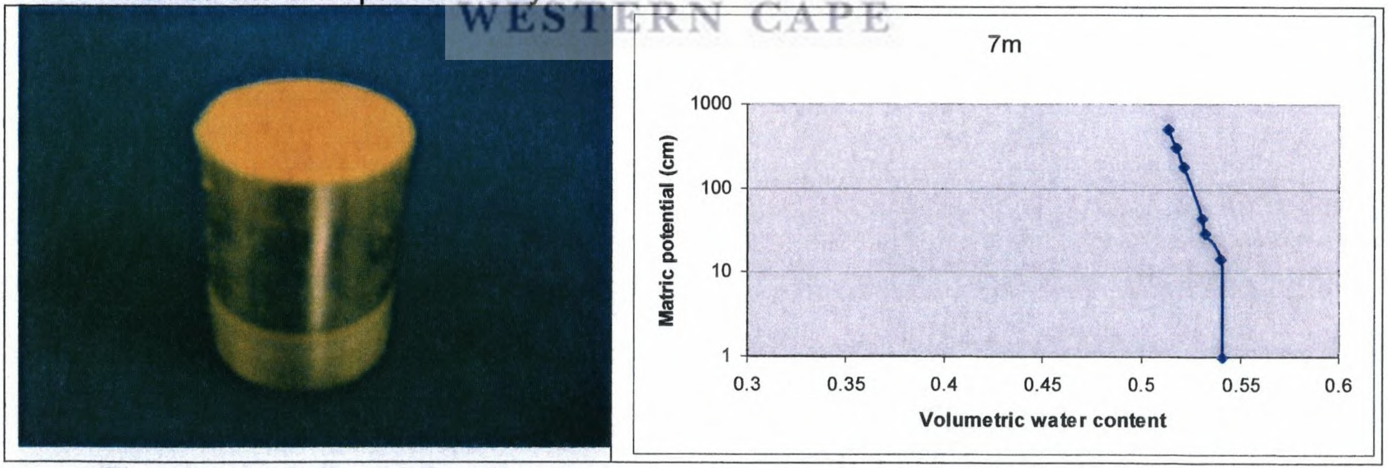
iThemba site 2: Depth= 4m: Silty Clay



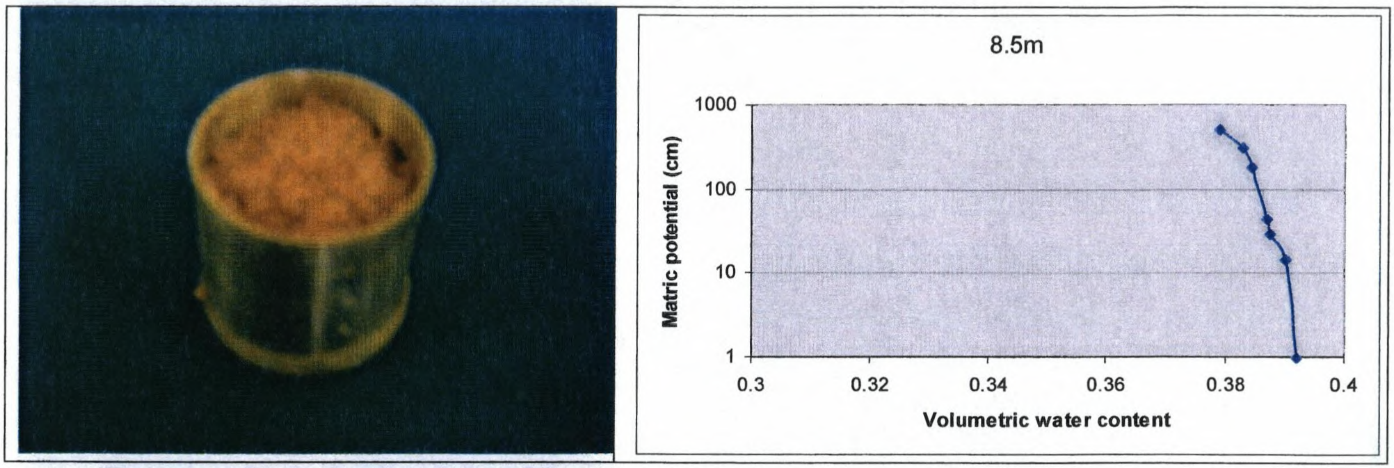
iThemba site 2: Depth= 5m: Silty Clay



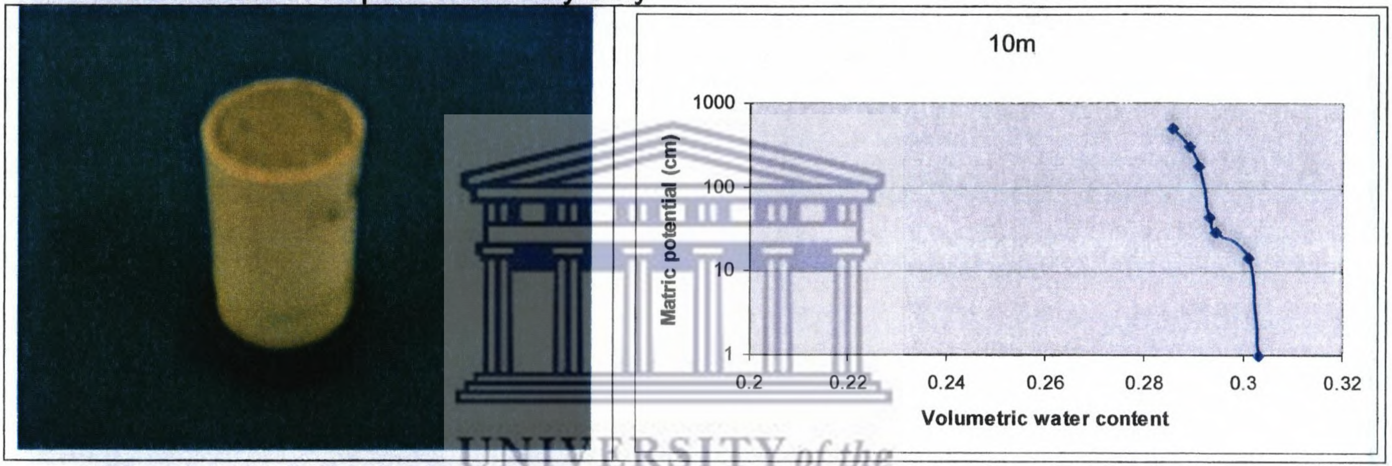
iThemba site 2: Depth=6m: Clay



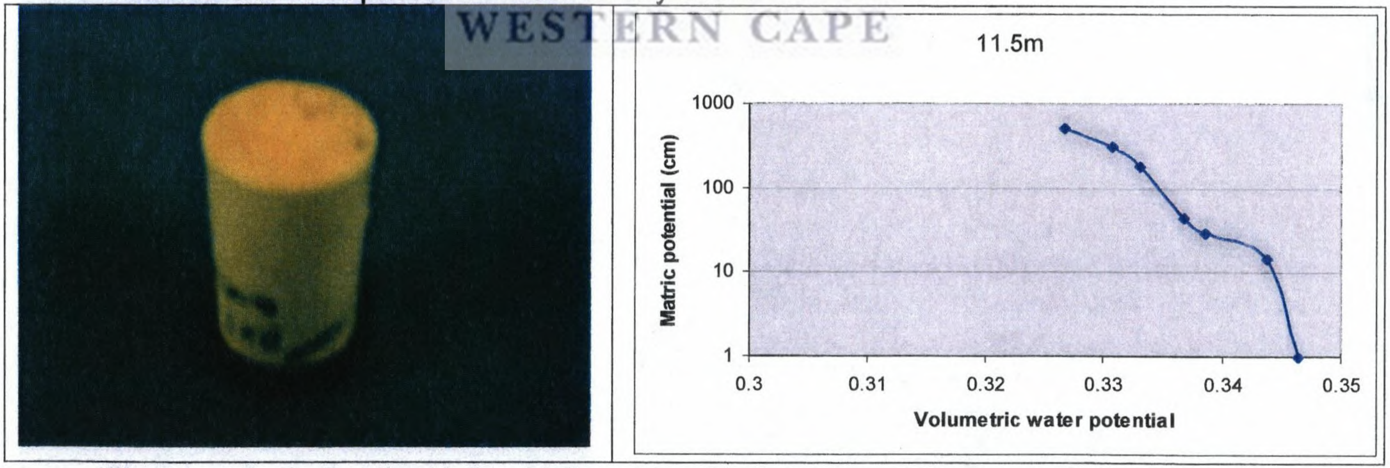
iThemba site 2: Depth=7m: Clay



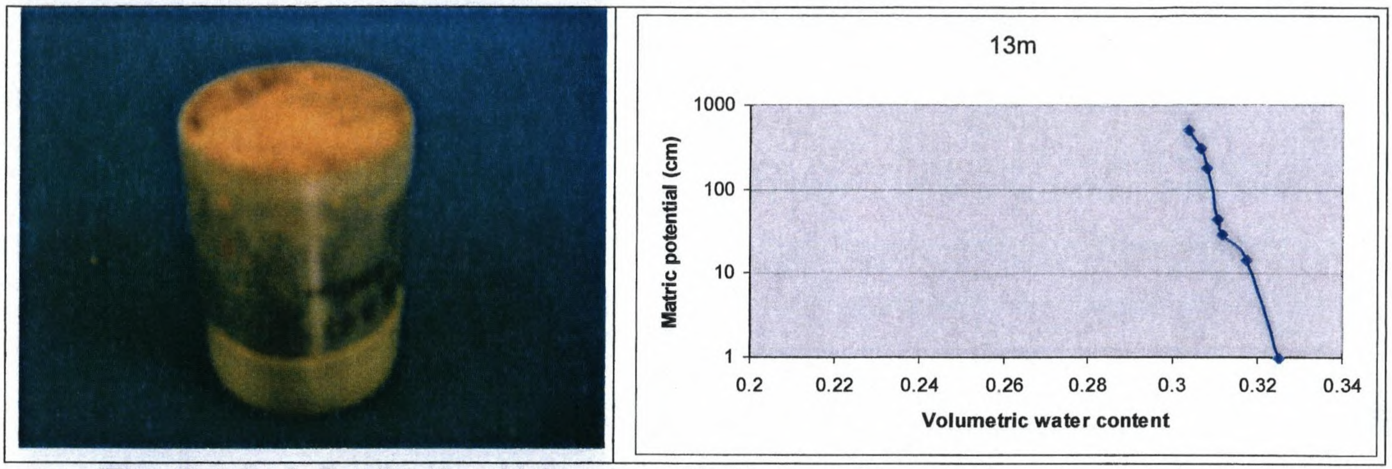
iThemba site 2: Depth= 8.5m: Silty Clay



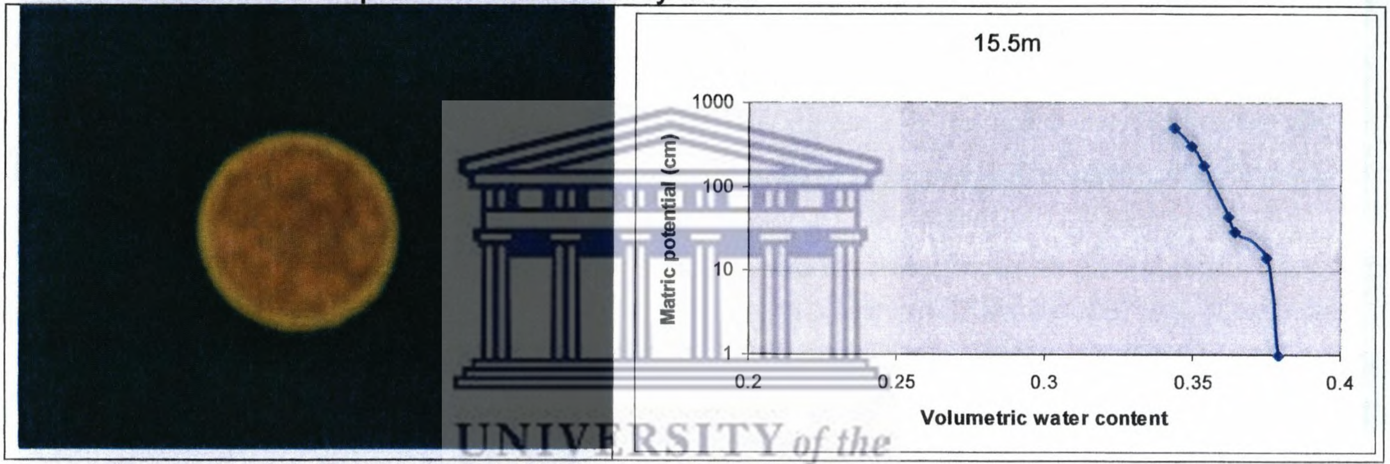
iThemba site 2: Depth=10m: Malmesbury Shale



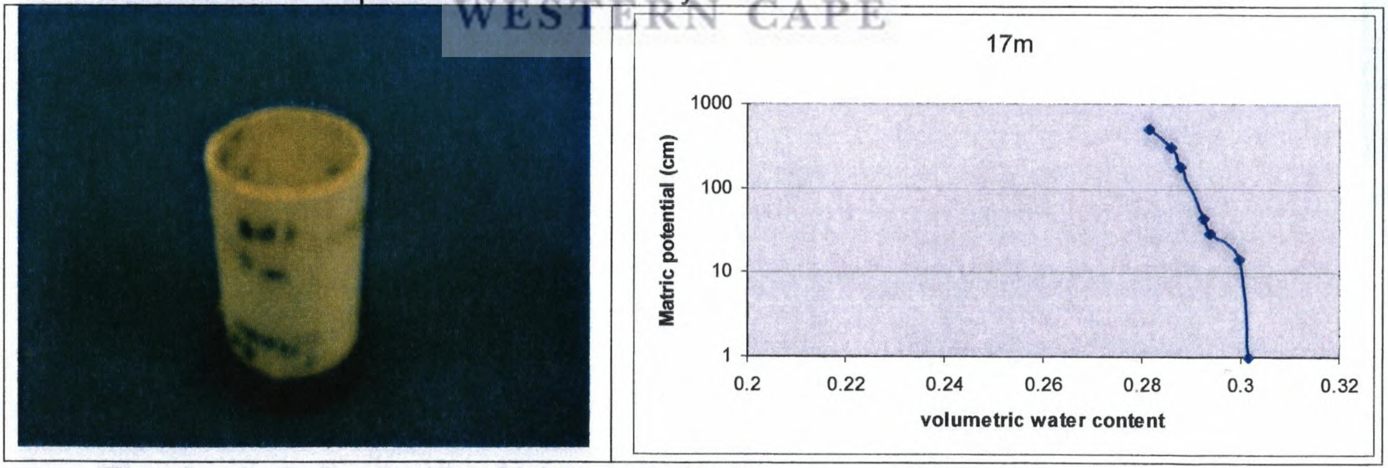
iThemba site 2: Depth=11.5m: Malmesbury Shale



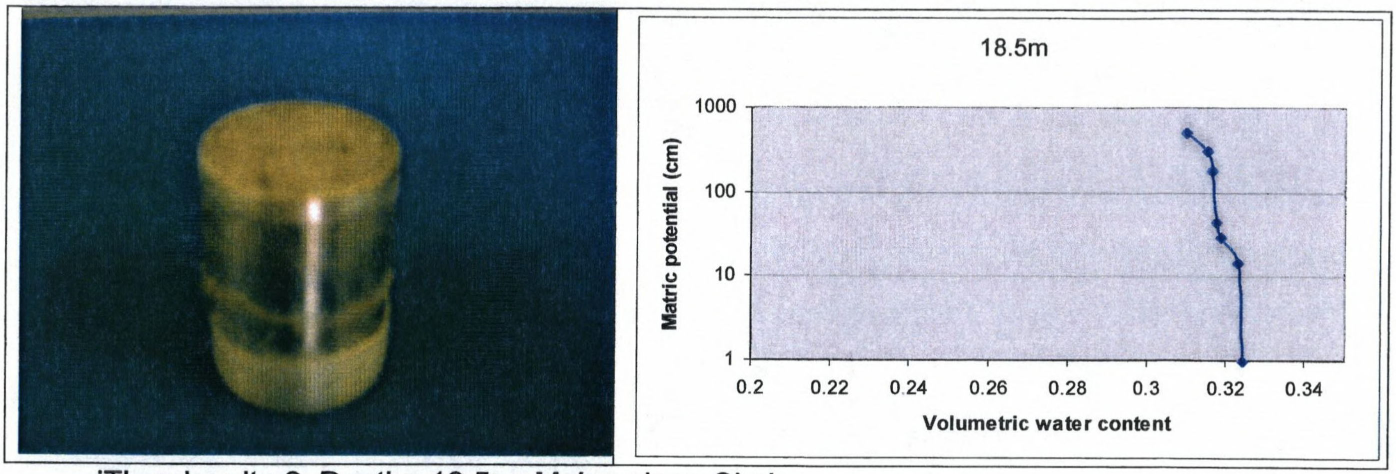
iThemba site 2: Depth=13m: Malmesbury Shale



iThemba site 2: Depth=15.5m: Malmesbury Shale

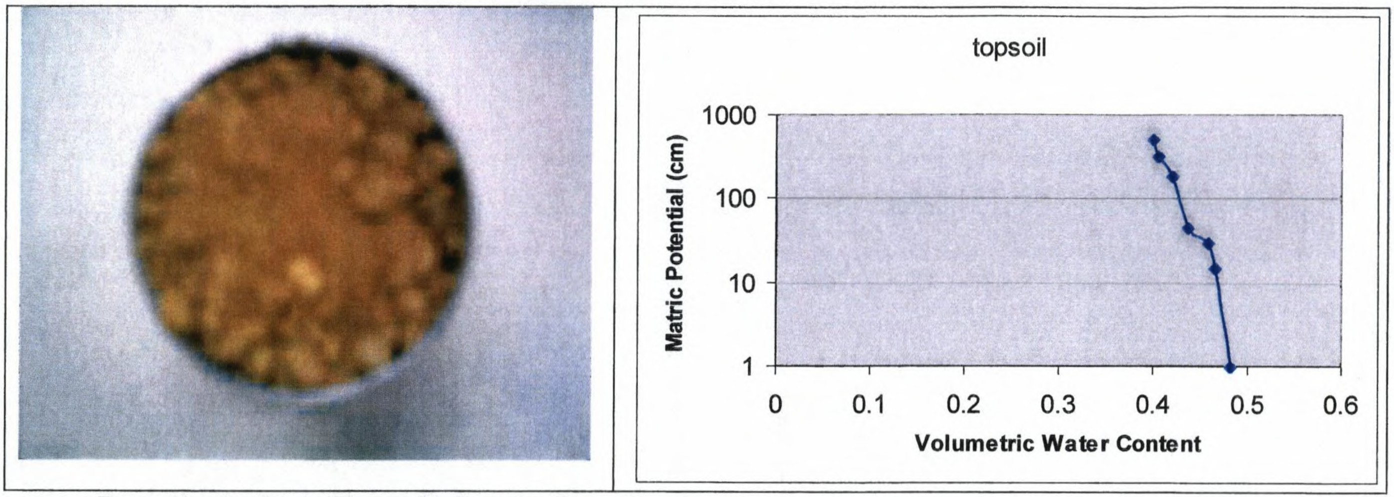


iThemba site 2: Depth=17m: Malmesbury Shale

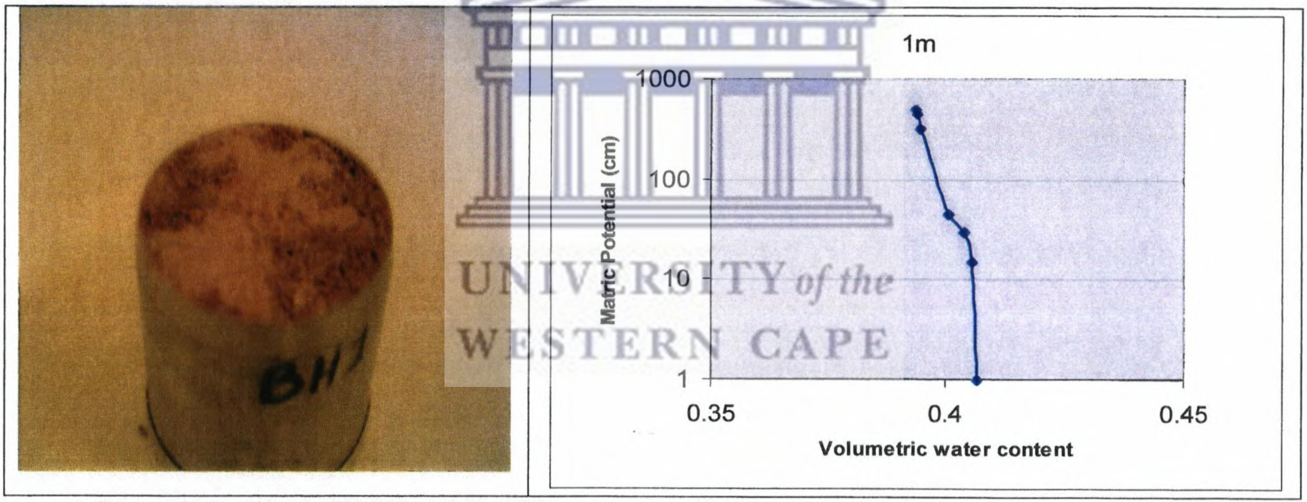


iThemba site 2: Depth= 18.5m: Malmesbury Shale

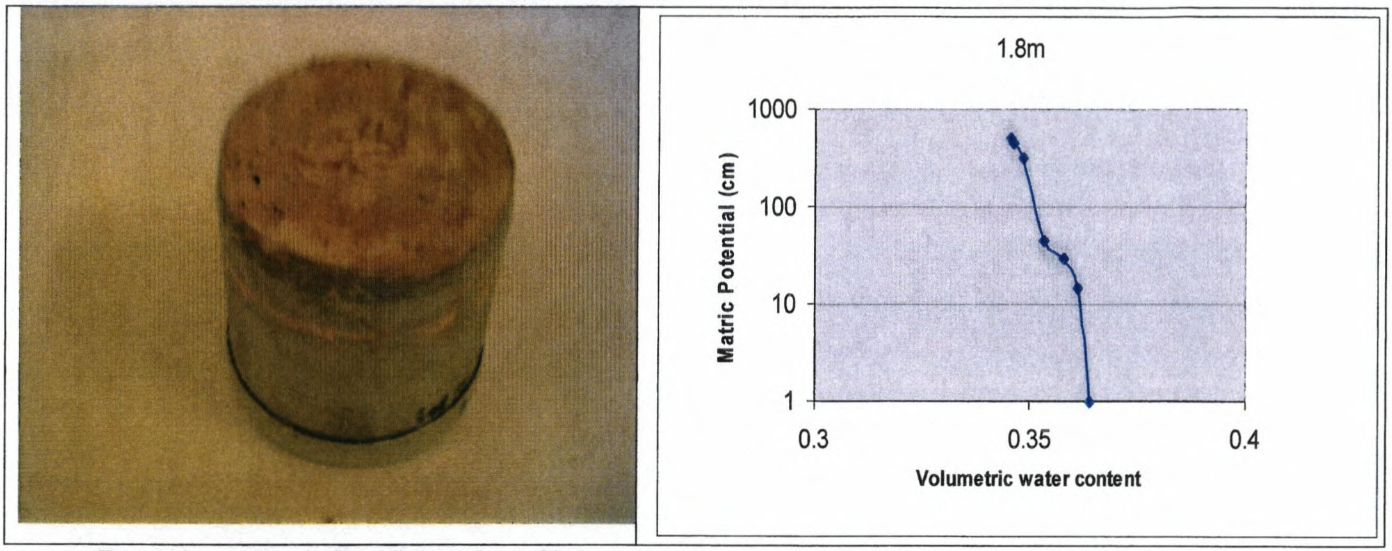
Berg river site 1



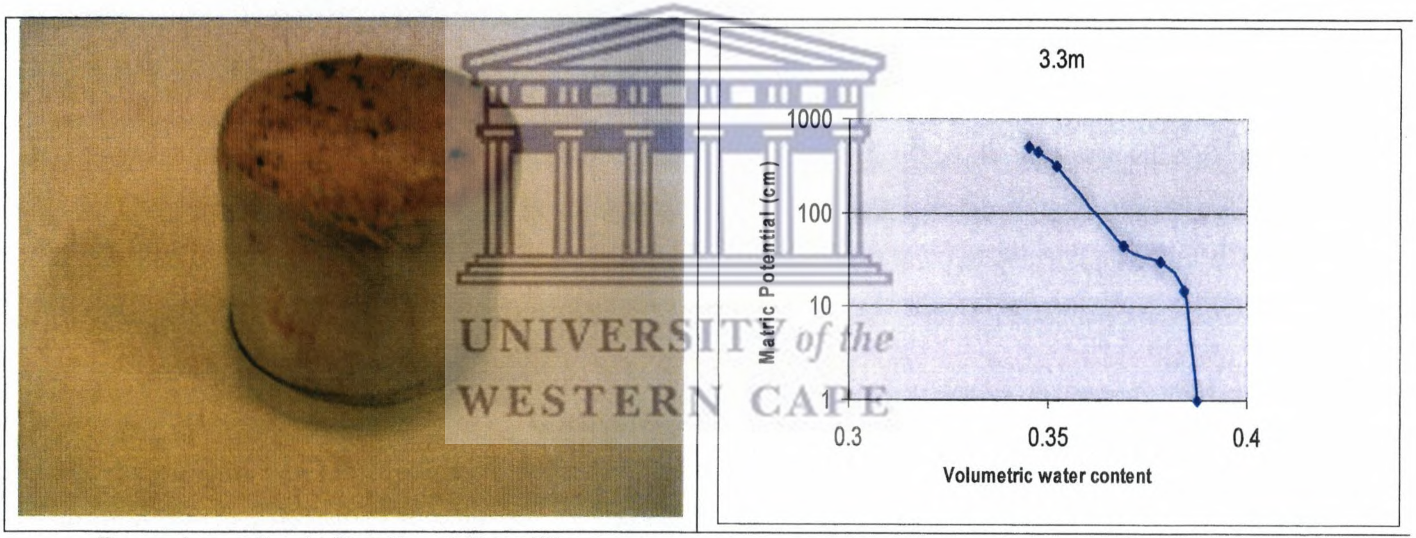
Berg river site 1: Topsoil: Sandy Clay Loam



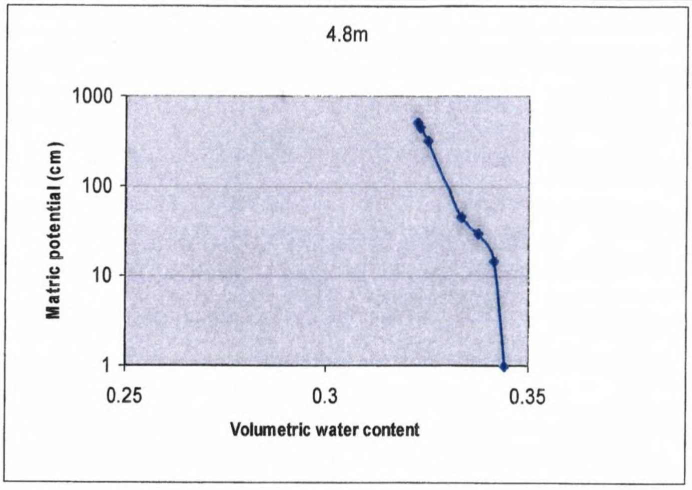
Berg river site 1: Depth= 1m : Clay



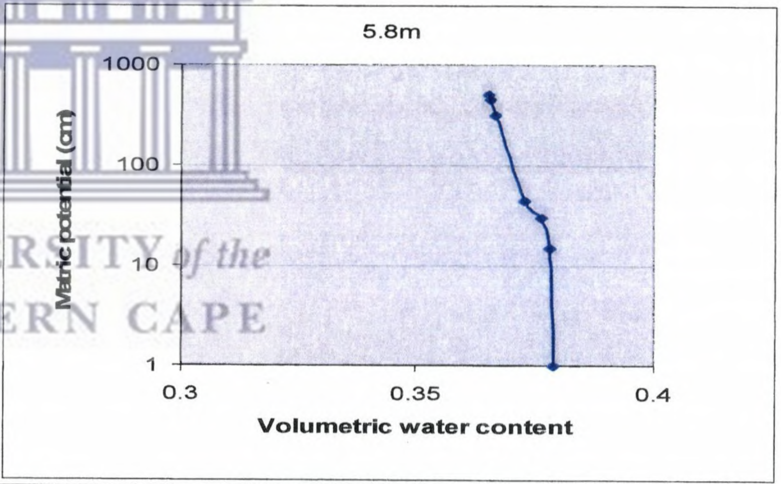
Berg river site 1: Depth= 1.8m: Clay



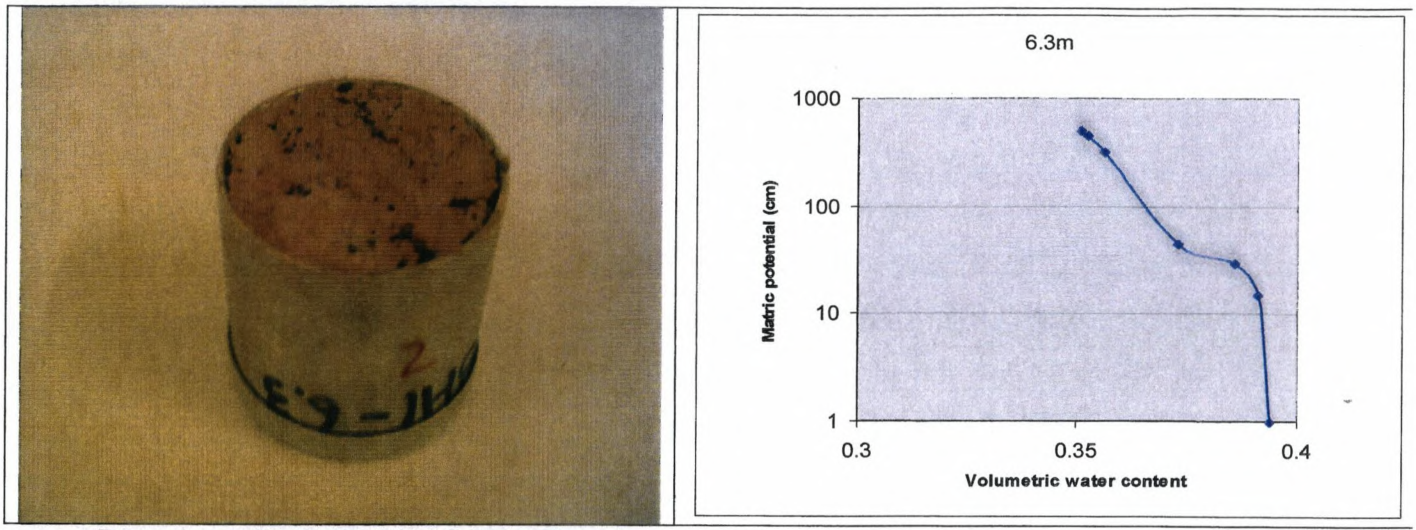
Berg river site 1: Depth= 3.3m: Clay



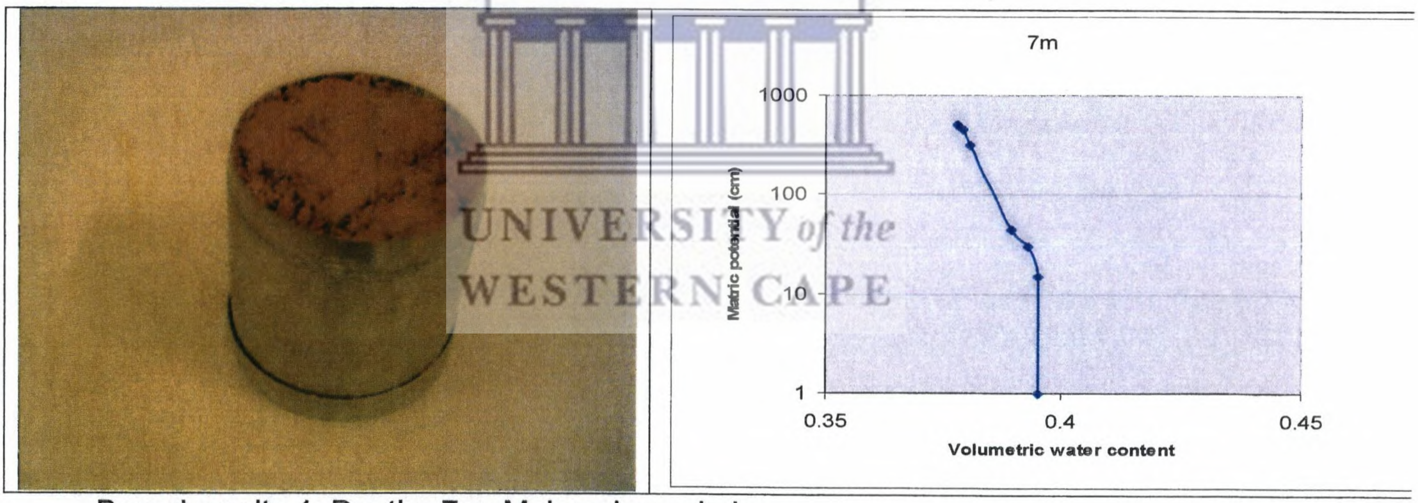
Berg river site 1: Depth= 4.8m: Clay



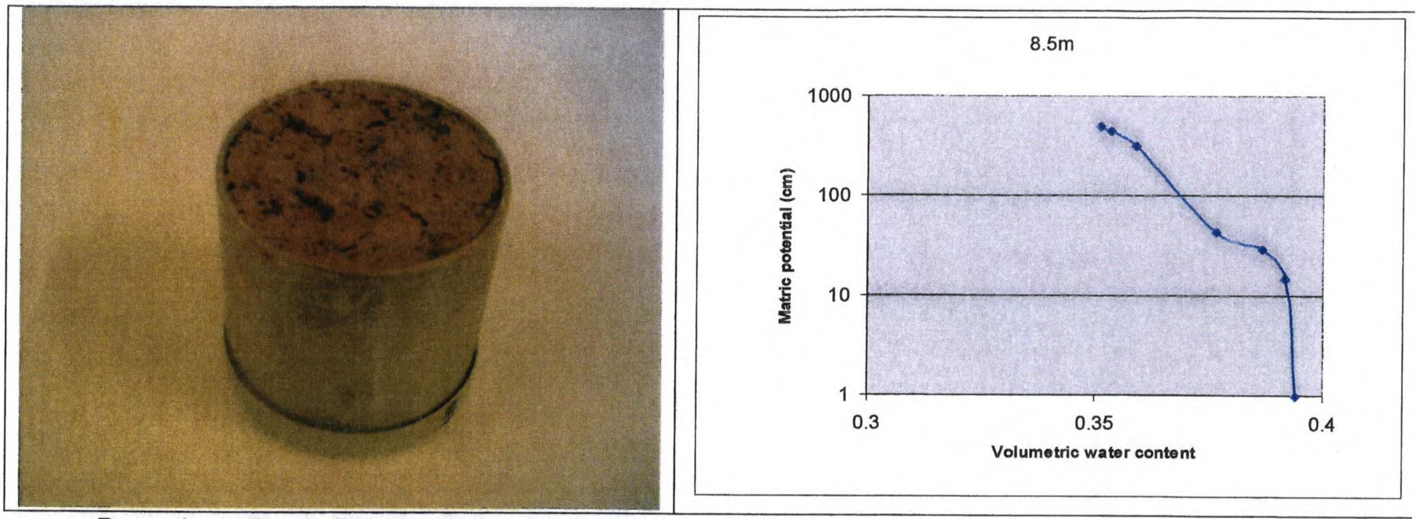
Berg river site 1: Depth= 5.8m: Clay



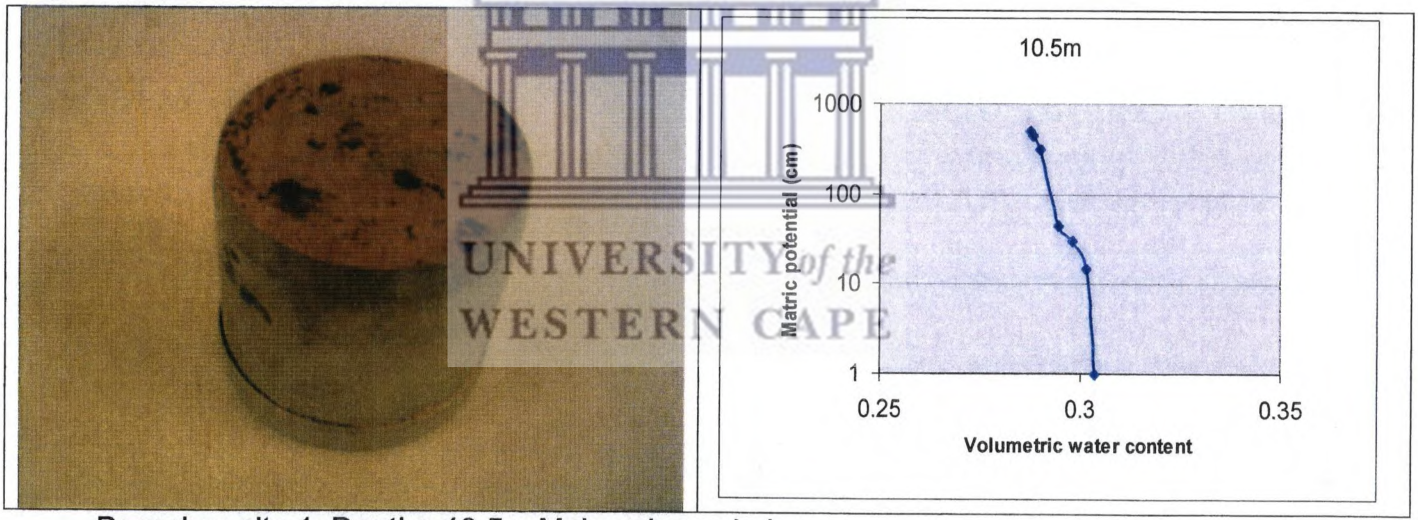
Berg river site 1: Depth= 6.3m: Clay



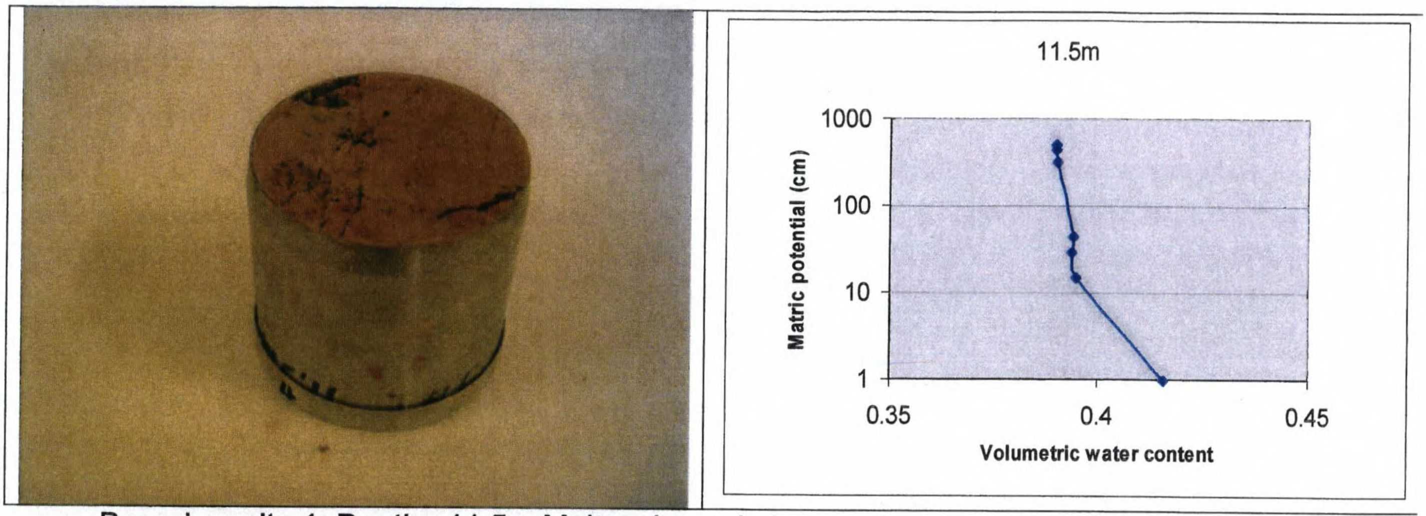
Berg river site 1: Depth= 7m: Malmesbury shales



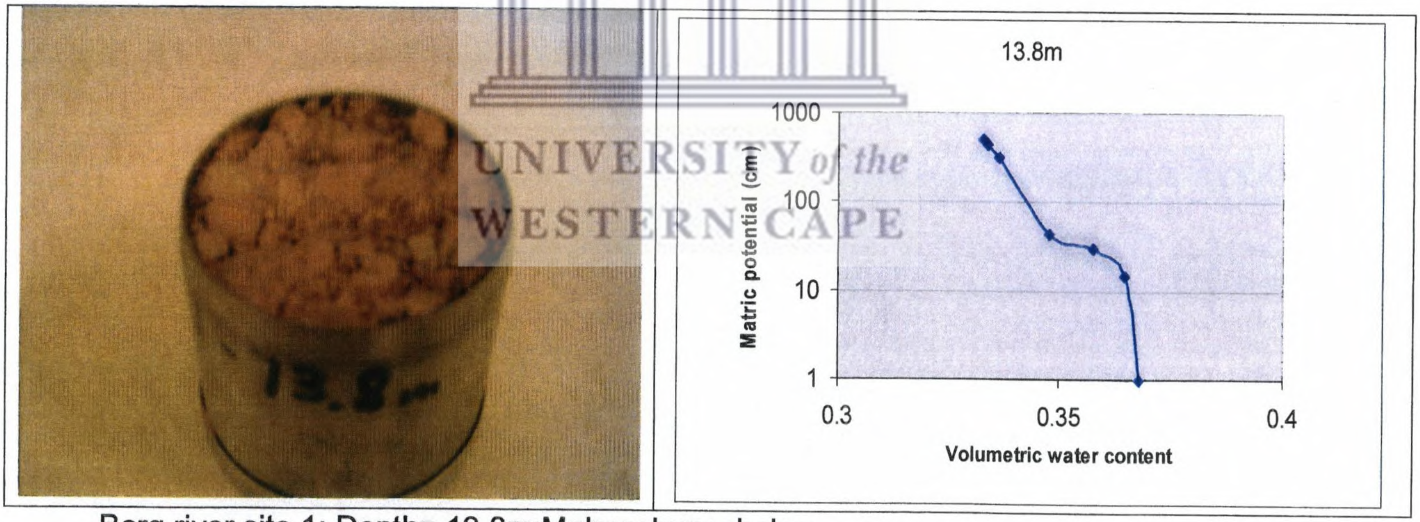
Berg river site 1: Depth= 8.5m :Malmesbury shales



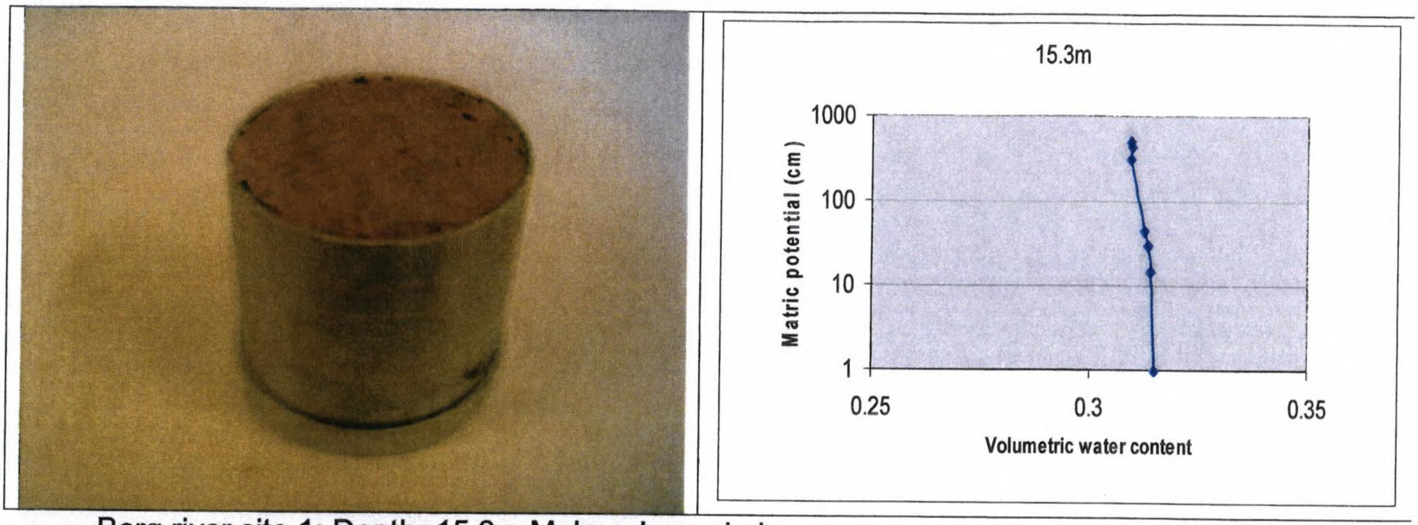
Berg river site 1: Depth= 10.5m:Malmesbury shales



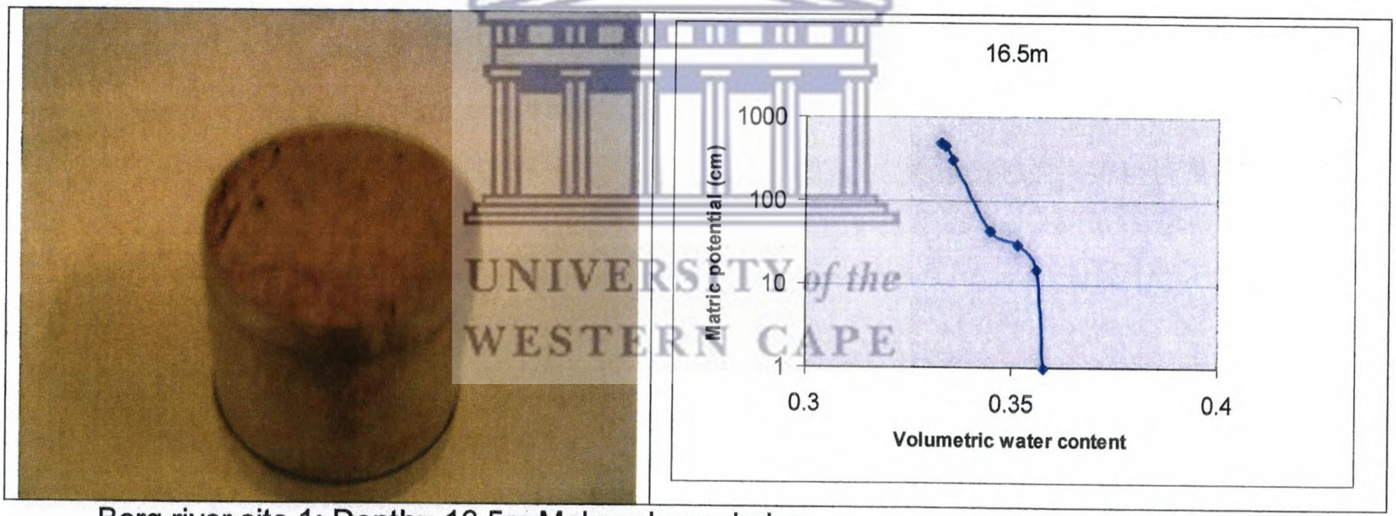
Berg river site 1: Depth= 11.5m:Malmesbury shales



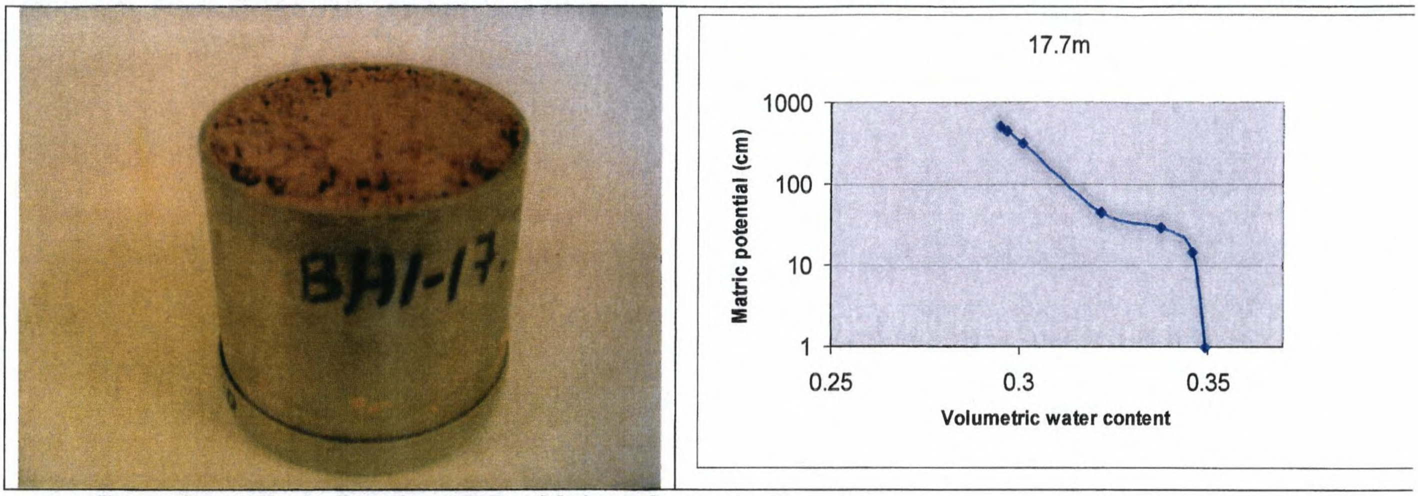
Berg river site 1: Depth= 13.8m:Malmesbury shales



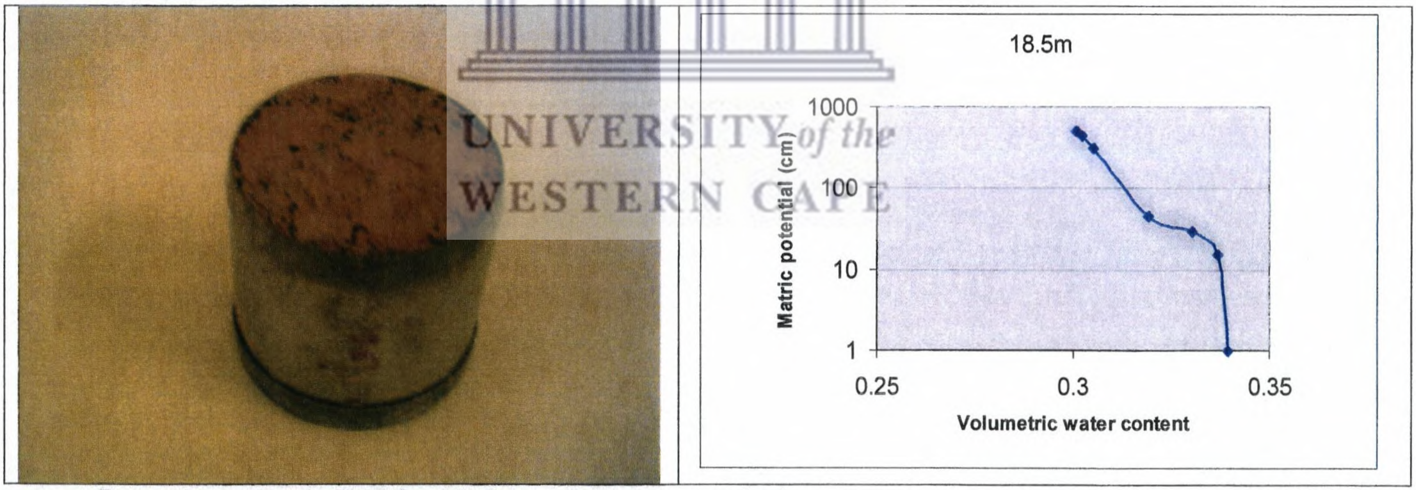
Berg river site 1: Depth=15.3m:Malmesbury shales



Berg river site 1: Depth= 16.5m:Malmesbury shales

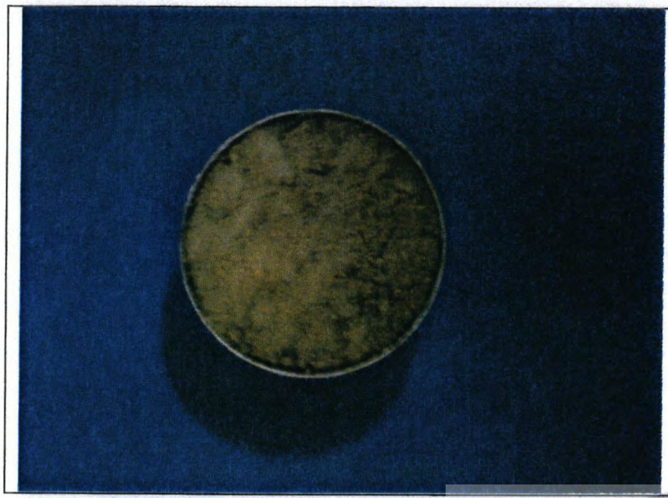


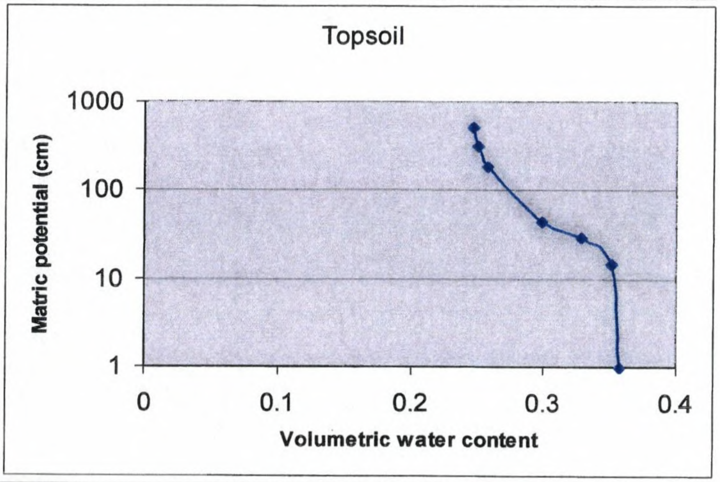
Berg river site 1: Depth= 17.7m:Malmesbury shales



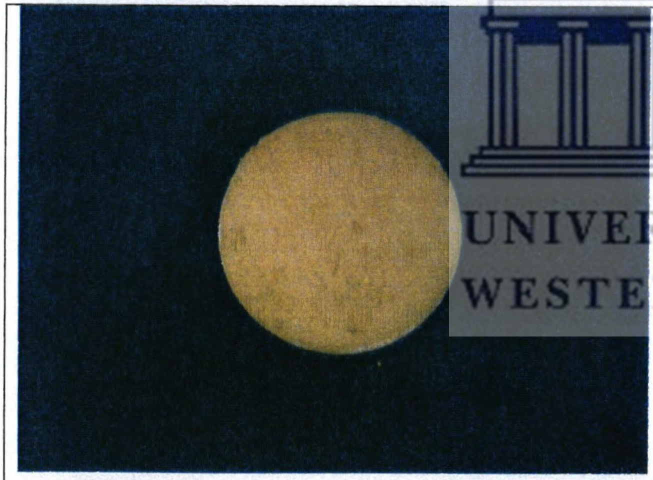
Berg river site 1: Depth=18.5m: :Malmesbury shales

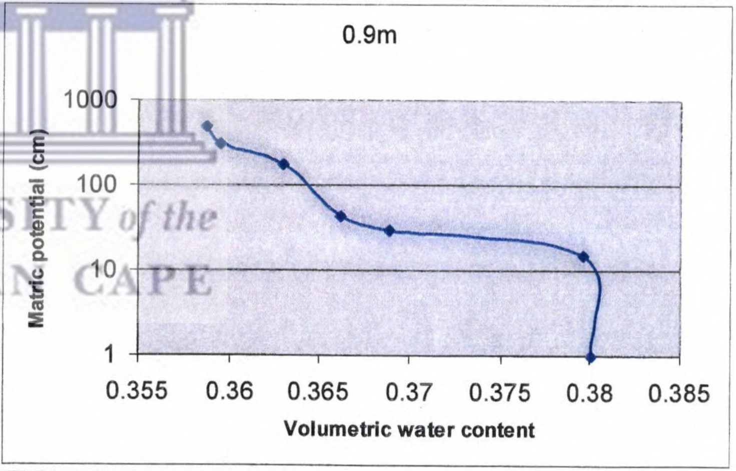
Berg river site 2



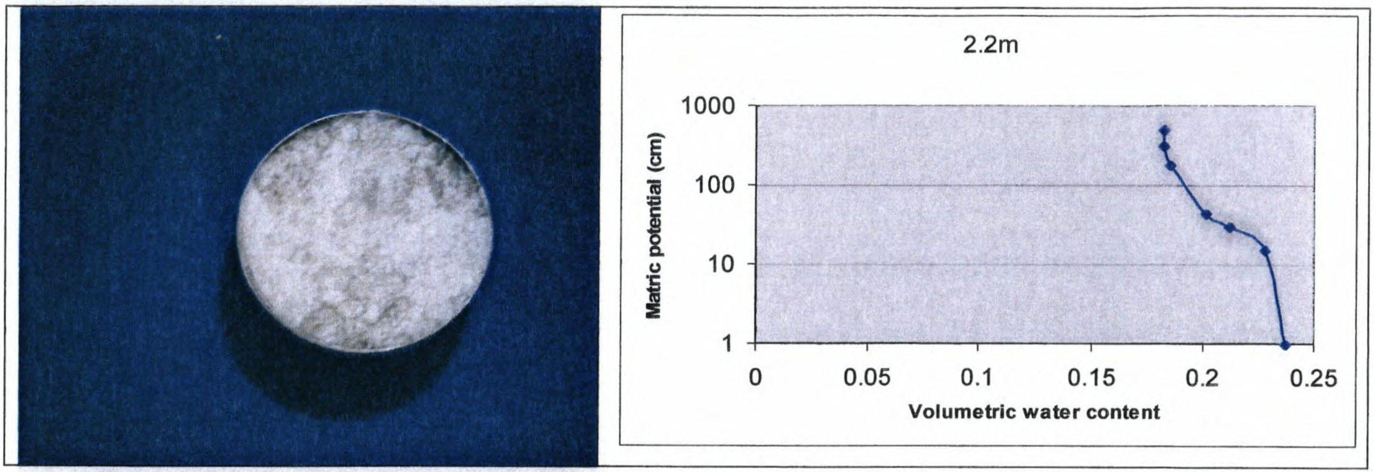


Berg river site 2: Topsoil: Clay loam

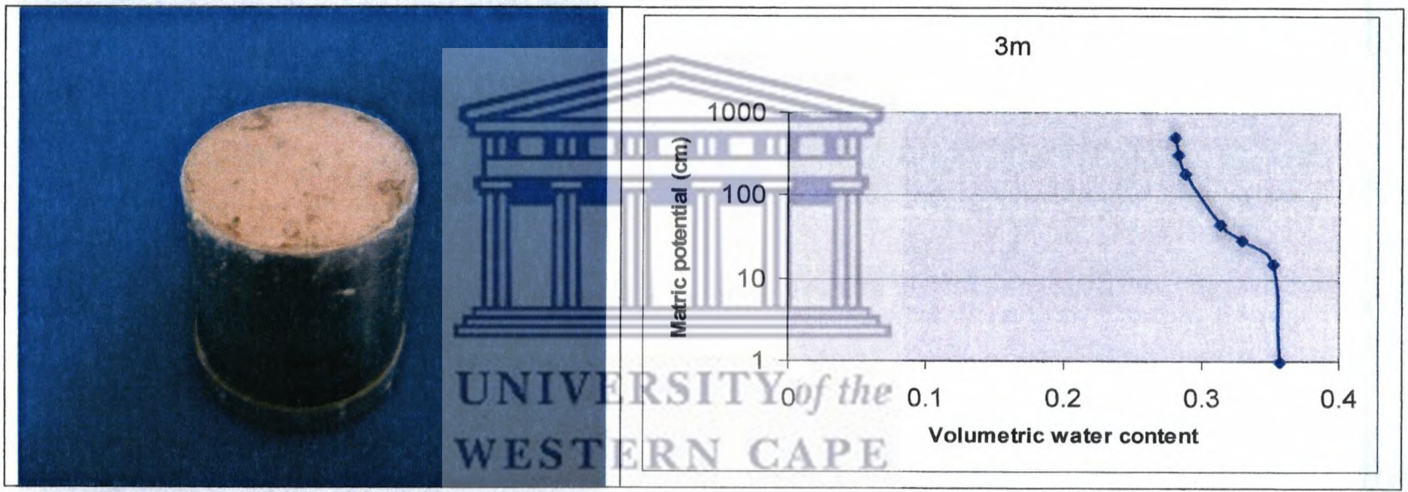




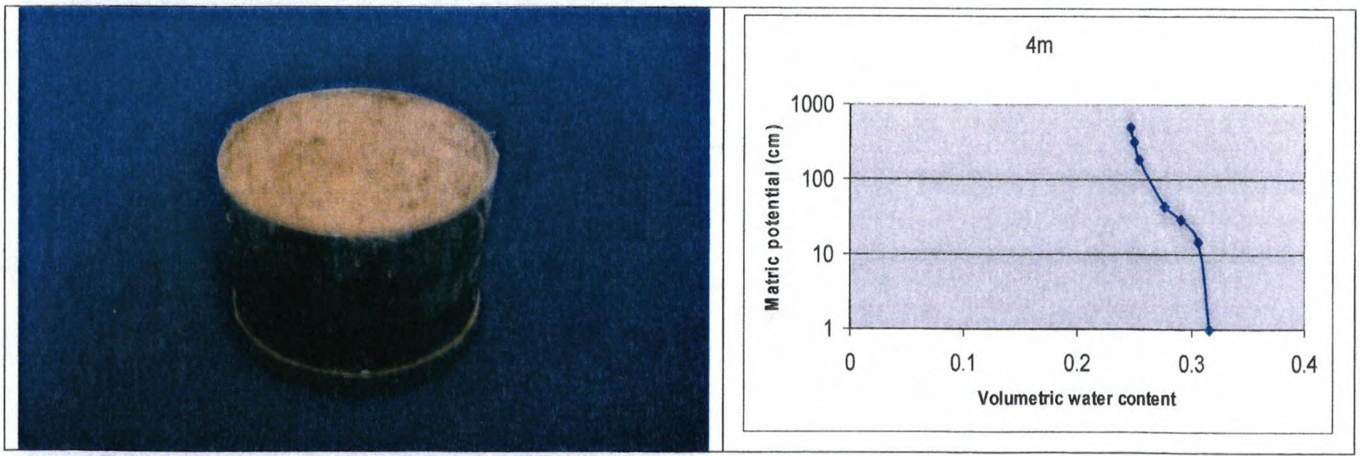
Berg river site 2: Depth=0.9m: Sandy clay



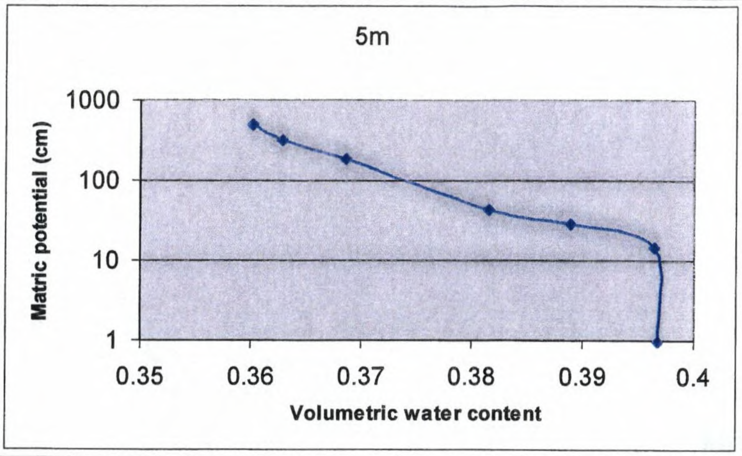
Berg river site 2: Depth= 2.2m: Silt loam



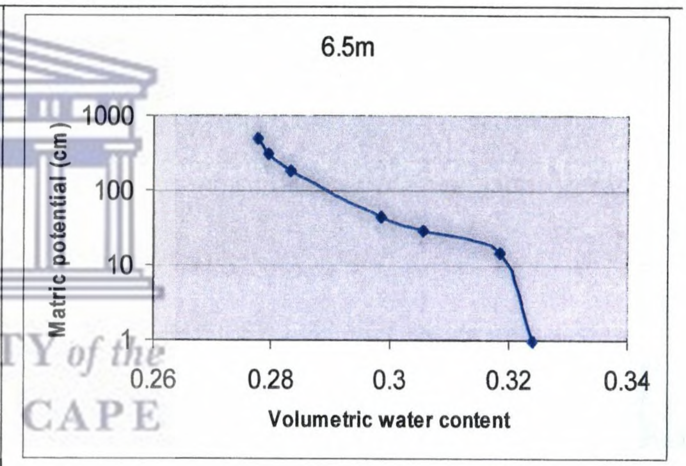
Berg river site 2: Depth= 3m: silt



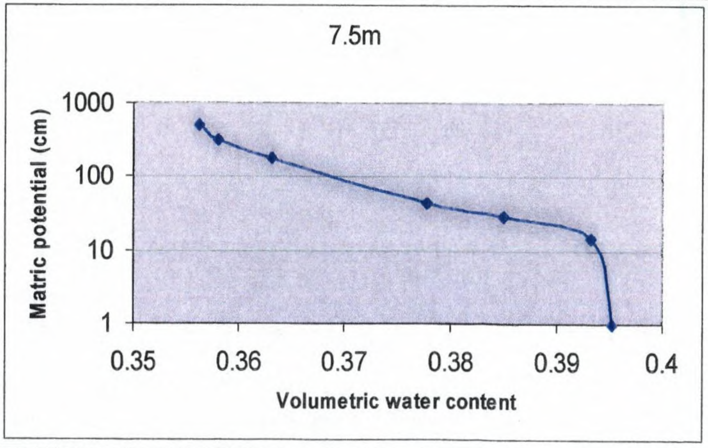
Berg river site 2: Depth= 4m: Silt



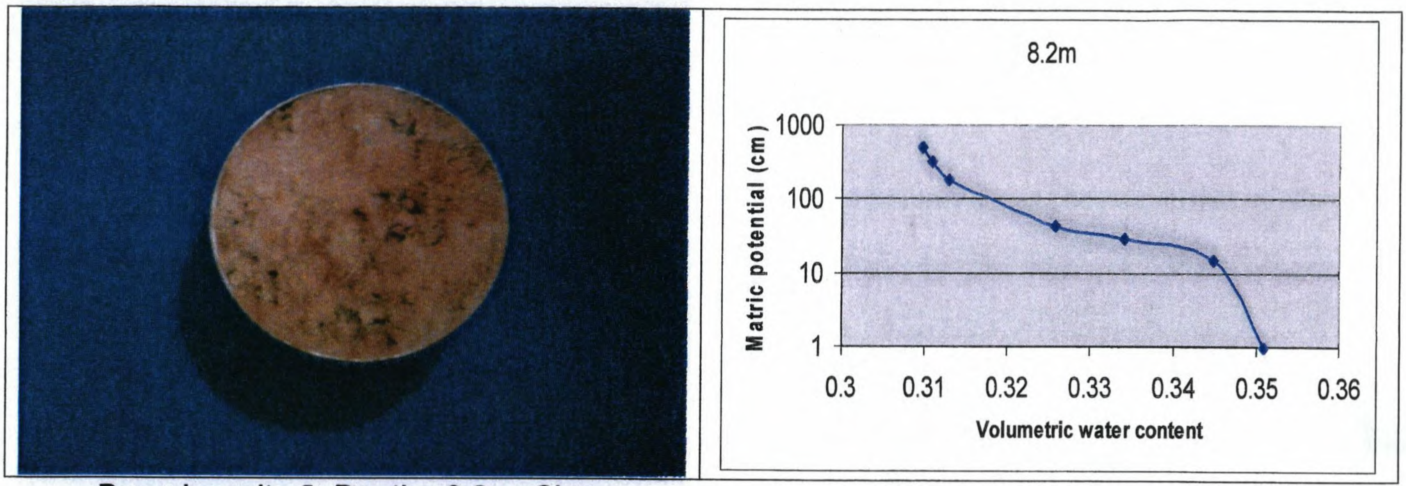
Berg river site 2: Depth= 5m:Silt loam



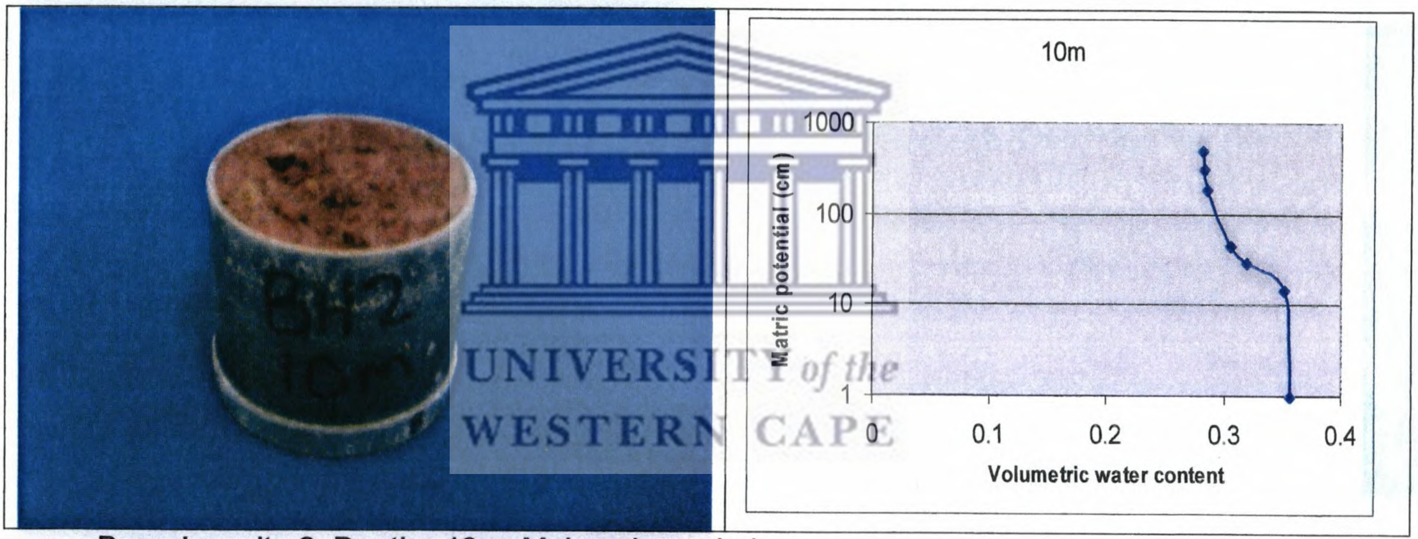
Berg river site 2: Depth= 6.5m: Clay



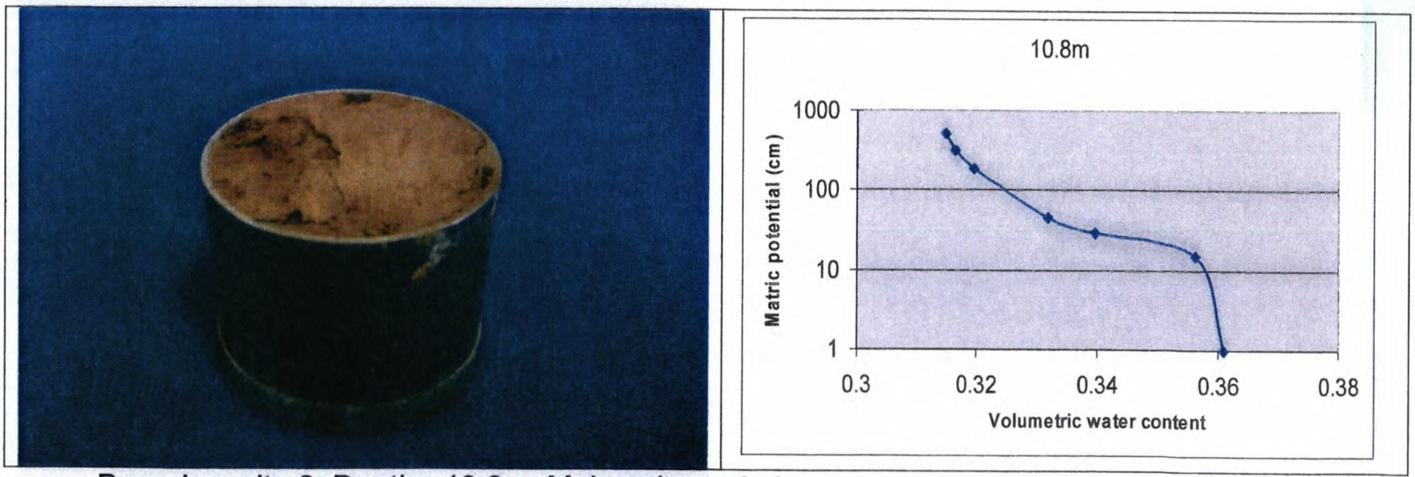
Berg river site 2: Depth= 7.5m:Silty clay



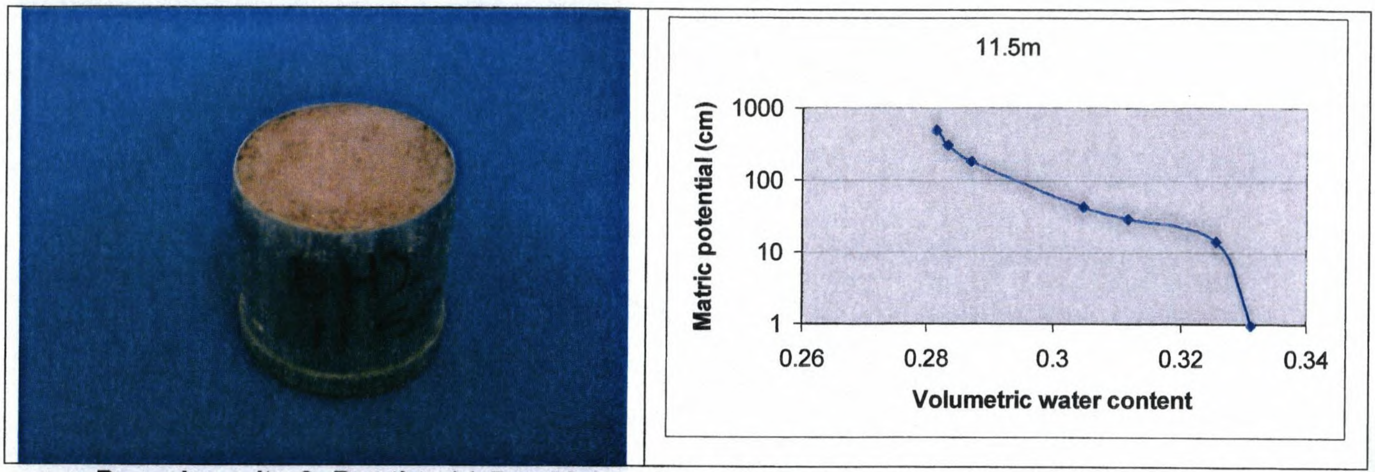
Berg river site 2: Depth= 8.2m: Clay



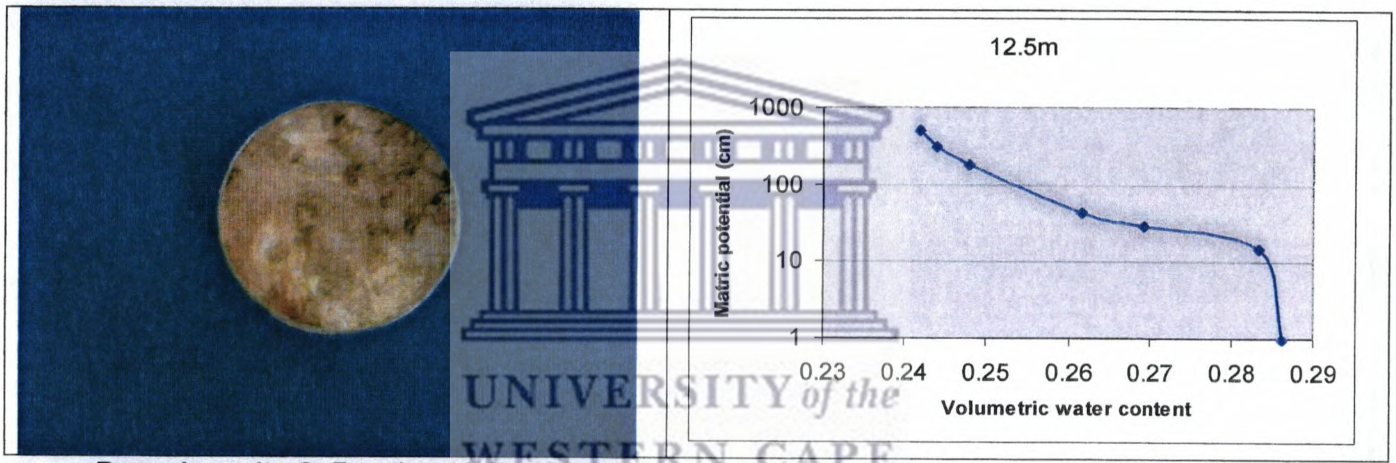
Berg river site 2: Depth= 10m: Malmesbury shales



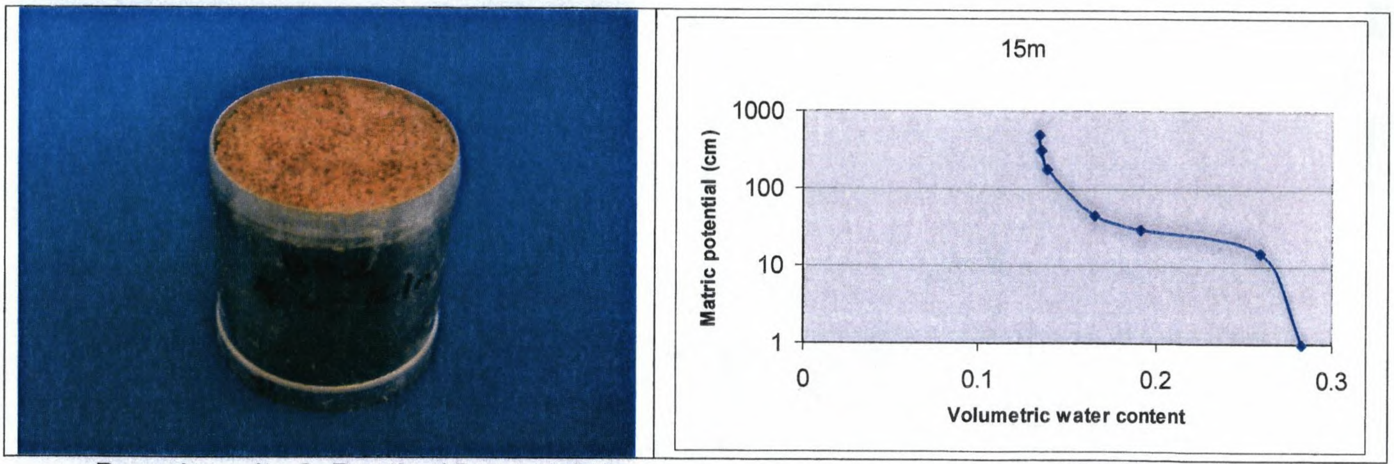
Berg river site 2: Depth= 10.8m: Malmesbury shales



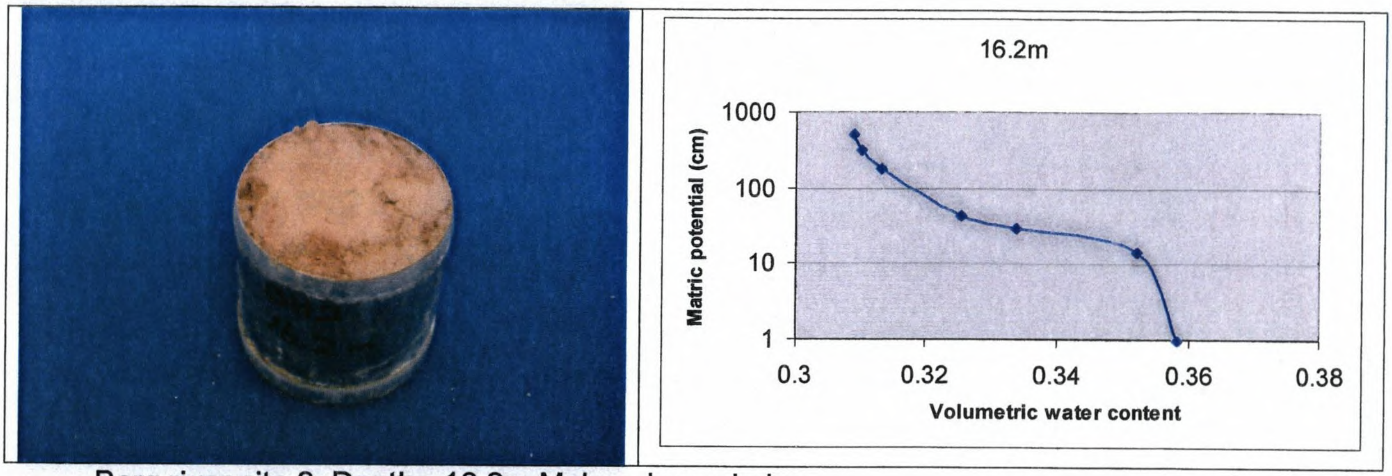
Berg river site 2: Depth= 11.5m: Malmesbury shales



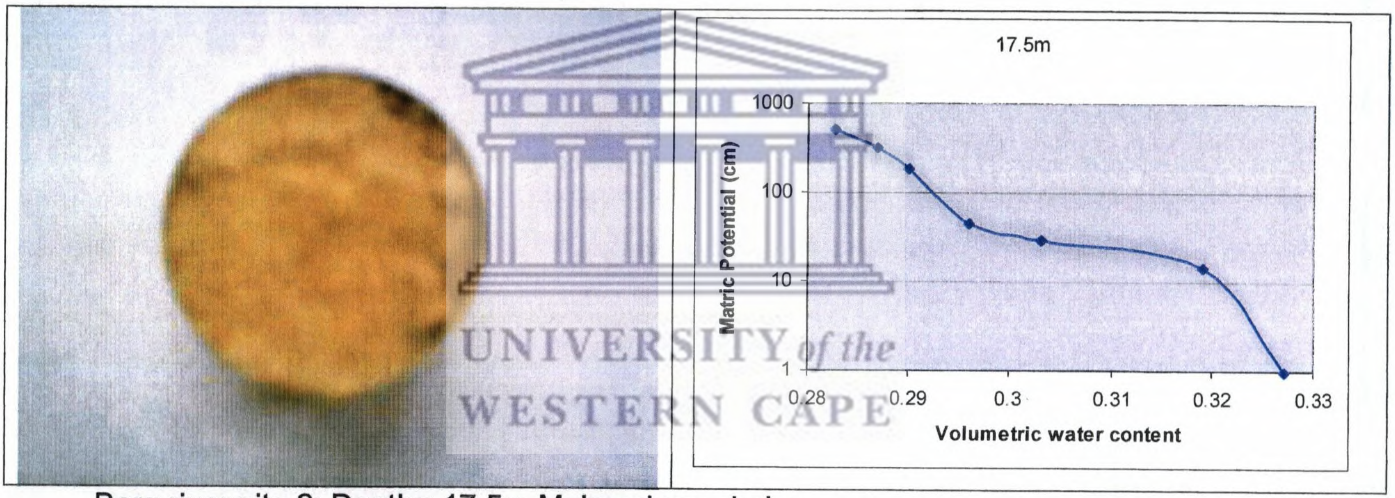
Berg river site 2: Depth= 12.5m: Malmesbury shales



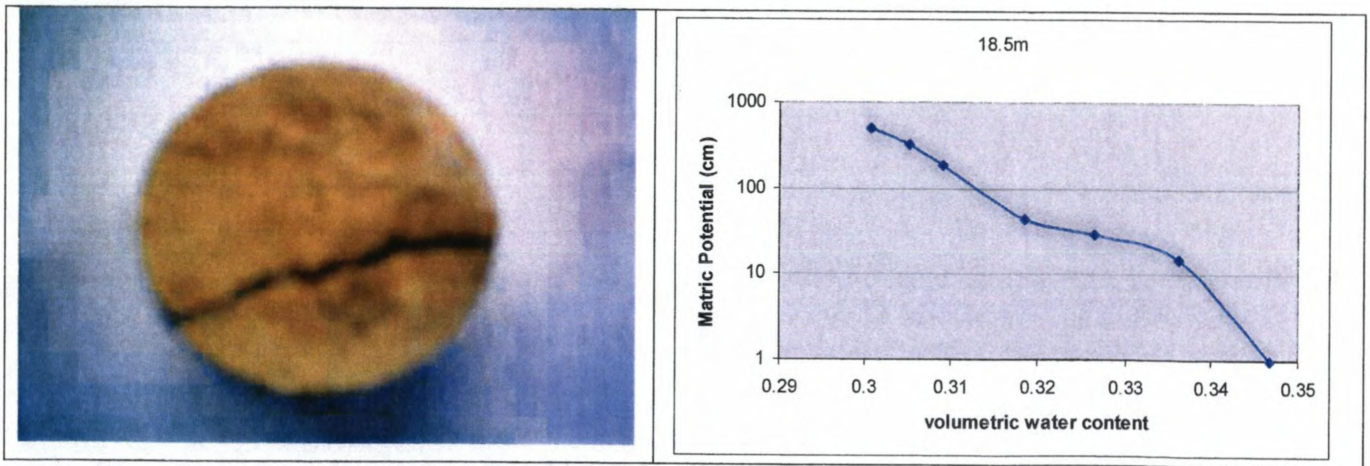
Berg river site 2: Depth=15m: sandy loam



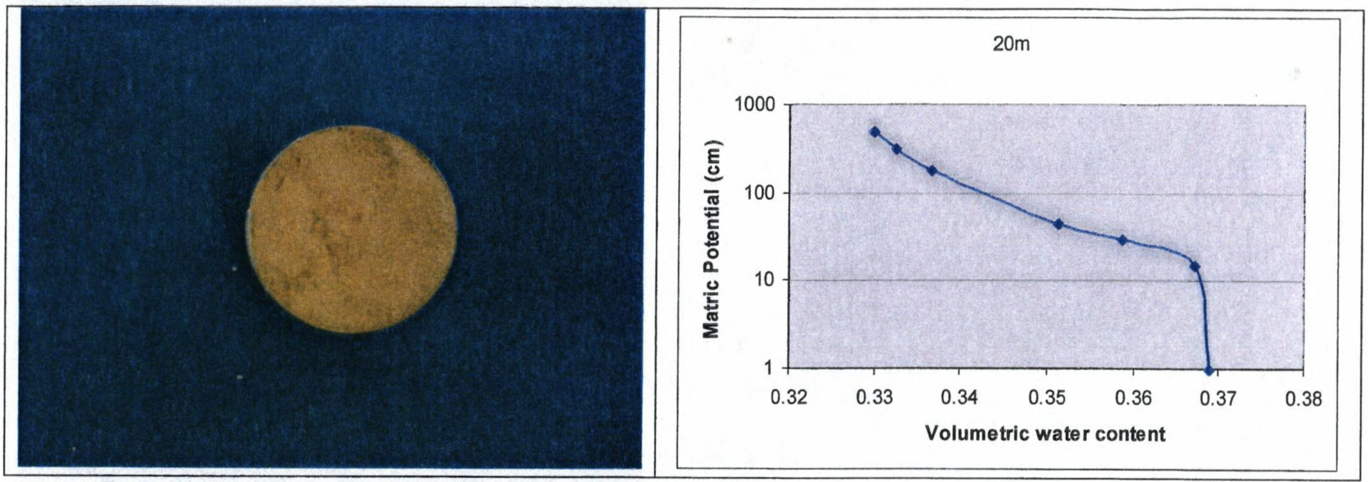
Berg river site 2: Depth= 16.2m Malmesbury shales



Berg river site 2: Depth= 17.5m Malmesbury shales

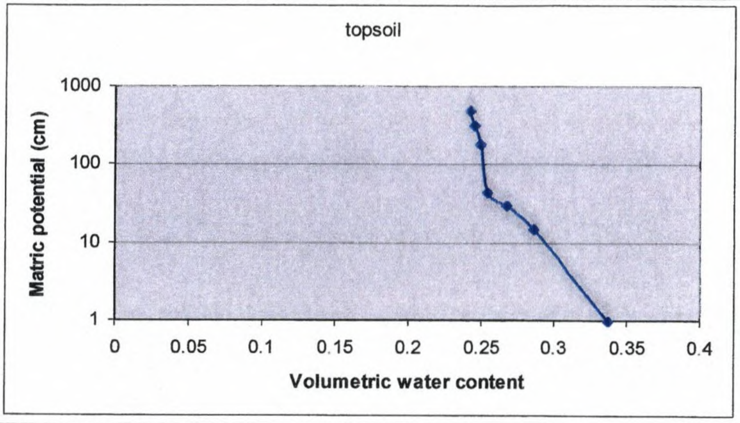


Berg river site 2: Depth= 18.5m: Malmesbury shales

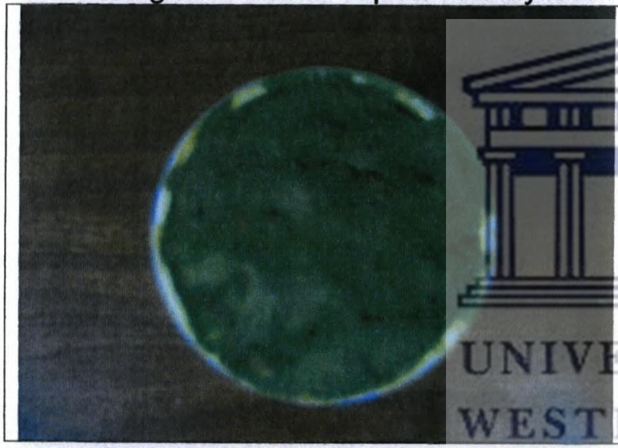


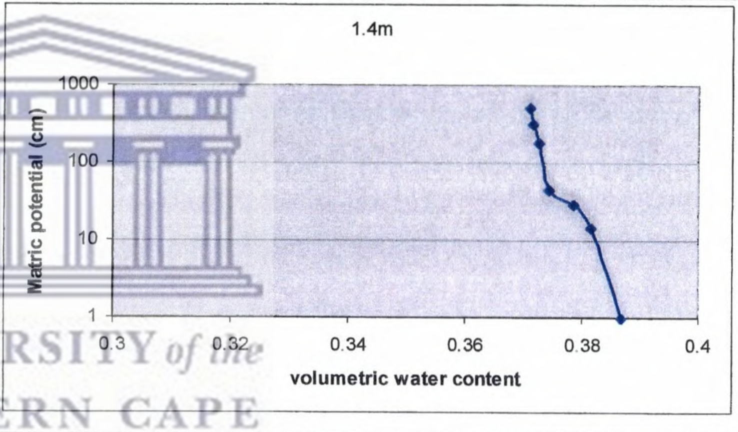
Berg river site 2: Depth= 20m: Malmesbury shales

Berg river site 3

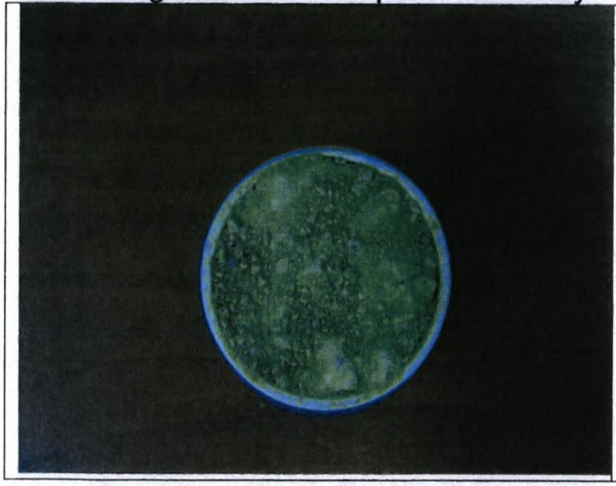


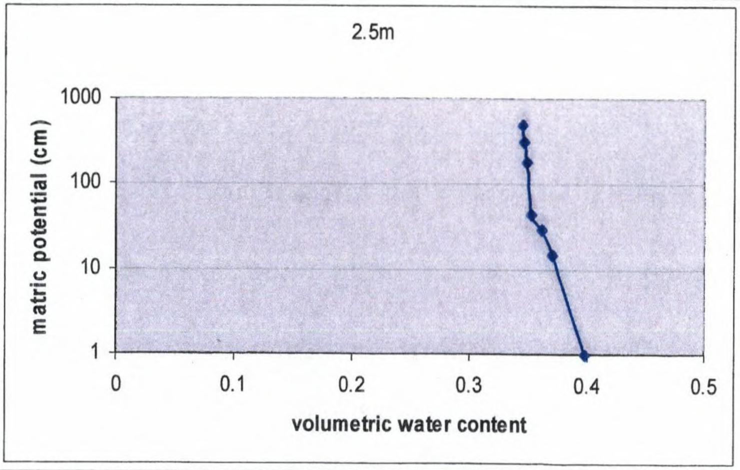
Berg river site 3: Topsoil: sandy loam



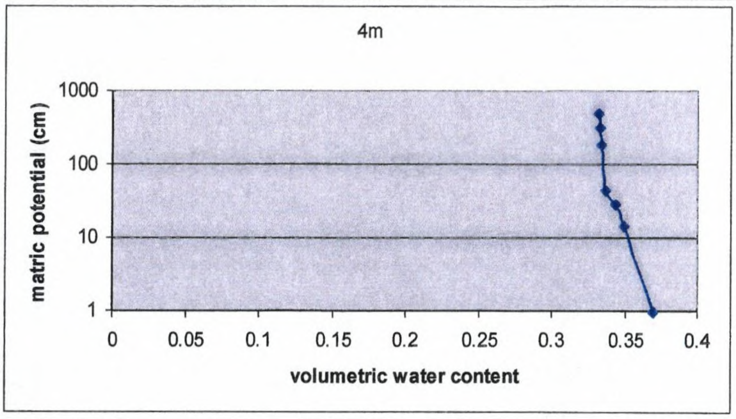


Berg river site 3: Depth= 1.4m: clay

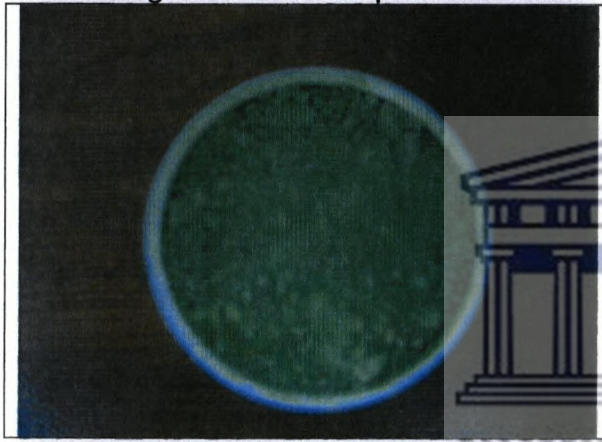


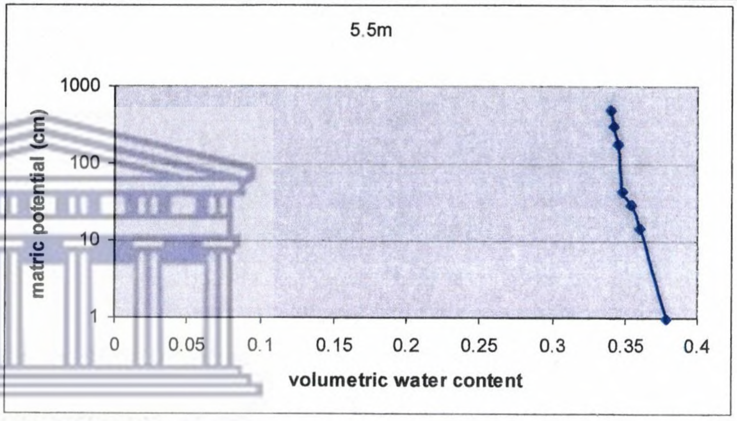


Berg river site 3: Depth= 2.5m : clay

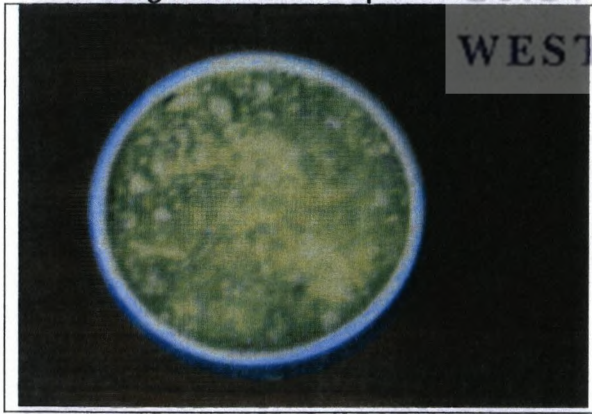


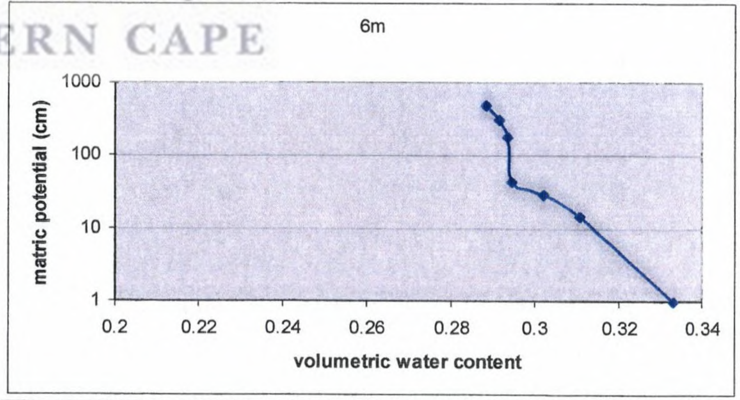
Berg river site 3: Depth= 4m: Malmesbury shale



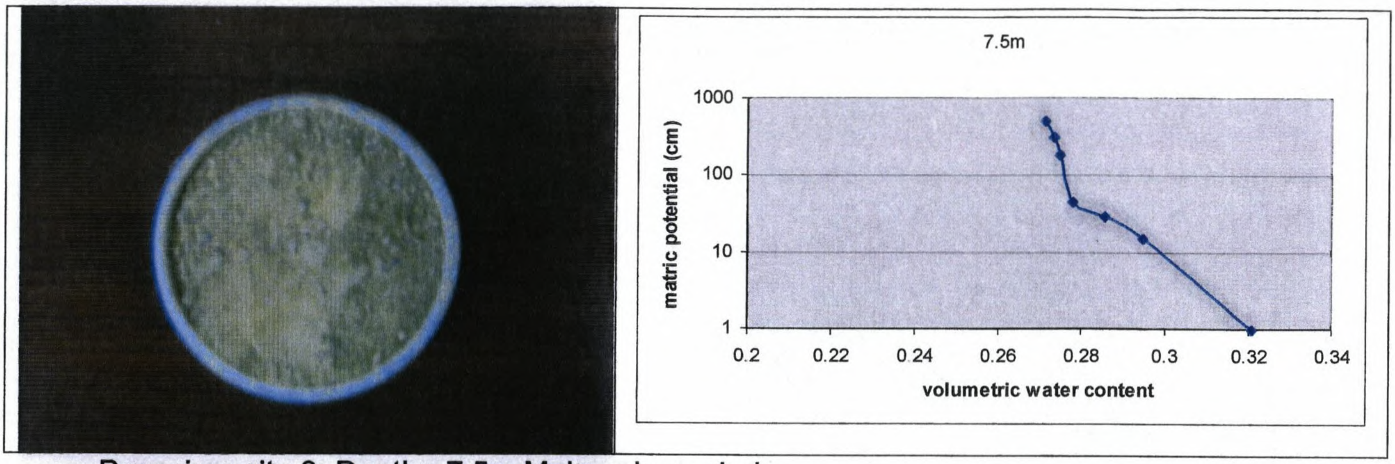


Berg river site3: Depth= 5.5m Malmesbury shale

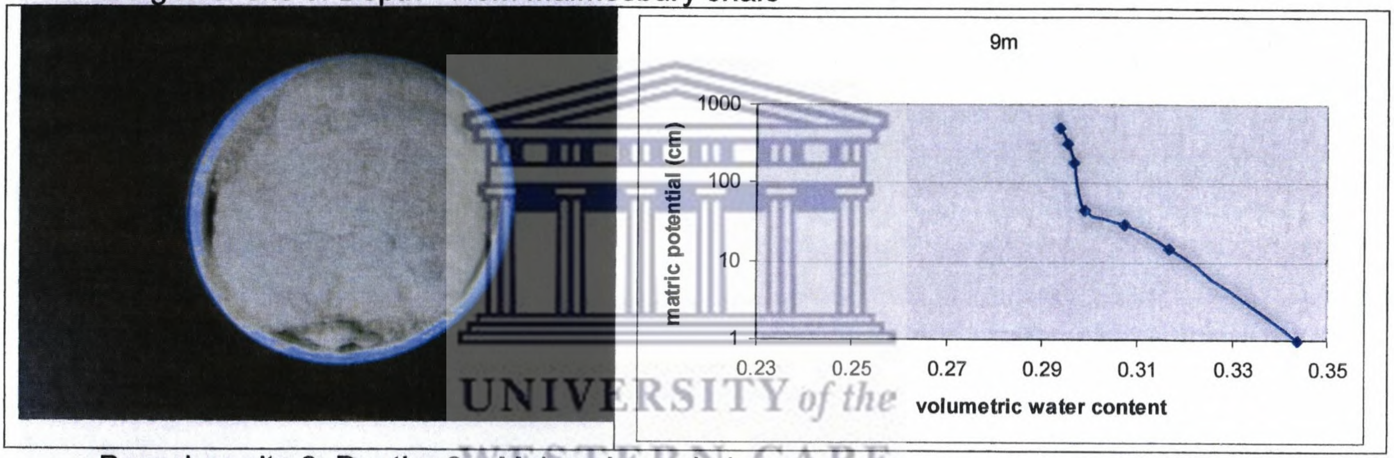




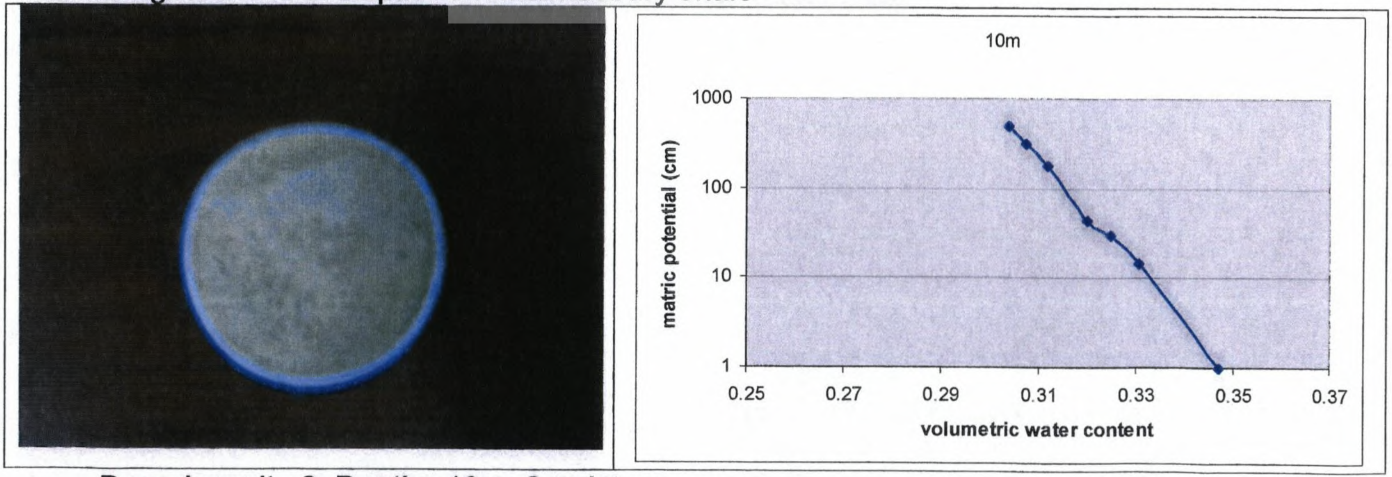
Berg river site 3: Depth= 6m Malmesbury shale



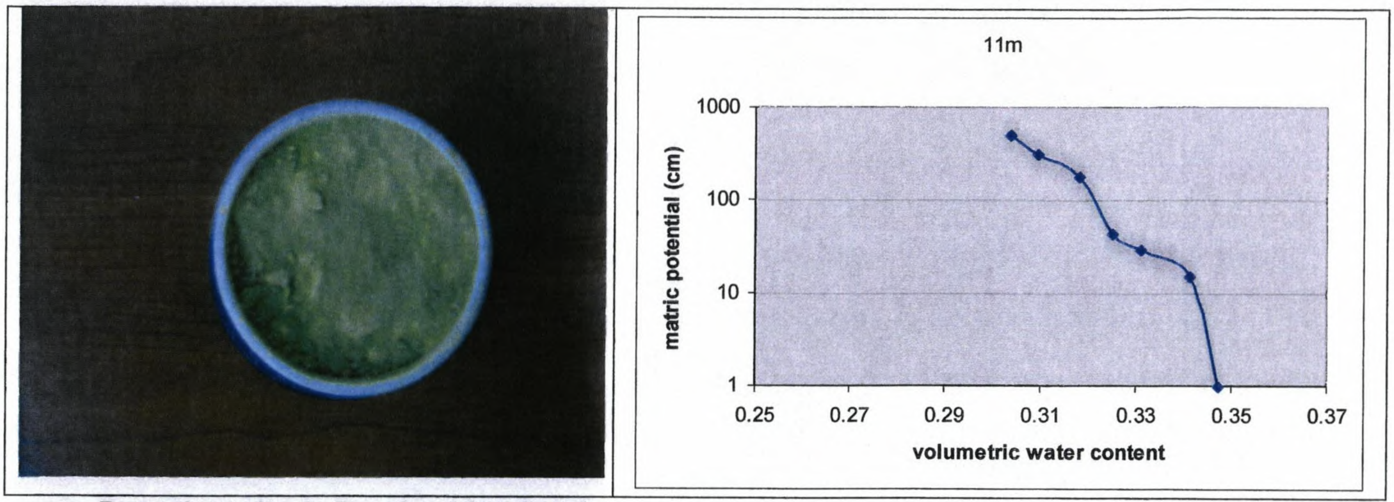
Berg river site 3: Depth= 7.5m Malmesbury shale



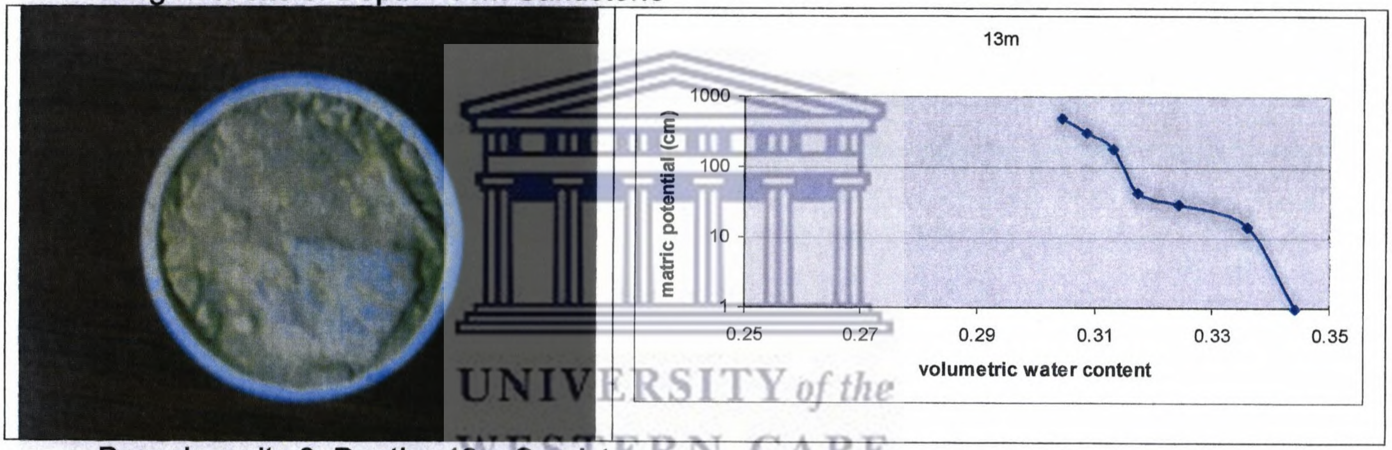
Berg river site 3: Depth= 9m Malmesbury shale



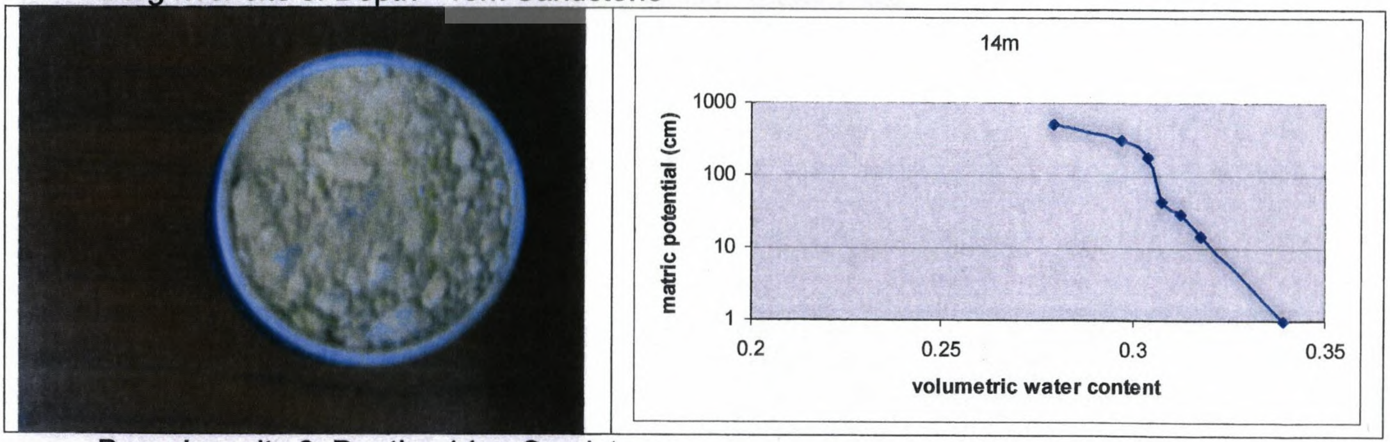
Berg river site 3: Depth= 10m: Sandstone



Berg river site 3: Depth= 11m Sandstone



Berg river site 3: Depth= 13m Sandstone



Berg river site 3: Depth= 14m: Sandstone

APPENDIX D

RETC - soil hydraulic estimates

Ithemba site 1

Ithemba Site 1

Van Genuchten variable m,n (Mualem)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d
topsoil	loamy sand	0.0485	0.38332	0.02777	2.22907	105.12
0.5	sand	0.0530	0.37977	0.01910	2.23451	642.98
1	loamy sand	0.0485	0.31075	0.05522	2.53667	105.12
1.5	silt	0.0501	0.40397	0.03221	1.39112	43.75
2.5	loamy sand	0.0485	0.30133	0.21683	5.57224	105.12
3	sand	0.0530	0.35672	0.04477	2.05499	642.98
4	sandy clay loam	0.0633	0.31442	0.44604	3.29698	13.19
6.5	sandy loam	0.0387	0.36218	0.07315	8.06679	38.25
7	silt loam	0.0645	0.30954	0.01878	1.08370	18.26
8.5	clay	0.0982	0.33502	0.01473	1.43801	14.75
10	clay	0.0982	0.36595	0.10924	6.89731	14.75
12	clay	0.0982	0.30803	0.00274	1.00500	14.75
13	clay	0.0982	0.29600	0.10087	7.42575	14.75
14	clay	0.0982	0.34344	0.12917	6.96506	14.75

Ithemba Site 1

Van Genuchten variable m,n (Burdine)

Sample Depth (m)	Texture/Lithology	ThetaR(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	loamy sand	0.0485	0.38332	0.02777	2.22907	105.12
0.5	sand	0.0530	0.37977	0.01910	2.23450	642.98
1	loamy sand	0.0485	0.31075	0.05523	2.53671	105.12
1.5	silt	0.0501	0.38779	0.00223	2.00500	43.75
2.5	loamy sand	0.0485	0.30131	0.21654	6.53241	105.12
3	sand	0.0530	0.35672	0.04477	2.05497	642.98
4	sandy clay loam	0.0633	0.31437	0.44235	3.66199	13.19
6.5	sandy loam	0.0387	0.36218	0.07317	8.20045	38.25
7	silt loam	0.0645	0.3010	0.00220	2.00500	18.26
8.5	clay	0.0982	0.33453	0.01995	2.00500	14.75
10	clay	0.0982	0.36595	0.10925	7.10761	14.75
12	clay	0.0982	0.30993	0.04715	2.00500	14.75
13	clay	0.0982	0.29599	0.10087	7.72978	14.75
14	clay	0.0982	0.34344	0.12916	7.07126	14.75

Ithemba Site 1						
Van Genuchten m=1-1/n						
Sample Depth (m)	Texture/Lithology	Theta R	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	loamy sand	0.0485	0.38788	0.01713	1.37171	105.12
0.5	sand	0.053	0.38328	0.0144	1.71399	642.98
1	loamy sand	0.0485	0.31388	0.03378	1.299	105.12
1.5	silt	0.0501	0.40473	0.02297	1.131	43.75
2.5	loamy sand	0.0485	0.31339	0.25994	1.31936	105.12
3	sand	0.053	0.35989	0.03435	1.49459	642.98
4	sandy clay loam	0.0633	0.31812	0.77422	1.02561	13.19
6.5	sandy loam	0.0387	0.36529	0.0367	1.10792	38.25
7	silt loam	0.0645	0.30949	0.01948	1.10243	18.26
8.5	clay	0.0982	0.33562	0.00875	1.09439	14.75
10	clay	0.0982	0.36753	0.06979	1.05716	14.75
12	clay	0.0982	0.30952	0.01564	1.08967	14.75
13	clay	0.0982	0.29713	0.05952	1.0627	14.75
14	clay	0.0982	0.34445	0.09717	1.02866	14.75

Ithemba Site 1						
Van Genuchten m=1- 2/n						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d
topsoil	loamy sand	0.0485	0.38312	0.02821	2.2932	105.12
0.5	sand	0.053	0.37824	0.02106	2.57581	642.98
1	loamy sand	0.0485	0.31116	0.05288	2.25102	105.12
1.5	silt	0.0501	0.40324	0.04676	2.0996	43.75
2.5	loamy sand	0.0485	0.3034	0.23049	2.32441	105.12
3	sand	0.053	0.35526	0.04829	2.4273	642.98
4	sandy clay loam	0.0633	0.31503	0.49475	2.02554	13.19
6.5	sandy loam	0.0387	0.36345	0.06246	2.08916	38.25
7	silt loam	0.0645	0.30835	0.04075	2.07612	18.26
8.5	clay	0.0982	0.33446	0.02076	2.0624	14.75
10	clay	0.0982	0.3664	0.10207	2.05034	14.75
12	clay	0.0982	0.30992	0.04917	2.05801	14.75
13	clay	0.0982	0.29634	0.09214	2.05423	14.75
14	clay	0.0982	0.34371	0.12726	2.02602	14.75

Ithemba Site 1

Brooks and Corey (Mualem)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	loamy sand	0.0485	0.3816	0.04097	0.24637	105.12
0.5	sand	0.053	0.3788	0.03623	0.43206	642.98
1	loamy sand	0.0485	0.30545	0.05754	0.23493	105.12
1.5	silt	0.0501	0.38962	0.01944	0.12561	43.75
2.5	loamy sand	0.0485	0.3013	0.21643	0.33023	105.12
3	sand	0.053	0.34484	0.05058	0.40593	642.98
4	sandy clay loam	0.0633	0.30192	0.01279	0.05108	13.19
6.5	sandy loam	0.0387	0.3621	0.07478	0.08243	38.25
7	silt loam	0.0645	0.30214	0.01945	0.09253	18.26
8.5	clay	0.0982	0.33256	0.01741	0.06439	14.75
10	clay	0.0982	0.35507	0.01923	0.07172	14.75
12	clay	0.0982	0.30443	0.01201	0.0978	14.75
13	clay	0.0982	0.29597	0.10083	0.05222	14.75
14	clay	0.0982	0.34343	0.12894	0.02564	14.75

Ithemba Site 1

Brooks and Corey (Burdine)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	loamy sand	0.0485	0.3816	0.04097	0.24637	105.12
0.5	sand	0.053	0.3788	0.03623	0.43206	642.98
1	loamy sand	0.0485	0.30545	0.05754	0.23493	105.12
1.5	silt	0.0501	0.38962	0.01944	0.12561	43.75
2.5	loamy sand	0.0485	0.3013	0.21643	0.33023	105.12
3	sand	0.053	0.34484	0.05058	0.40593	642.98
4	sandy clay loam	0.0633	0.30192	0.01279	0.05108	13.19
6.5	sandy loam	0.0387	0.3621	0.07478	0.08243	38.25
7	silt loam	0.0645	0.30214	0.01945	0.09253	18.26
8.5	clay	0.0982	0.33256	0.01741	0.06439	14.75
10	clay	0.0982	0.35507	0.01923	0.07172	14.75
12	clay	0.0982	0.30443	0.01201	0.0978	14.75
13	clay	0.0982	0.29597	0.10083	0.05222	14.75
14	clay	0.0982	0.34343	0.12894	0.02564	14.75

Ithemba site 2

Ithemba Site 2

Van Genuchten variable m,n (Mualem)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.29573	0.00938	1.005	38.25
0.5	loamy sand	0.0485	0.27524	0.02478	1.70254	105.12
1	loamy sand	0.0485	0.28661	0.03238	2.43045	105.12
2	clay loam	0.0792	0.31683	0.09098	7.64433	8.18
3	sandy loam	0.0387	0.36204	0.06238	1.95451	38.25
4	silty clay	0.1108	0.47257	0.00098	1.84761	9.61
5	silty clay	0.1108	0.49339	0.00021	1.35787	9.61
6	clay	0.0982	0.4525	0.06479	9.77575	14.75
7	clay	0.0982	0.54134	0.00309	1.005	14.75
8.5	silty clay	0.1108	0.39008	0.0019	1.005	9.61
10	Malmesbury Shale	0.0982	0.303	0.2154	5.39635	14.75
11.5	Malmesbury Shale	0.0982	0.34338	0.00259	1.005	14.75
13	Malmesbury Shale	0.0982	0.31791	0.00174	1.005	14.75
15.5	Malmesbury Shale	0.0982	0.37901	0.1458	7.25327	14.75
17	Malmesbury Shale	0.0982	0.30087	0.03668	1.005	14.75
18.5	Malmesbury Shale	0.0982	0.32218	0.00196	1.005	14.75

Ithemba Site 2

Van Genuchten variable m,n (Burdine)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.29519	0.03439	2.005	38.25
0.5	loamy sand	0.0485	0.27451	0.02793	2.005	105.12
1	loamy sand	0.0485	0.28661	0.03238	2.43045	105.12
2	clay loam	0.0792	0.31683	0.09102	8.22052	8.18
3	sandy loam	0.0387	0.36205	0.06243	2.005	38.25
4	silty clay	0.1108	0.47254	0.00148	2.005	9.61
5	silty clay	0.1108	0.49308	0.00182	2.005	9.61
6	clay	0.0982	0.45255	0.06487	8.66673	14.75
7	clay	0.0982	0.54064	0.08507	13.92823	14.75
8.5	silty clay	0.1108	0.39184	0.11481	2.005	9.61
10	Malmesbury Shale	0.0982	0.303	0.21543	5.32054	14.75
11.5	Malmesbury Shale	0.0982	0.34631	0.15781	6.18748	14.75
13	Malmesbury Shale	0.0982	0.3324	8.0379	2.7783	14.75
15.5	Malmesbury Shale	0.0982	0.37901	0.14579	7.31976	14.75
17	Malmesbury Shale	0.0982	0.30161	0.13358	7.91435	14.75
18.5	Malmesbury Shale	0.0982	0.32056	0.00127	2.005	14.75

Ithemba Site 2

Van Genuchten m=1-1/n

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.2941	0.01218	1.17562	38.25
0.5	loamy sand	0.0485	0.2768	0.01774	1.31828	105.12
1	loamy sand	0.0485	0.29031	0.0225	1.57265	105.12
2	clay loam	0.0792	0.31797	0.04938	1.05224	8.18
3	sandy loam	0.0387	0.36406	0.03903	1.11693	38.25
4	silty clay	0.1108	0.47259	0.00045	1.74493	9.61
5	silty clay	0.1108	0.49337	0.00044	1.39959	9.61
6	clay	0.0982	0.45499	0.03678	1.04371	14.75
7	clay	0.0982	0.54193	0.05062	1.02045	14.75
8.5	silty clay	0.1108	0.39194	0.06515	1.01202	9.61
10	Malmesbury Shale	0.0982	0.3041	0.25059	1.01845	14.75
11.5	Malmesbury Shale	0.0982	0.34711	0.13304	1.01917	14.75
13	Malmesbury Shale	0.0982	0.3253	0.5471	1.0175	14.75
15.5	Malmesbury Shale	0.0982	0.38068	0.12784	1.0326	14.75
17	Malmesbury Shale	0.0982	0.30245	0.10681	1.02557	14.75
18.5	Malmesbury Shale	0.0982	0.32491	0.12265	1.01424	14.75

Ithemba Site 2

Van Genuchten m=1- 2/n

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.29556	0.04203	2.10491	38.25
0.5	loamy sand	0.0485	0.27399	0.03051	2.24811	105.12
1	loamy sand	0.0485	0.28646	0.03268	2.47891	105.12
2	clay loam	0.0792	0.31719	0.08085	2.04422	8.18
3	sandy loam	0.0387	0.3619	0.06421	2.09763	38.25
4	silty clay	0.1108	0.4725	0.00173	2.11802	9.61
5	silty clay	0.1108	0.49314	0.00284	2.0599	9.61
6	clay	0.0982	0.45378	0.06143	2.03632	14.75
7	clay	0.0982	0.54124	0.08158	2.01739	14.75
8.5	silty clay	0.1108	0.39183	0.11509	2.01014	9.61
10	Malmesbury Shale	0.0982	0.30322	0.23126	2.01791	14.75
11.5	Malmesbury Shale	0.0982	0.3465	0.15984	2.01777	14.75
13	Malmesbury Shale	0.0982	0.3262	1.1746	2.0155	14.75
15.5	Malmesbury Shale	0.0982	0.37947	0.15049	2.03037	14.75
17	Malmesbury Shale	0.0982	0.30187	0.13611	2.02338	14.75
18.5	Malmesbury Shale	0.0982	0.32456	0.15825	2.01302	14.75

Ithemba Site 2						
Brooks and Corey (Mualem)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.2891	0.03275	0.10516	38.25
0.5	loamy sand	0.0485	0.27265	0.04233	0.2131	105.12
1	loamy sand	0.0485	0.28315	0.04207	0.41992	105.12
2	clay loam	0.0792	0.3168	0.09112	0.0421	8.18
3	sandy loam	0.0387	0.3574	0.06371	0.09308	38.25
4	silty clay	0.1108	0.47253	0.00638	0.02494	9.61
5	silty clay	0.1108	0.4931	0.0069	0.02505	9.61
6	clay	0.0982	0.45215	0.06292	0.03456	14.75
7	clay	0.0982	0.5406	0.08454	0.01679	14.75
8.5	silty clay	0.1108	0.3891	0.01223	0.01926	9.61
10	Malmesbury Shale	0.0982	0.29785	0.01894	0.02696	14.75
11.5	Malmesbury Shale	0.0982	0.34132	0.0186	0.02678	14.75
13	Malmesbury Shale	0.0982	0.32543	1.16547	0.01559	14.75
15.5	Malmesbury Shale	0.0982	0.379	0.14555	0.03026	14.75
17	Malmesbury Shale	0.0982	0.29687	0.02175	0.03207	14.75
18.5	Malmesbury Shale	0.0982	0.32095	0.00965	0.02973	14.75

Ithemba Site 2						
Brooks and Corey (Burdine)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.2891	0.03275	0.10516	38.25
0.5	loamy sand	0.0485	0.27265	0.04233	0.2131	105.12
1	loamy sand	0.0485	0.28315	0.04207	0.41992	105.12
2	clay loam	0.0792	0.3168	0.09112	0.0421	8.18
3	sandy loam	0.0387	0.3574	0.06371	0.09308	38.25
4	silty clay	0.1108	0.47253	0.00638	0.02494	9.61
5	silty clay	0.1108	0.4931	0.0069	0.02505	9.61
6	clay	0.0982	0.45215	0.06292	0.03456	14.75
7	clay	0.0982	0.5406	0.08454	0.01679	14.75
8.5	silty clay	0.1108	0.3891	0.01223	0.01926	9.61
10	Malmesbury Shale	0.0982	0.29785	0.01894	0.02696	14.75
11.5	Malmesbury Shale	0.0982	0.34132	0.0186	0.02678	14.75
13	Malmesbury Shale	0.0982	0.32543	1.16547	0.01559	14.75
15.5	Malmesbury Shale	0.0982	0.379	0.14555	0.03026	14.75
17	Malmesbury Shale	0.0982	0.29687	0.02175	0.03207	14.75
18.5	Malmesbury Shale	0.0982	0.32095	0.00965	0.02973	14.75

Bergriver site 1

Bergriver site 1						
Van Genuchten variable m,n (Mualem)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.4781	0.03443	1.005	13.19
1	clay	0.0982	0.40674	0.09187	5.31199	14.75
1.8	clay	0.0982	0.36372	0.14287	4.94659	14.75
3.3	clay	0.0982	0.38787	0.08322	4.21317	14.75
4.8	clay	0.0982	0.34424	0.11742	4.90731	14.75
5.8	clay	0.0982	0.37921	0.07999	4.64339	14.75
6.3	clay	0.0982	0.39399	0.0835	5.16607	14.75
7	Malmesbury Shale	0.0982	0.39528	0.05693	4.15874	14.75
8.5	Malmesbury Shale	0.0982	0.39393	0.06965	4.89401	14.75
10.5	Malmesbury Shale	0.0982	0.30363	0.13342	4.95892	14.75
11.5	Malmesbury Shale	0.0982	0.39345	0.47157	3.19807	14.75
13.8	Malmesbury Shale	0.0982	0.36837	0.11377	1.93706	14.75
15.3	Malmesbury Shale	0.0982	0.3147	0.09951	3.53812	14.75
16.5	Malmesbury Shale	0.0982	0.35799	0.10248	5.89084	14.75
17.7	Malmesbury Shale	0.0982	0.34951	0.08448	4.98095	14.75
18.5	Malmesbury Shale	0.0982	0.33958	0.09333	4.12008	14.75

Bergriver site 1						
Van Genuchten variable m,n (Burdine)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.482	0.13769	3.31322	13.19
1	clay	0.0982	0.40671	0.09195	7.87556	14.75
1.8	clay	0.0982	0.36371	0.14243	6.22589	14.75
3.3	clay	0.0982	0.38771	0.08417	7.13223	14.75
4.8	clay	0.0982	0.34421	0.11721	6.69013	14.75
5.8	clay	0.0982	0.37912	0.07991	8.98802	14.75
6.3	clay	0.0982	0.39382	0.0839	9.83194	14.75
7	Malmesbury Shale	0.0982	0.39504	0.05591	9.92299	14.75
8.5	Malmesbury Shale	0.0982	0.39382	0.06965	5.75221	14.75
10.5	Malmesbury Shale	0.0982	0.30361	0.13269	6.74019	14.75
11.5	Malmesbury Shale	0.0982	0.39343	0.46538	3.64393	14.75
13.8	Malmesbury Shale	0.0982	0.36752	0.11135	8.63962	14.75
15.3	Malmesbury Shale	0.0982	0.31469	0.09986	3.75574	14.75
16.5	Malmesbury Shale	0.0982	0.35791	0.10133	10.70413	14.75
17.7	Malmesbury Shale	0.0982	0.3492	0.08419	9.47957	14.75
18.5	Malmesbury Shale	0.0982	0.33925	0.09176	10.21136	14.75

Bergriver site 1 Van Genuchten m=1-1/n						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.48485	0.10354	1.05809	13.19
1	clay	0.0982	0.4076	0.06931	1.01432	14.75
1.8	clay	0.0982	0.36474	0.12859	1.01909	14.75
3.3	clay	0.0982	0.3901	0.05566	1.053	14.75
4.8	clay	0.0982	0.34538	0.09358	1.02688	14.75
5.8	clay	0.0982	0.3801	0.05625	1.01741	14.75
6.3	clay	0.0982	0.39658	0.05914	1.0525	14.75
7	Malmesbury Shale	0.0982	0.39641	0.03346	1.02392	14.75
8.5	Malmesbury Shale	0.0982	0.39647	0.04335	1.05648	14.75
10.5	Malmesbury Shale	0.0982	0.30453	0.11673	1.02258	14.75
11.5	Malmesbury Shale	0.0982	0.39475	1.17173	1.00534	14.75
13.8	Malmesbury Shale	0.0982	0.36981	0.0983	1.04065	14.75
15.3	Malmesbury Shale	0.0982	0.31503	0.07734	1.00831	14.75
16.5	Malmesbury Shale	0.0982	0.35955	0.08325	1.03089	14.75
17.7	Malmesbury Shale	0.0982	0.35268	0.06074	1.08183	14.75
18.5	Malmesbury Shale	0.0982	0.34175	0.07067	1.05566	14.75

Bergriver site 1 Van Genuchten m=1- 2/n						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.48233	0.13151	2.05319	13.19
1	clay	0.0982	0.407	0.08955	2.01292	14.75
1.8	clay	0.0982	0.36394	0.14454	2.01791	14.75
3.3	clay	0.0982	0.38855	0.0786	2.04667	14.75
4.8	clay	0.0982	0.34451	0.11492	2.02469	14.75
5.8	clay	0.0982	0.3795	0.07725	2.01541	14.75
6.3	clay	0.0982	0.3949	0.08051	2.04675	14.75
7	Malmesbury Shale	0.0982	0.39568	0.05344	2.02	14.75
8.5	Malmesbury Shale	0.0982	0.39491	0.0655	2.04847	14.75
10.5	Malmesbury Shale	0.0982	0.30384	0.13486	2.02106	14.75
11.5	Malmesbury Shale	0.0982	0.39363	0.53717	2.00544	14.75
13.8	Malmesbury Shale	0.0982	0.36829	0.11534	2.03782	14.75
15.3	Malmesbury Shale	0.0982	0.31476	0.09548	2.00757	14.75
16.5	Malmesbury Shale	0.0982	0.35849	0.10297	2.02831	14.75
17.7	Malmesbury Shale	0.0982	0.35064	0.08166	2.07331	14.75
18.5	Malmesbury Shale	0.0982	0.34023	0.09157	2.05042	14.75

Bergriver site 1

Brooks and Corey (Mualem)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.4443	0.0024	0.5869	13.19
1	clay	0.0982	0.4067	0.09196	0.01254	14.75
1.8	clay	0.0982	0.3637	0.14215	0.01778	14.75
3.3	clay	0.0982	0.3877	0.08529	0.04462	14.75
4.8	clay	0.0982	0.3442	0.11702	0.02424	14.75
5.8	clay	0.0982	0.3791	0.08017	0.01482	14.75
6.3	clay	0.0982	0.3938	0.08413	0.04504	14.75
7	Malmesbury Shale	0.0982	0.395	0.05551	0.019	14.75
8.5	Malmesbury Shale	0.0982	0.39275	0.06366	0.04658	14.75
10.5	Malmesbury Shale	0.0982	0.3036	0.13237	0.02089	14.75
11.5	Malmesbury Shale	0.0982	0.3934	0.45696	0.00547	14.75
13.8	Malmesbury Shale	0.0982	0.3675	0.11098	0.03751	14.75
15.3	Malmesbury Shale	0.0982	0.3147	0.10382	0.00731	14.75
16.5	Malmesbury Shale	0.0982	0.3579	0.10113	0.02786	14.75
17.7	Malmesbury Shale	0.0982	0.3491	0.08393	0.07094	14.75
18.5	Malmesbury Shale	0.0982	0.3392	0.09135	0.0493	14.75

Bergriver site 1

Brooks and Corey (Burdine)

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy clay loam	0.0633	0.4443	0.00242	0.5869	13.19
1	clay	0.0982	0.4067	0.09196	0.01254	14.75
1.8	clay	0.0982	0.3637	0.14215	0.01778	14.75
3.3	clay	0.0982	0.3877	0.08529	0.04462	14.75
4.8	clay	0.0982	0.3442	0.11702	0.02424	14.75
5.8	clay	0.0982	0.3791	0.08017	0.01482	14.75
6.3	clay	0.0982	0.3938	0.08413	0.04504	14.75
7	Malmesbury Shale	0.0982	0.395	0.05551	0.019	14.75
8.5	Malmesbury Shale	0.0982	0.39275	0.06366	0.04658	14.75
10.5	Malmesbury Shale	0.0982	0.3036	0.13237	0.02089	14.75
11.5	Malmesbury Shale	0.0982	0.3934	0.45696	0.00547	14.75
13.8	Malmesbury Shale	0.0982	0.3675	0.11098	0.03751	14.75
15.3	Malmesbury Shale	0.0982	0.3147	0.10382	0.00731	14.75
16.5	Malmesbury Shale	0.0982	0.3579	0.10113	0.02786	14.75
17.7	Malmesbury Shale	0.0982	0.3491	0.08393	0.07094	14.75
18.5	Malmesbury Shale	0.0982	0.3392	0.09135	0.0493	14.75

Bergriver site 2
Van Genuchten variable m,n (Mualem)

Sample Depth (m)	Texture/Lithology	ThetaR(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.35748	0.08278	10.27992	8.18
0.9	sandy clay	0.1169	0.38012	0.16578	5.73867	11.35
2.2	silt loam	0.0645	0.22958	0.00873	1.005	18.26
3	silt	0.0501	0.36023	0.11632	1.81119	43.75
4	silt	0.0501	0.31592	0.13023	3.62812	43.75
5	silt loam	0.0645	0.39765	0.07607	2.81202	18.26
6.5	clay	0.0982	0.32529	0.13404	1.66021	14.75
7.5	silty clay	0.1108	0.39569	0.08898	3.67813	9.61
8.2	clay	0.0982	0.35131	0.16398	2.27543	14.75
10	Malmesbury Shale	0.0982	0.35616	0.14108	4.62669	14.75
10.8	Malmesbury Shale	0.0982	0.36181	0.17396	1.98005	14.75
11.5	Malmesbury Shale	0.0982	0.33228	0.13064	2.01293	14.75
12.5	Malmesbury Shale	0.0982	0.2873	0.11863	2.08856	14.75
15	sandy loam	0.0387	0.28242	0.14507	8.92786	38.25
16.2	Malmesbury Shale	0.0982	0.35858	0.19308	2.92767	14.75
17.5	Malmesbury Shale	0.0982	0.32724	0.28688	3.96301	14.75
18.5	Malmesbury Shale	0.0982	0.34686	0.28884	2.70614	14.75
20	Malmesbury Shale	0.0982	0.3701	0.08168	1.78061	14.75

Bergriver site 2
Van Genuchten variable m,n (Burdine)

Sample Depth (m)	Texture/Lithology	ThetaR(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.35736	0.08262	12.83856	8.18
0.9	sandy clay	0.1169	0.38011	0.16488	6.9833	11.35
2.2	silt loam	0.0645	0.22211	0.01404	2.005	18.26
3	silt	0.0501	0.35799	0.11288	8.29484	43.75
4	silt	0.0501	0.31563	0.12874	7.00674	43.75
5	silt loam	0.0645	0.38932	0.00202	2.005	18.26
6.5	clay	0.0982	0.32411	0.13216	8.36354	14.75
7.5	silty clay	0.1108	0.39525	0.08765	11.10526	9.61
8.2	clay	0.0982	0.35081	0.15769	6.42287	14.75
10	Malmesbury Shale	0.0982	0.35583	0.13777	8.08665	14.75
10.8	Malmesbury Shale	0.0982	0.36082	0.15855	6.81249	14.75
11.5	Malmesbury Shale	0.0982	0.33131	0.12632	9.00531	14.75
12.5	Malmesbury Shale	0.0982	0.28624	0.11306	8.91547	14.75
15	sandy loam	0.0387	0.28242	0.14507	8.92743	38.25
16.2	Malmesbury Shale	0.0982	0.35821	0.18465	6.16435	14.75
17.5	Malmesbury Shale	0.0982	0.32721	0.2858	4.7954	14.75
18.5	Malmesbury Shale	0.0982	0.34673	0.28493	3.84251	14.75
20	Malmesbury Shale	0.0982	0.36896	0.08735	11.22718	14.75

Bergriver site2

Van Genuchten m=1-1/n

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.36388	0.05885	1.1714	8.18
0.9	sandy clay	0.1169	0.38184	0.20688	1.02058	11.35
2.2	silt loam	0.0645	0.24066	0.1624	1.10013	18.26
3	silt	0.0501	0.36292	0.10237	1.08327	43.75
4	silt	0.0501	0.31916	0.10972	1.08361	43.75
5	silt loam	0.0645	0.39912	0.04724	1.04037	18.26
6.5	clay	0.0982	0.32677	0.12026	1.06259	14.75
7.5	silty clay	0.1108	0.39756	0.06096	1.04575	9.61
8.2	clay	0.0982	0.35343	0.16061	1.04614	14.75
10	Malmesbury Shale	0.0982	0.36145	0.15364	1.09213	14.75
10.8	Malmesbury Shale	0.0982	0.36405	0.17432	1.04907	14.75
11.5	Malmesbury Shale	0.0982	0.33418	0.11251	1.06709	14.75
12.5	Malmesbury Shale	0.0982	0.28902	0.10188	1.07637	14.75
15	sandy loam	0.0387	0.29104	0.15383	1.25935	38.25
16.2	Malmesbury Shale	0.0982	0.36188	0.21798	1.05154	14.75
17.5	Malmesbury Shale	0.0982	0.3311	0.40087	1.04482	14.75
18.5	Malmesbury Shale	0.0982	0.34965	0.34487	1.03736	14.75
20	Malmesbury Shale	0.0982	0.37131	0.06184	1.05015	14.75

Bergriver site 2

Van Genuchten m=1- 2/n

Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.36046	0.07917	2.1541	8.18
0.9	sandy clay	0.1169	0.38059	0.18798	2.02011	11.35
2.2	silt loam	0.0645	0.2381	0.16668	2.09659	18.26
3	silt	0.0501	0.35981	0.11891	2.07803	43.75
4	silt	0.0501	0.31655	0.12869	2.07814	43.75
5	silt loam	0.0645	0.39794	0.07254	2.03466	18.26
6.5	clay	0.0982	0.32488	0.13643	2.05888	14.75
7.5	silty clay	0.1108	0.39619	0.08527	2.04052	9.61
8.2	clay	0.0982	0.35142	0.1649	2.04423	14.75
10	Malmesbury Shale	0.0982	0.35766	0.15325	2.0895	14.75
10.8	Malmesbury Shale	0.0982	0.36165	0.17151	2.04746	14.75
11.5	Malmesbury Shale	0.0982	0.33218	0.12999	2.06286	14.75
12.5	Malmesbury Shale	0.0982	0.28729	0.11972	2.07134	14.75
15	sandy loam	0.0387	0.28498	0.15512	2.25579	38.25
16.2	Malmesbury Shale	0.0982	0.35902	0.19965	2.05044	14.75
17.5	Malmesbury Shale	0.0982	0.32786	0.30932	2.04456	14.75
18.5	Malmesbury Shale	0.0982	0.34716	0.29667	2.03654	14.75
20	Malmesbury Shale	0.0982	0.36995	0.0858	2.04454	14.75

Bergriver site 2						
Brooks and Corey (Mualem)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.3572	0.08232	0.14884	8.18
0.9	sandy clay	0.1169	0.3801	0.16446	0.02041	11.35
2.2	silt loam	0.0645	0.2373	0.15953	0.0968	18.26
3	silt	0.0501	0.3579	0.11224	0.07792	43.75
4	silt	0.0501	0.3156	0.1285	0.07734	43.75
5	silt loam	0.0645	0.3967	0.07438	0.03327	18.26
6.5	clay	0.0982	0.3241	0.132	0.05864	14.75
7.5	silty clay	0.1108	0.3952	0.0872	0.03931	9.61
8.2	clay	0.0982	0.3508	0.1574	0.04424	14.75
10	Malmesbury shale	0.0982	0.3558	0.13742	0.09077	14.75
10.8	Malmesbury shale	0.0982	0.3608	0.1582	0.04779	14.75
11.5	Malmesbury shale	0.0982	0.3313	0.12618	0.06252	14.75
12.5	Malmesbury shale	0.0982	0.2862	0.11257	0.07127	14.75
15	sandy loam	0.0387	0.2824	0.14498	0.26023	38.25
16.2	Malmesbury shale	0.0982	0.3582	0.18434	0.05083	14.75
17.5	Malmesbury shale	0.0982	0.3272	0.28535	0.04481	14.75
18.5	Malmesbury shale	0.0982	0.3467	0.28401	0.03651	14.75
20	Malmesbury shale	0.0982	0.3689	0.0868	0.0433	14.75

Bergriver site 2						
Brooks and Corey (Burdine)						
Sample Depth (m)	Texture/Lithology	ThetaR (cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	clay loam	0.0792	0.3572	0.08232	0.14884	8.18
0.9	sandy clay	0.1169	0.3801	0.16446	0.02041	11.35
2.2	silt loam	0.0645	0.2373	0.15953	0.0968	18.26
3	silt	0.0501	0.3579	0.11224	0.07792	43.75
4	silt	0.0501	0.3156	0.1285	0.07734	43.75
5	silt loam	0.0645	0.3967	0.07438	0.03327	18.26
6.5	clay	0.0982	0.3241	0.132	0.05864	14.75
7.5	silty clay	0.1108	0.3952	0.0872	0.03931	9.61
8.2	clay	0.0982	0.3508	0.1574	0.04424	14.75
10	Malmesbury shale	0.0982	0.3558	0.13742	0.09077	14.75
10.8	Malmesbury shale	0.0982	0.3608	0.1582	0.04779	14.75
11.5	Malmesbury shale	0.0982	0.3313	0.12618	0.06252	14.75
12.5	Malmesbury Shale	0.0982	0.2862	0.11257	0.07127	14.75
15	sandy loam	0.0387	0.2824	0.14498	0.26023	38.25
16.2	Malmesbury Shale	0.0982	0.3582	0.18434	0.05083	14.75
17.5	Malmesbury Shale	0.0982	0.3272	0.28535	0.04481	14.75
18.5	Malmesbury Shale	0.0982	0.3467	0.28401	0.03651	14.75
20	Malmesbury Shale	0.0982	0.3689	0.0868	0.0433	14.75

Bergriver site 3

Bergriver site 3 Van Genuchten variable m,n (Mualem)						
Sample Depth (m)	Texture/Lithology	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.42138	6.06539	1.50311	38.25
1.4	clay	0.0982	0.3877	0.9215	1.9155	14.75
2.5	clay	0.0982	0.3974	4.36154	1.51641	14.75
4	Malmesbury shale	0.0982	0.36887	5.89484	1.4022	14.75
5.5	Malmesbury shale	0.0982	0.37901	2.51642	1.62085	14.75
6	Malmesbury shale	0.0982	0.33312	6.09563	1.38777	14.75
7.5	Malmesbury shale	0.0982	0.32074	6.17024	1.41121	14.75
9	Malmesbury shale	0.0982	0.34375	9.20578	1.318	14.75
10	sandstone	0.1169	0.35037	0.76465	1.35014	11.35
11	sandstone	0.1169	0.34739	0.13915	6.90551	11.35
13	sandstone	0.1169	0.34423	0.28514	3.7442	11.35
14	sandstone	0.1169	0.34582	0.82341	1.005	11.35

Bergriver site 3 Van Genuchten variable m,n (Burdine)						
Sample Depth (m)	Texture/Lithology	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.42138	6.05914	3.72297	38.25
1.4	clay	0.0982	0.3872	0.7780	2.5779	14.75
2.5	clay	0.0982	0.39739	4.35665	2.41994	14.75
4	Malmesbury shale	0.0982	0.36886	5.88668	2.9920	14.75
5.5	Malmesbury shale	0.0982	0.379	2.51434	2.74388	14.75
6	Malmesbury shale	0.0982	0.33312	6.08737	2.30606	14.75
7.5	Malmesbury shale	0.0982	0.32074	6.16205	2.9640	14.75
9	Malmesbury shale	0.0982	0.34374	9.19254	2.7340	14.75
10	sandstone	0.1169	0.34719	0.54294	3.80097	11.35
11	sandstone	0.1169	0.34739	0.13913	7.10956	11.35
13	sandstone	0.1169	0.3442	0.28386	4.67728	11.35
14	sandstone	0.1169	0.34123	0.62135	2.0050	11.35

Bergriver site 3

Van Genuchten m=1-1/n

Sample Depth (m)	Texture/Lithology	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.42141	6.07115	1.04821	38.25
1.4	clay	0.0982	0.3902	2.2621	1.0100	14.75
2.5	clay	0.0982	0.39742	4.35538	1.02615	14.75
4	Malmesbury shale	0.0982	0.36888	5.89781	1.01927	14.75
5.5	Malmesbury shale	0.0982	0.37903	2.48546	1.02136	14.75
6	Malmesbury shale	0.0982	0.33314	6.09817	1.02655	14.75
7.5	Malmesbury shale	0.0982	0.32076	6.17511	1.03235	14.75
9	Malmesbury shale	0.0982	0.34376	9.22098	1.02814	14.75
10	sandstone	0.1169	0.35258	0.94277	1.03736	11.35
11	sandstone	0.1169	0.34907	0.10931	1.05239	11.35
13	sandstone	0.1169	0.34734	0.37198	1.03957	11.35
14	sandstone	0.1169	0.34539	0.80911	1.04787	11.35

Bergriver site 3

Van Genuchten m=1- 2/n

Sample Depth (m)	Texture/Lithology	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.42138	6.03819	2.04825	38.25
1.4	clay	0.0982	0.3876	0.8863	2.0101	14.75
2.5	clay	0.0982	0.39739	4.3442	2.02616	14.75
4	Malmesbury shale	0.0982	0.36886	5.86651	2.01928	14.75
5.5	Malmesbury shale	0.0982	0.3790	2.51101	2.02133	14.75
6	Malmesbury shale	0.0982	0.33312	6.06852	2.02657	14.75
7.5	Malmesbury shale	0.0982	0.32074	6.14076	2.03238	14.75
9	Malmesbury shale	0.0982	0.34374	9.1533	2.02817	14.75
10	sandstone	0.1169	0.34832	0.61711	2.03692	11.35
11	sandstone	0.1169	0.34783	0.13837	2.04808	11.35
13	sandstone	0.1169	0.34472	0.30314	2.03903	11.35
14	sandstone	0.1169	0.34108	0.61377	2.0467	11.35

Bergriver site 3

Brooks and Corey (Mualem)

Sample Depth (m)	Texture	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d
topsoil	Texture/Lithology	0.0387	0.42137	6.05914	0.04822	38.25
1.4	clay	0.0982	0.3867	0.6588	0.0101	14.75
2.5	clay	0.0982	0.39739	4.35639	0.02615	14.75
4	Malmesbury shale	0.0982	0.36886	5.88666	0.01927	14.75
5.5	Malmesbury shale	0.0982	0.379	2.51422	0.02132	14.75
6	Malmesbury shale	0.0982	0.33312	6.08703	0.02656	14.75
7.5	Malmesbury shale	0.0982	0.32074	6.16203	0.03236	14.75
9	Malmesbury shale	0.0982	0.34374	9.19251	0.02815	14.75
10	sandstone	0.1169	0.34698	0.52975	0.0369	11.35
11	sandstone	0.1169	0.34737	0.13894	0.04757	11.35
13	sandstone	0.1169	0.34419	0.28342	0.03915	11.35
14	sandstone	0.1169	0.3395	0.53188	0.04662	11.35

Bergriver site 3

Brooks and Corey (Burdine)

Sample Depth (m)	Texture/Lithology	Theta R(cm3/cm3)	ThetaS (cm3/cm3)	Alpha (1/cm)	n	Ksat (cm/d)
topsoil	sandy loam	0.0387	0.42137	6.05914	0.04822	38.25
1.4	clay	0.0982	0.3867	0.6588	0.0101	14.75
2.5	clay	0.0982	0.39739	4.35639	0.02615	14.75
4	Malmesbury shale	0.0982	0.36886	5.88666	0.01927	14.75
5.5	Malmesbury shale	0.0982	0.379	2.51422	0.02132	14.75
6	Malmesbury shale	0.0982	0.33312	6.08703	0.02656	14.75
7.5	Malmesbury shale	0.0982	0.32074	6.16203	0.03236	14.75
9	Malmesbury shale	0.0982	0.34374	9.19251	0.02815	14.75
10	sandstone	0.1169	0.34698	0.52975	0.0369	11.35
11	sandstone	0.1169	0.34737	0.13894	0.04757	11.35
13	sandstone	0.1169	0.34419	0.28342	0.03915	11.35
14	sandstone	0.1169	0.3395	0.53188	0.04662	11.35

APPENDIX E

RETC graphs:
log(h) vs K

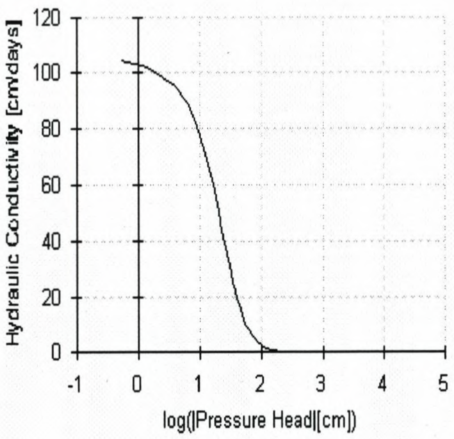
Models used in RETC:

1 – Van Genuchten variable m,n (Mualem)
2 - Van Genuchten variable m,n (Burdine)
3 – Van Genuchten m=1-1/n (Mualem)
4 – Van genuchten m=1-2/n (Burdine)
5 – Brooks and Corey (Mualem)
6 – Brooks and Corey (Burdine)

Note that for some depths at both iThemba and Berg river sites, RETC model 2 (Van Genuchten variable m,n (Burdine) gives an error in the construction of graphs due to not enough data available. For this reason some graphs of RETC model 2 were not constructed and thus not included in this Appendix.

iThemba site 1

Topsoil: Loamy sand



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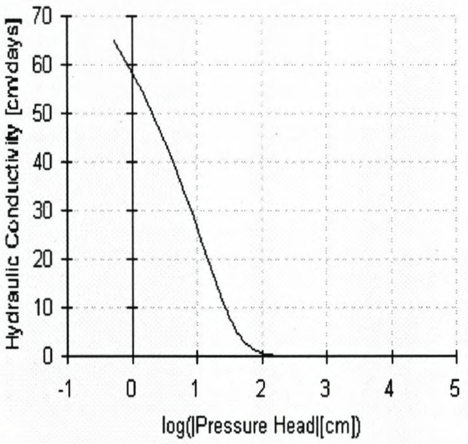

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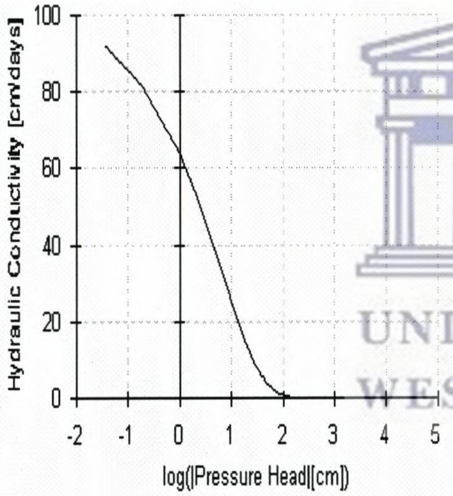

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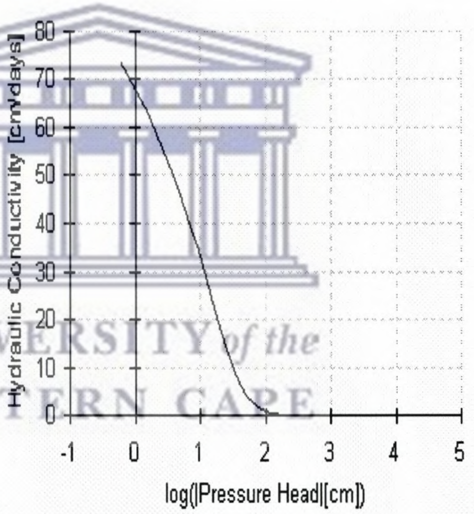

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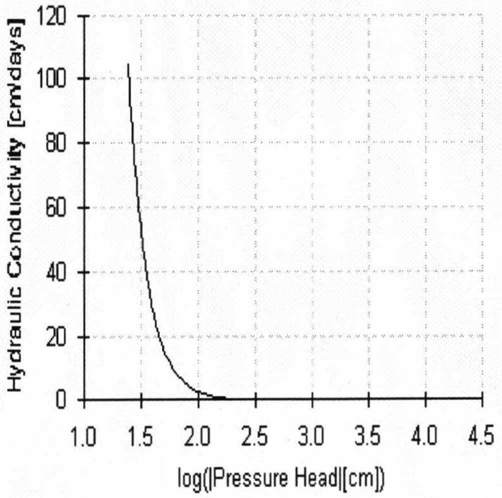

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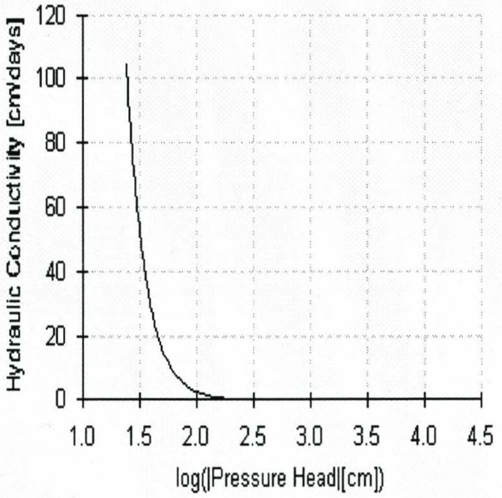
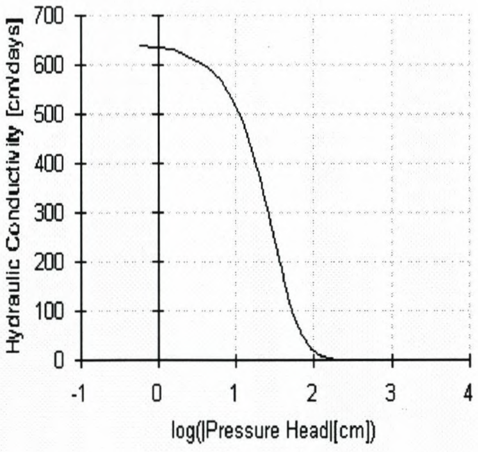


6

0.5m: Sand



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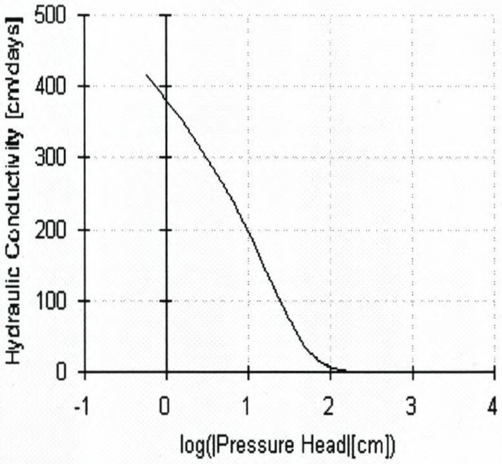

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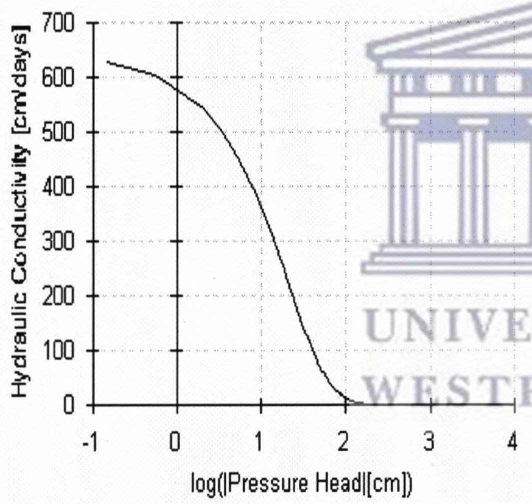

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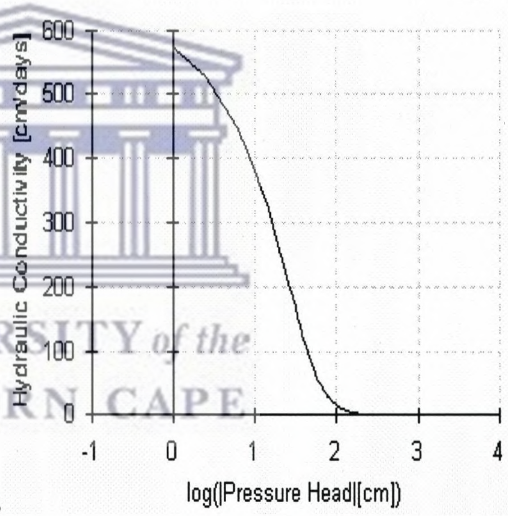

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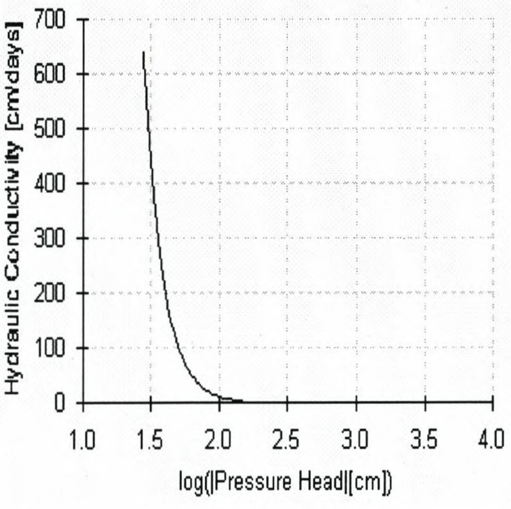

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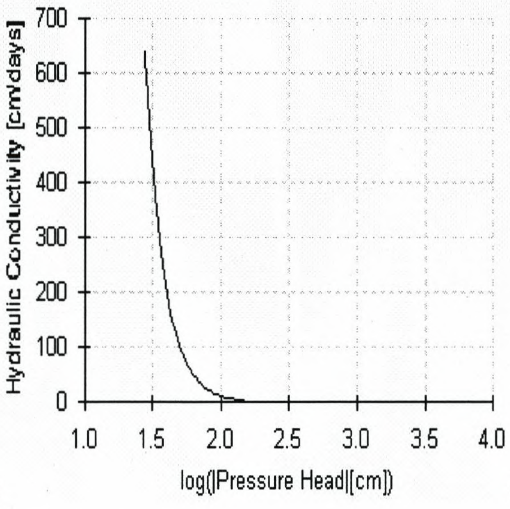

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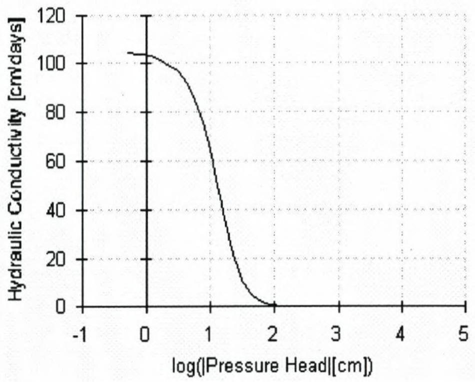
1m: Loamy sand



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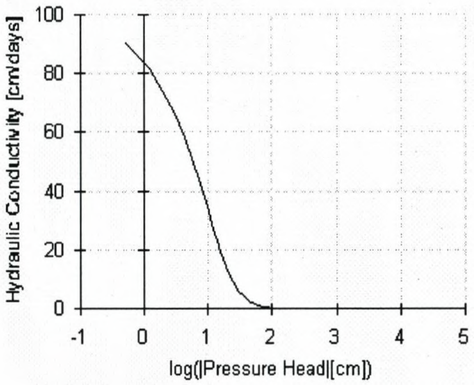

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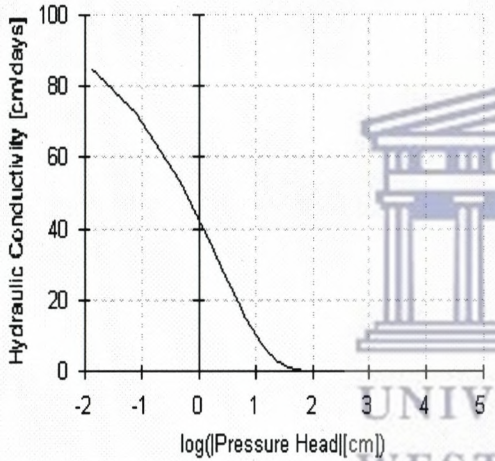

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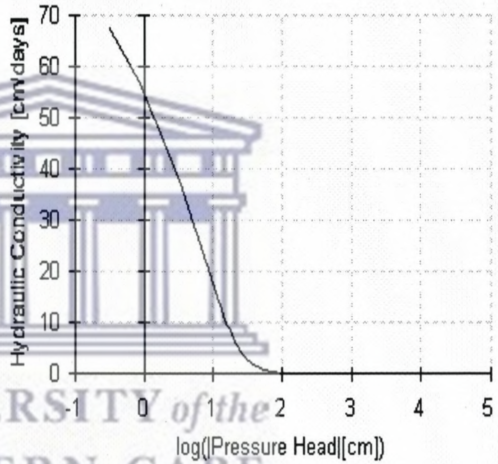

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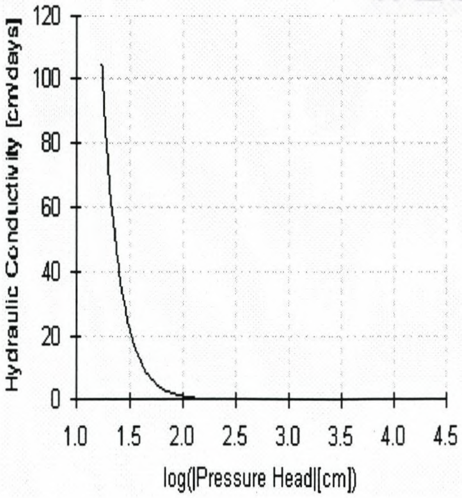

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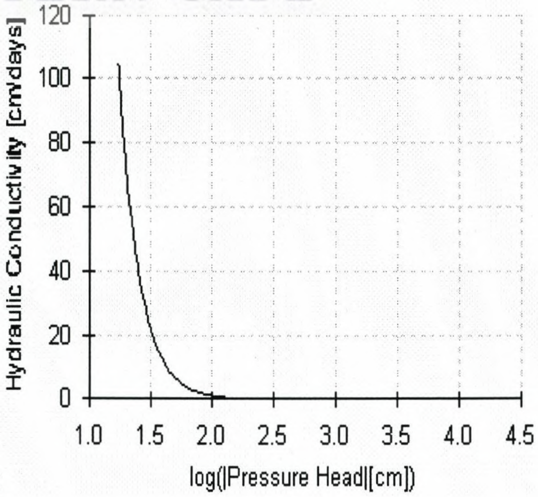

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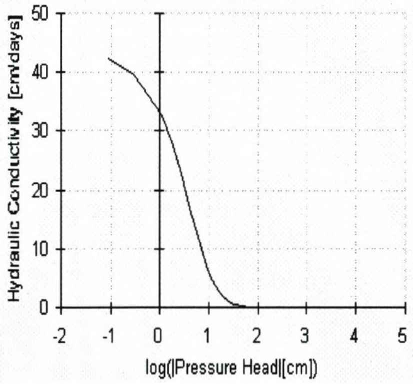
1.5m: Silt



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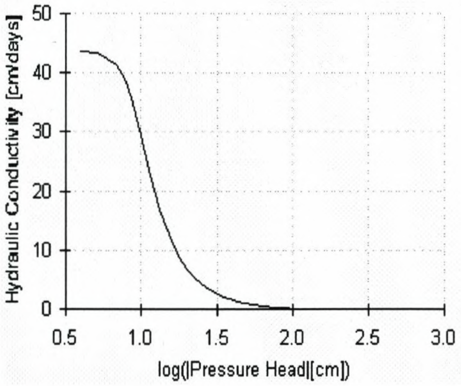

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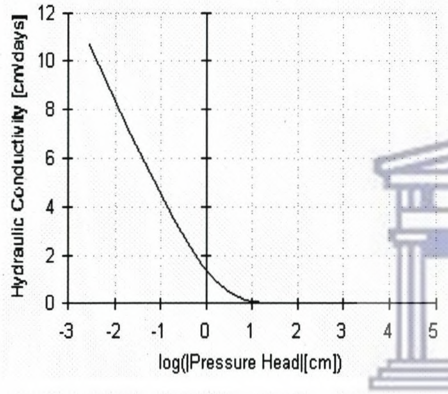

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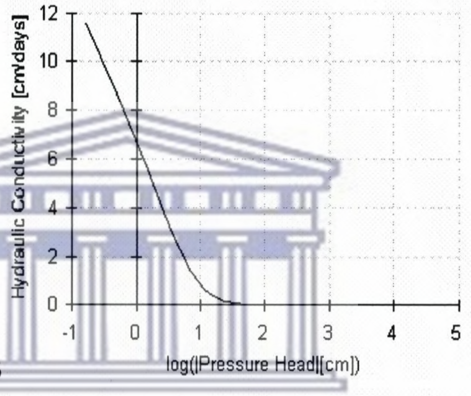

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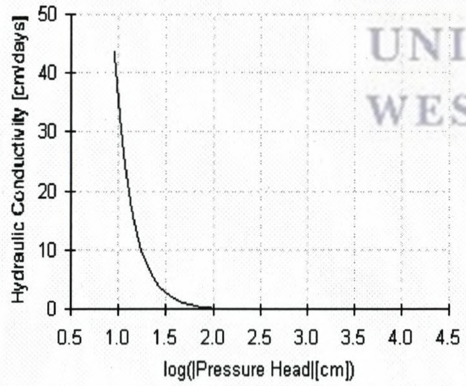

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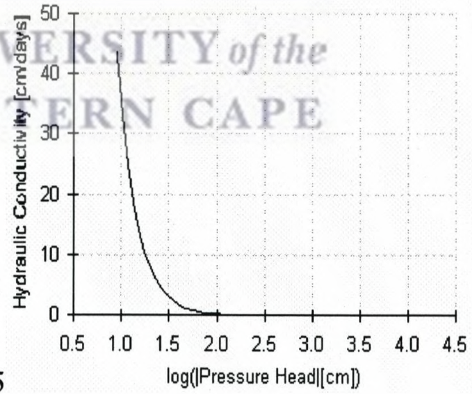
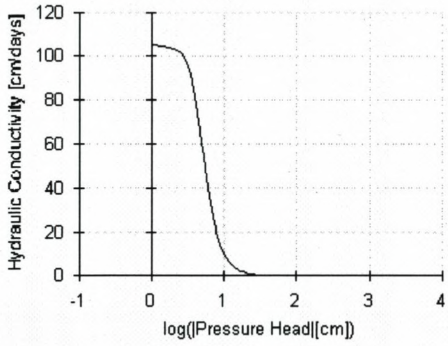


6

2.5m Loamy Sand



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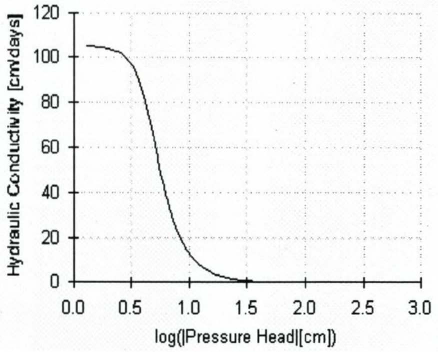

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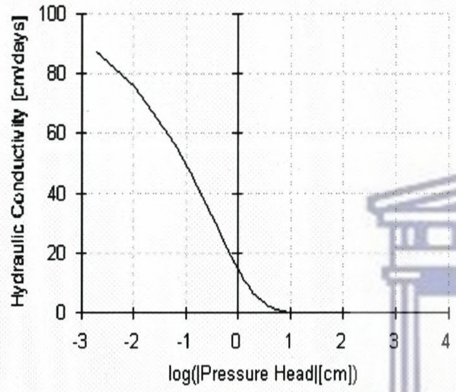

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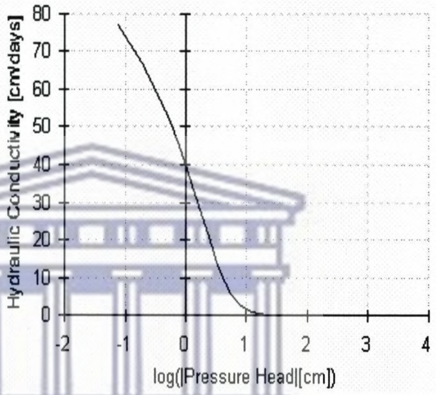

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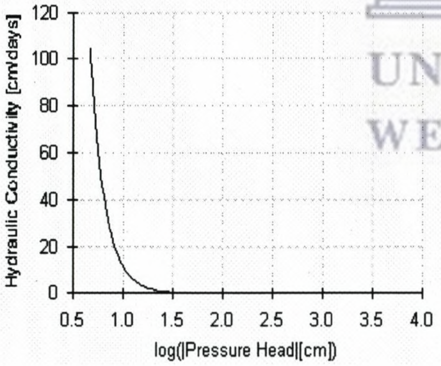

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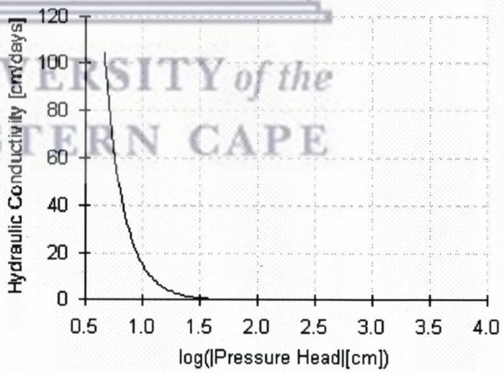

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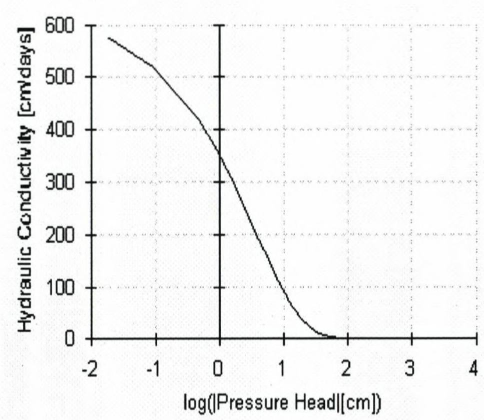
3m: Sand



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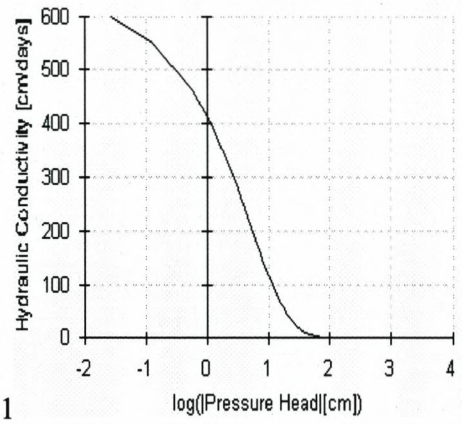

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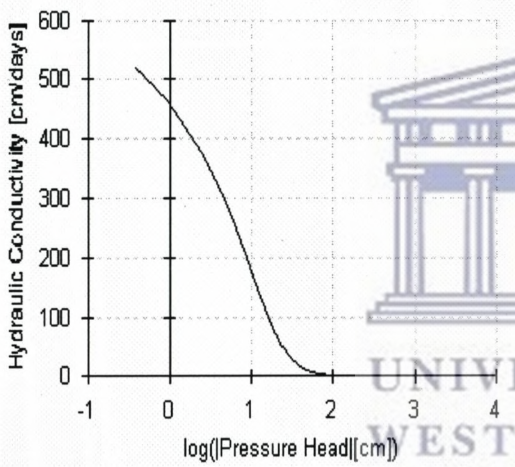

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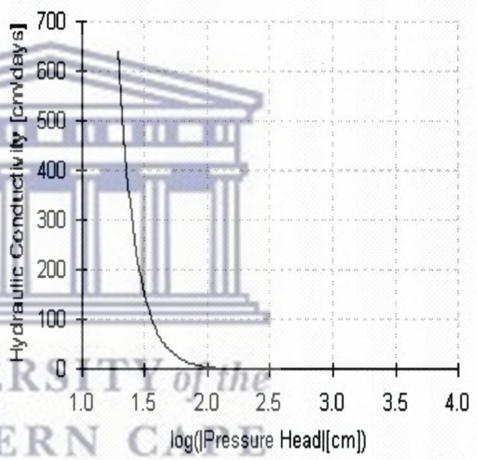

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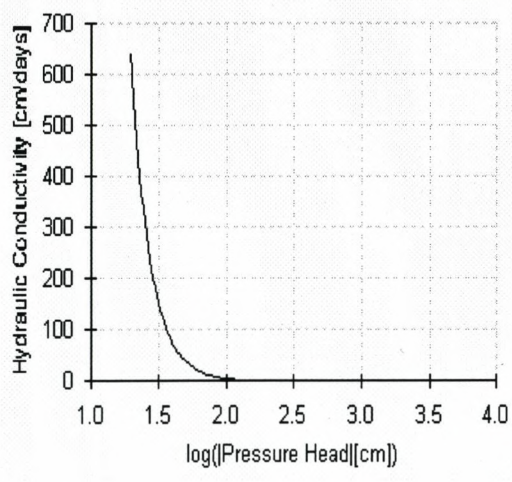

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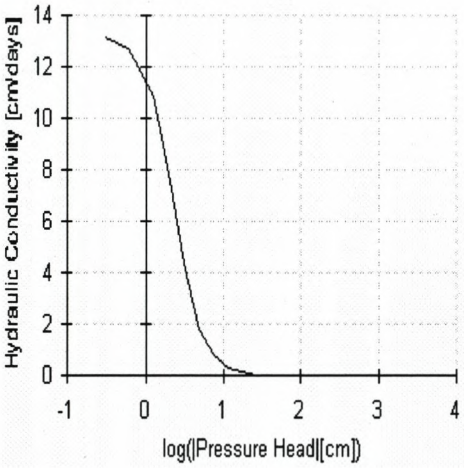
4m: Sandy clay loam:



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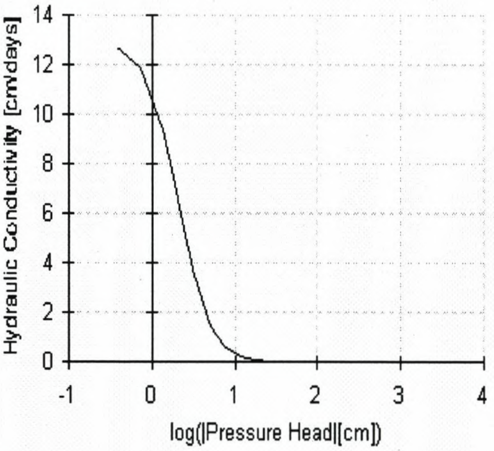

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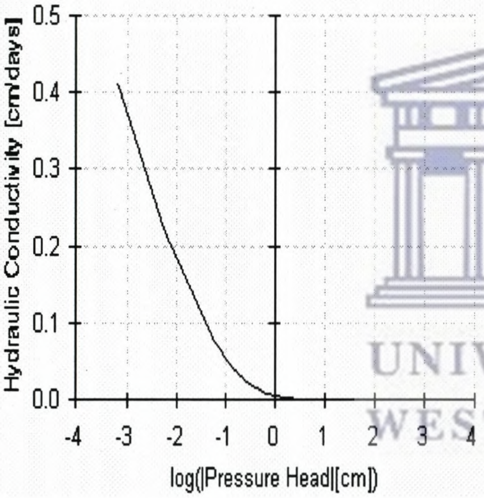

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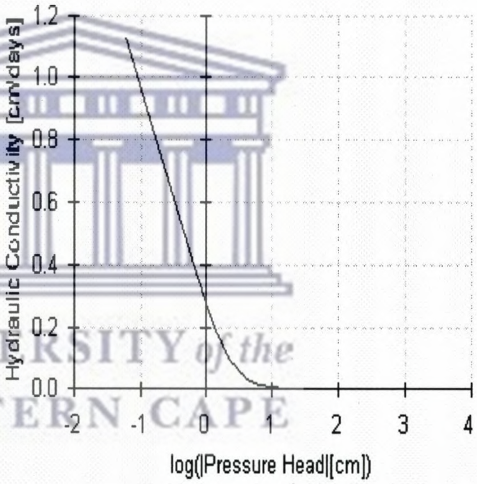

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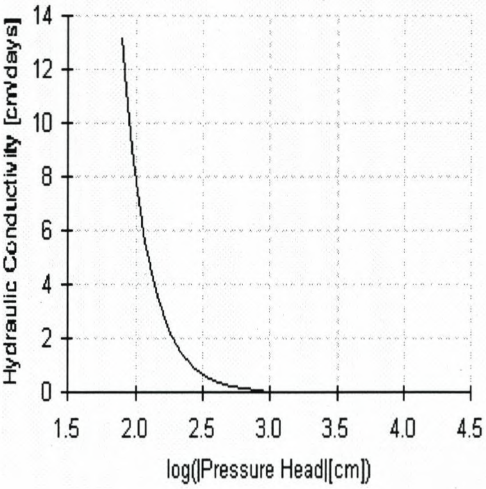

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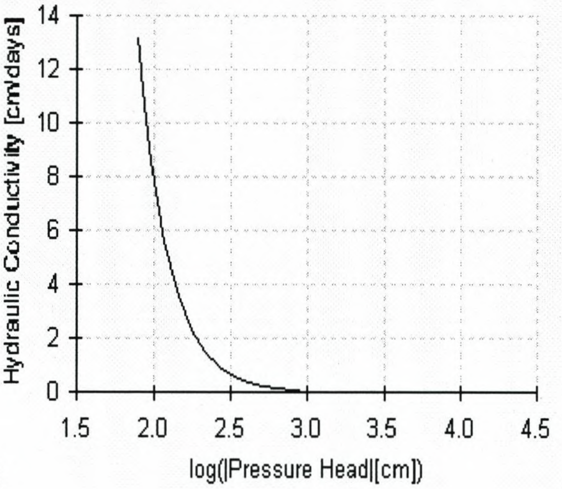

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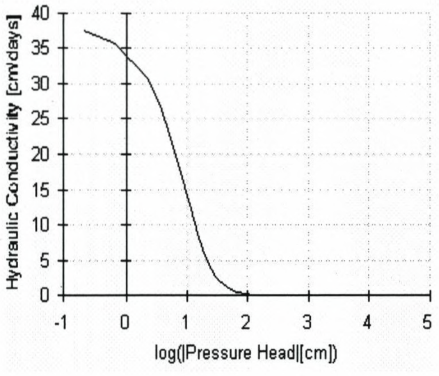
6.5m: Sandy Loam



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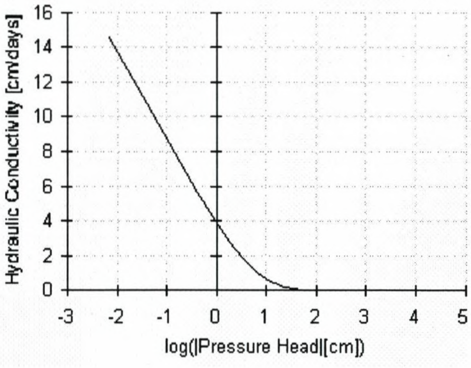

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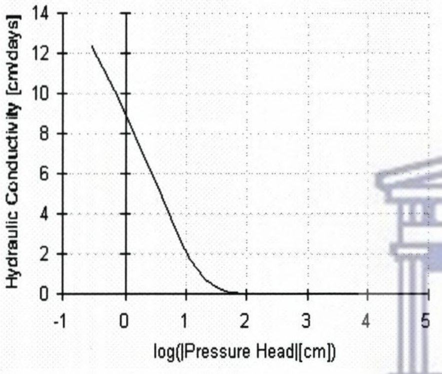

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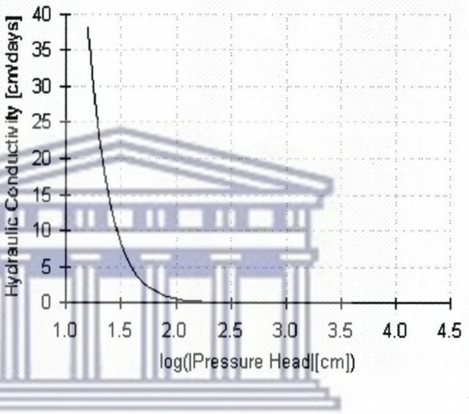

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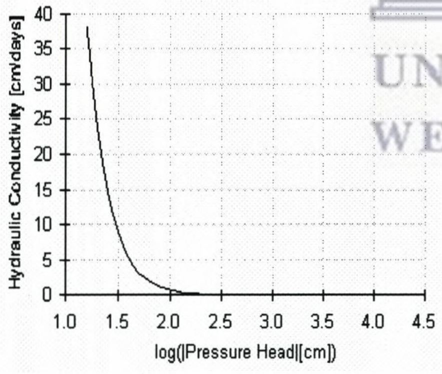
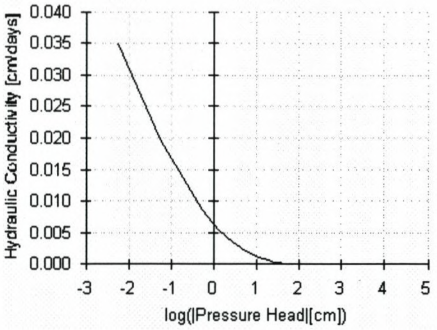


6

7m: Silt loam



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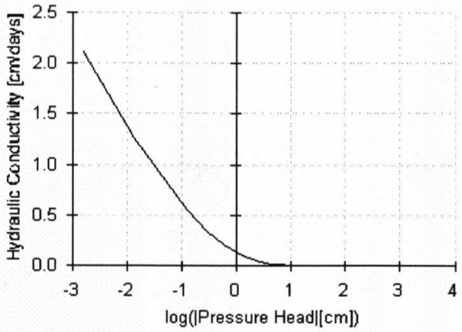

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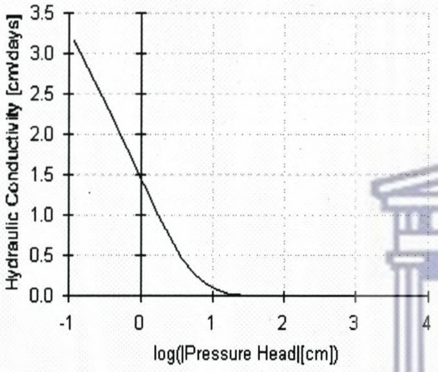

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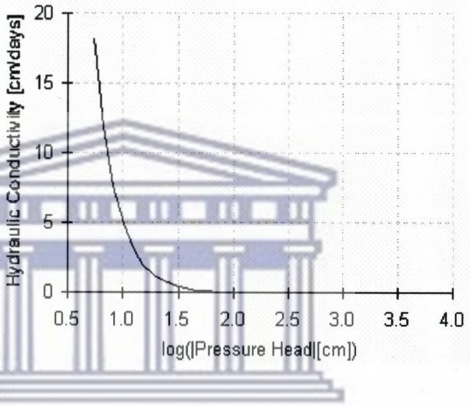

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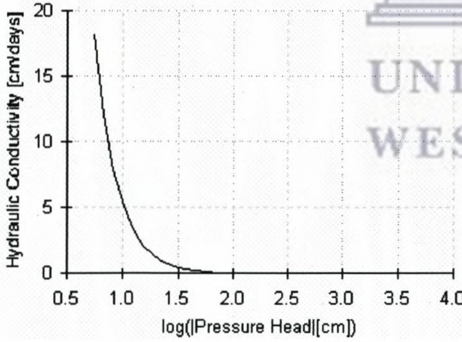
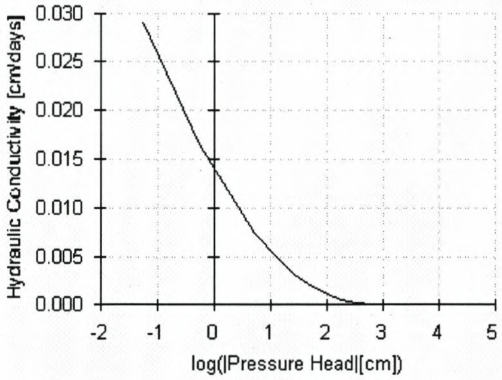


6

8.5: Clay



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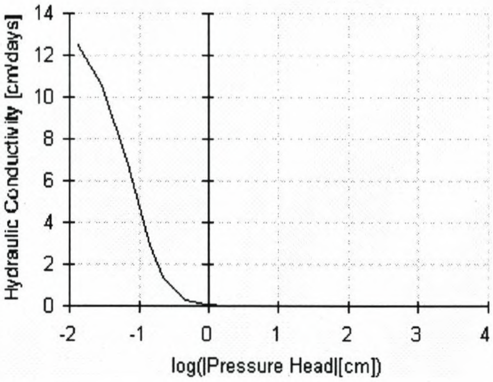

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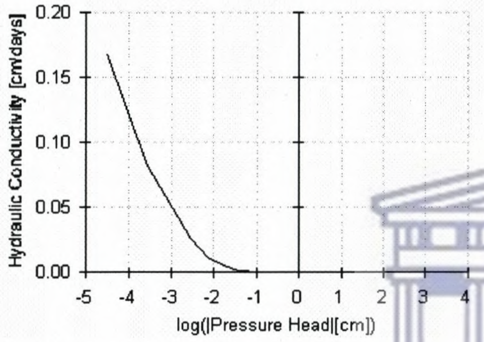

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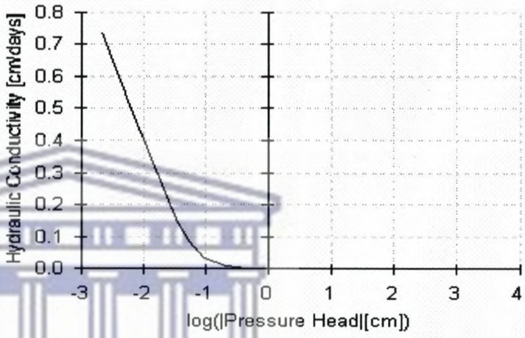

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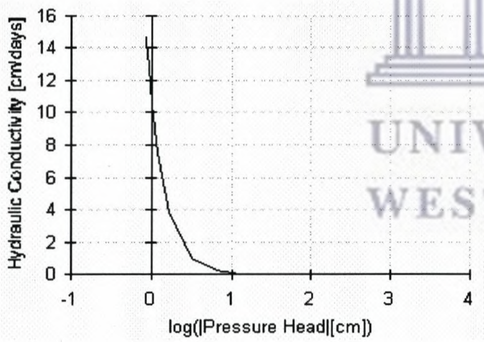

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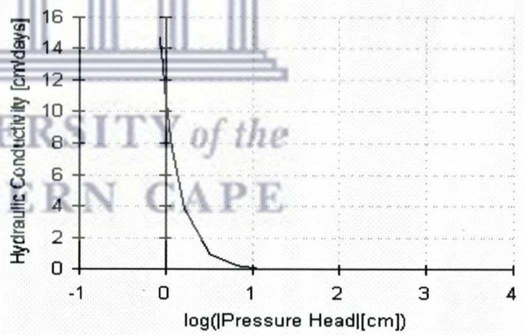

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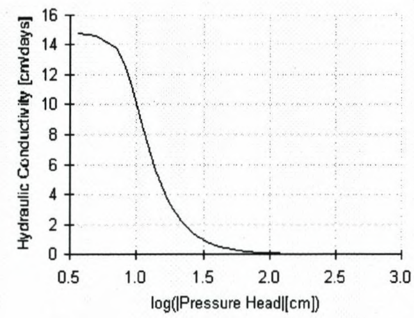
10m:Clay



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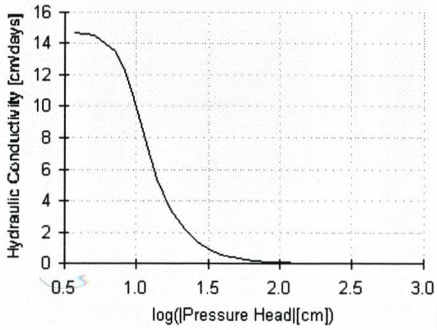

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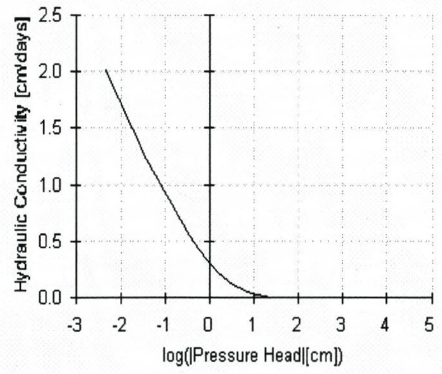
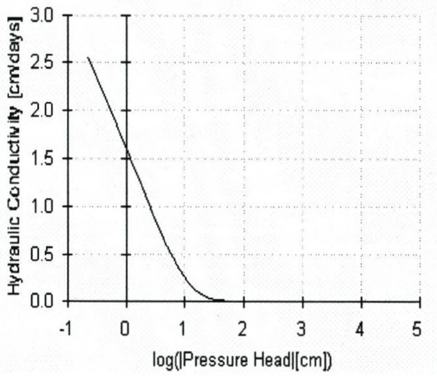
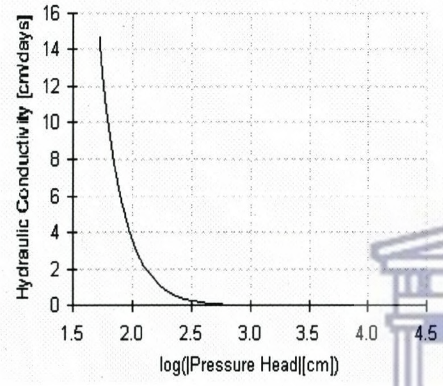

Hydraulic Conductivity [cm/days]
2.5
2.0
1.5
1.0
0.5
0.0
-3
-2
-1
0
1
2
3
4
5
log(|Pressure Head|[cm])

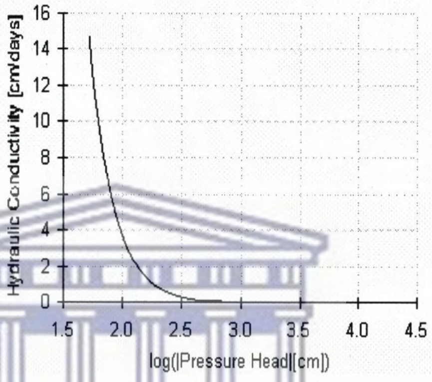
3


Hydraulic Conductivity [cm/days]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-1
0
1
2
3
4
5
log(|Pressure Head|[cm])

4

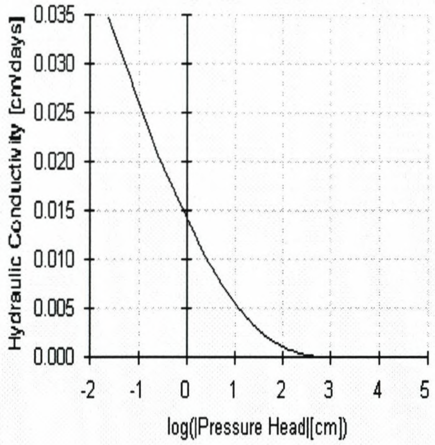

Hydraulic Conductivity [cm/days]
16
14
12
10
8
6
4
2
0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
log(|Pressure Head|[cm])

5


Hydraulic Conductivity [cm/days]
16
14
12
10
8
6
4
2
0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
log(|Pressure Head|[cm])

6

12m: Clay



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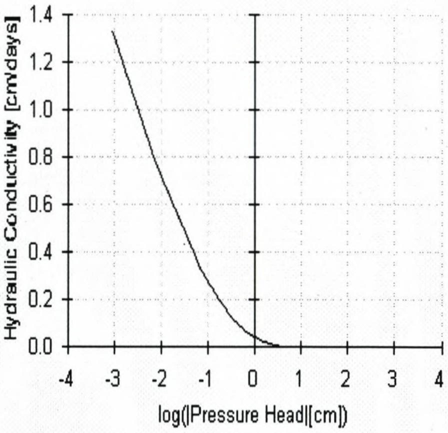

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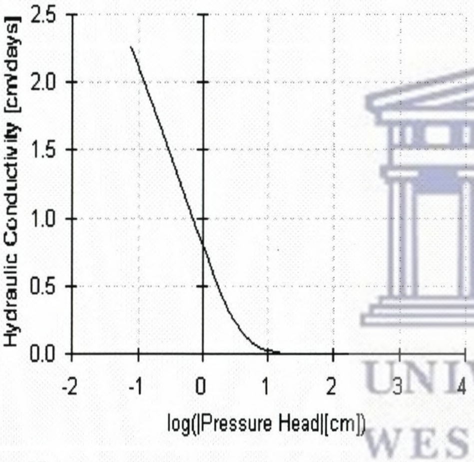

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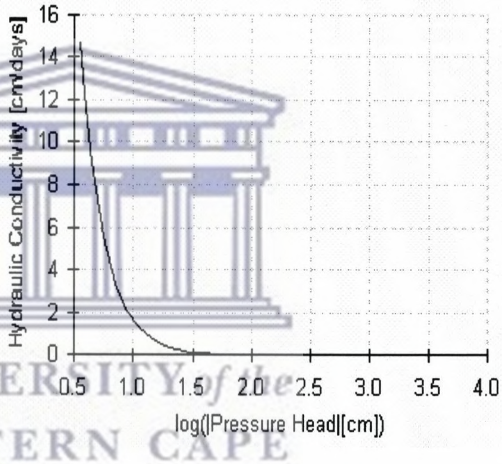

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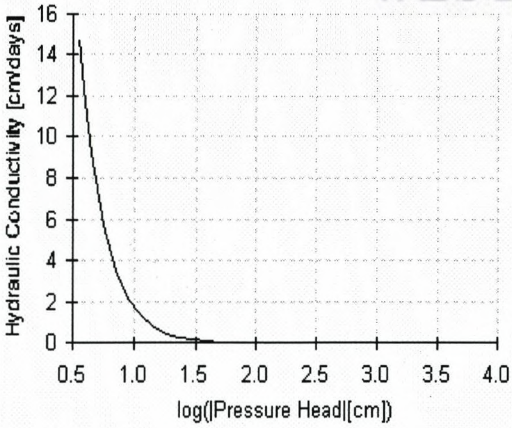
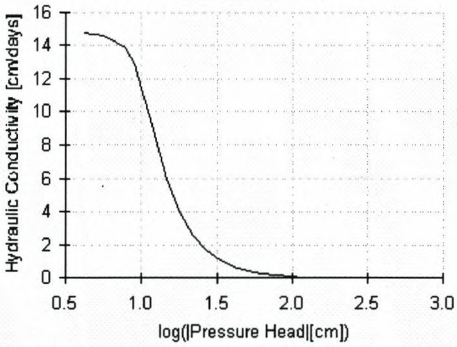


6

13m: Clay



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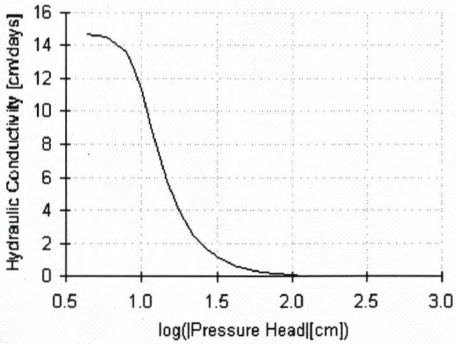

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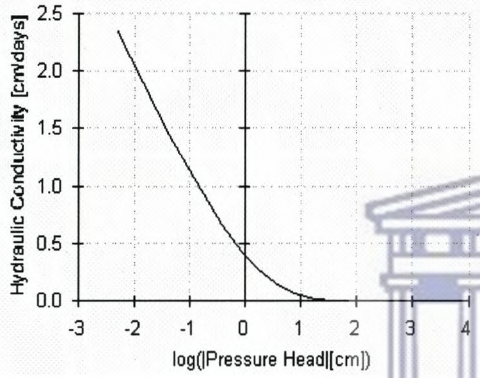

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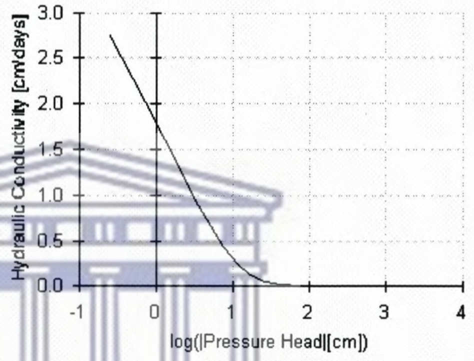

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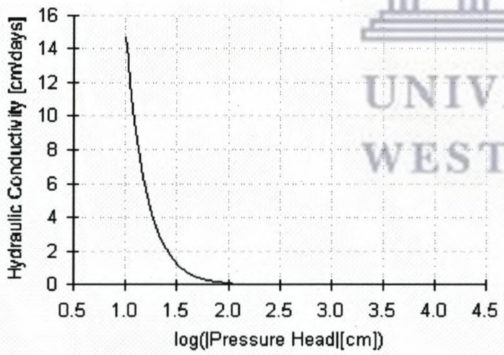

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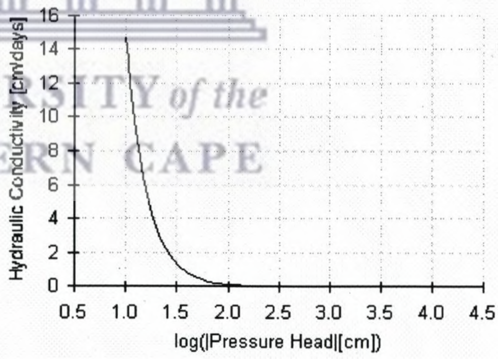
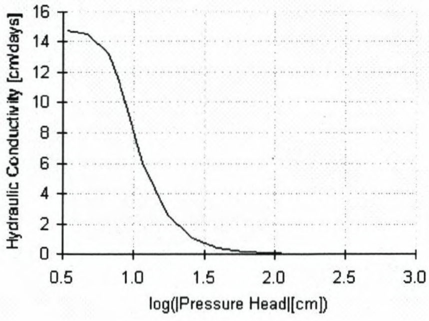


6

14m: Clay



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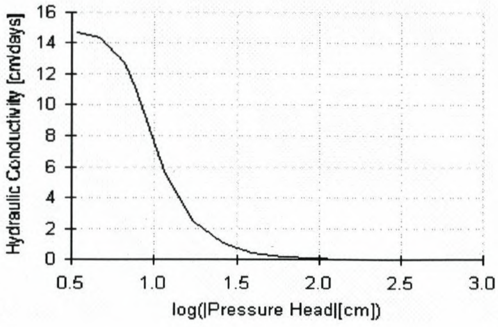

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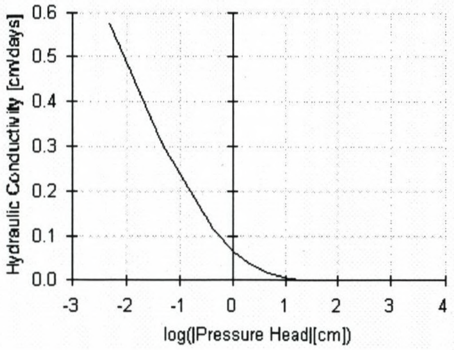
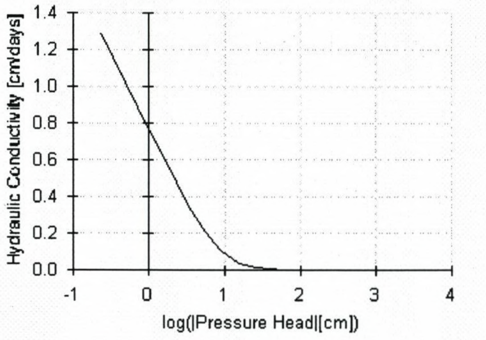
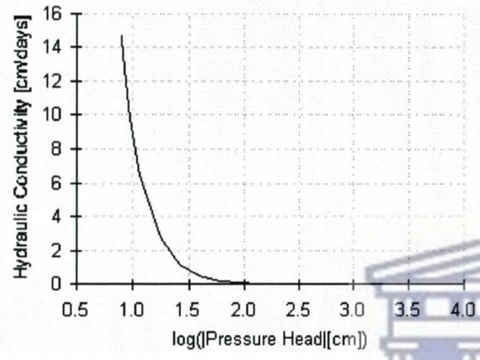

Hydraulic Conductivity [cm/days]
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-3
-2
-1
0
1
2
3
4
log(|Pressure Head|[cm])

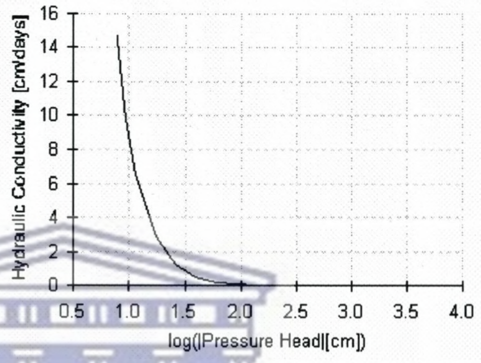
3


Hydraulic Conductivity [cm/days]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-1
0
1
2
3
4
log(|Pressure Head|[cm])

4


Hydraulic Conductivity [cm/days]
16
14
12
10
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
log(|Pressure Head|[cm])

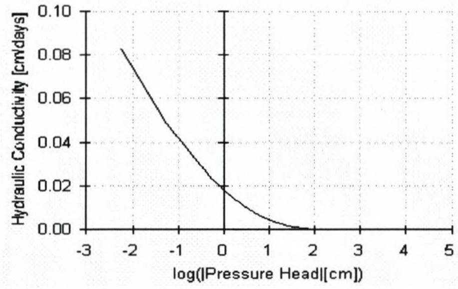
5


Hydraulic Conductivity [cm/days]
16
14
12
10
8
6
4
2
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
log(|Pressure Head|[cm])

6

Ithemba site 2

Topsoil: Sandy Loam



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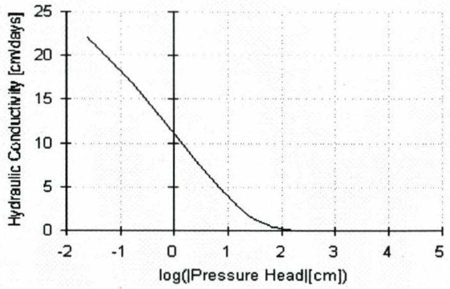

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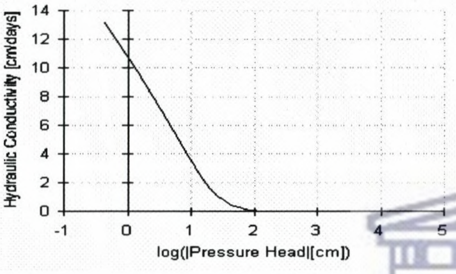

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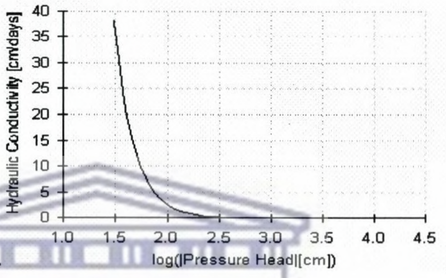

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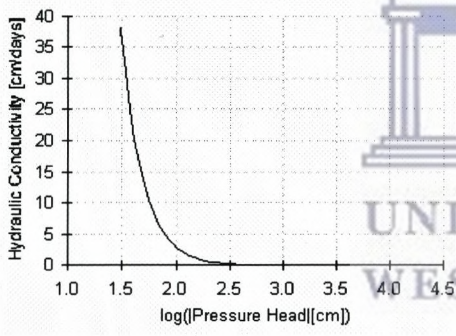
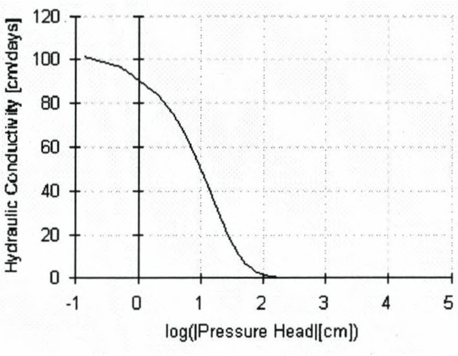


6

0.5m: Loamy Sand



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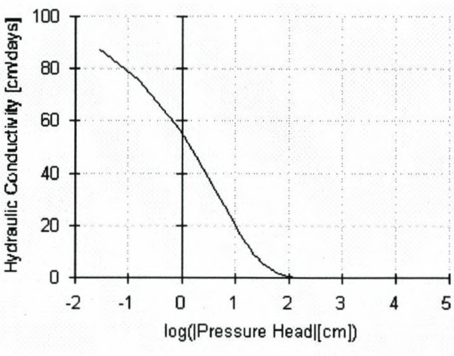

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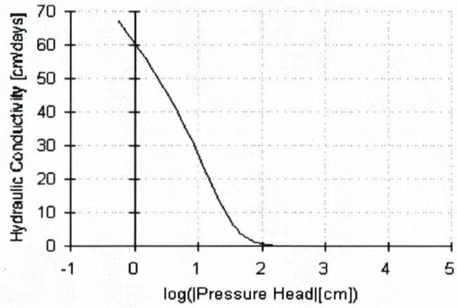

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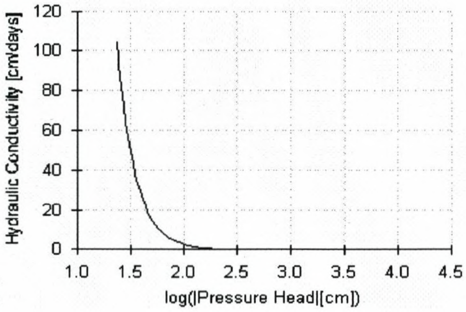

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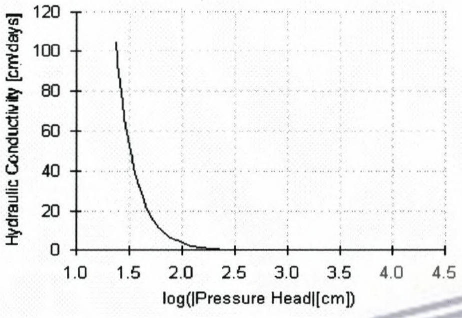

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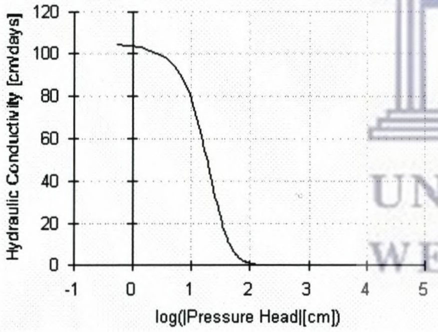
1m: Loamy Sand



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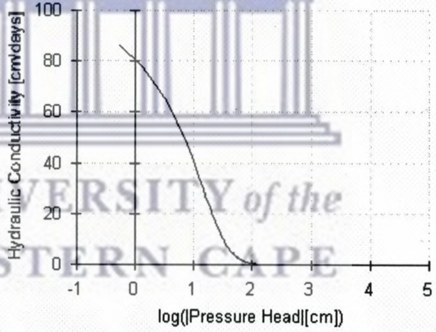

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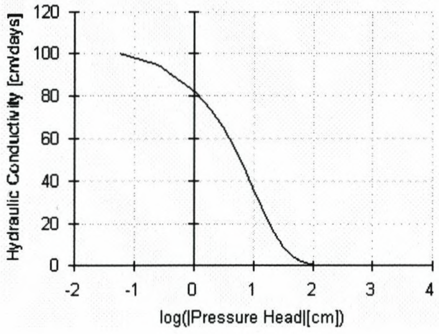

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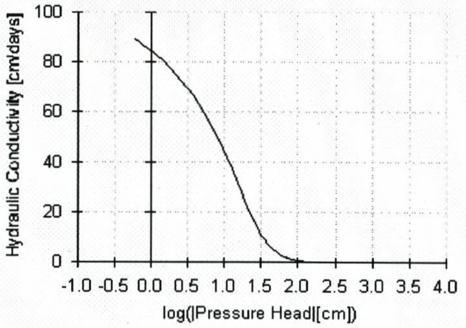

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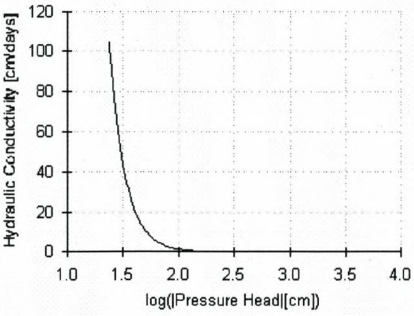

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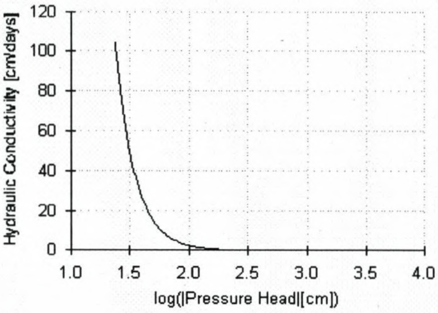
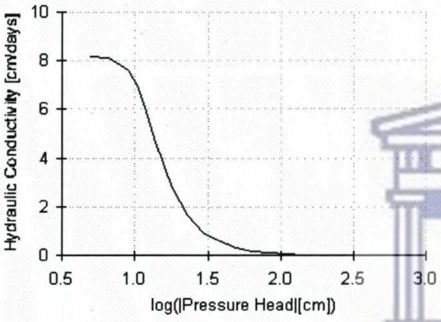


6

2m: Clay Loam



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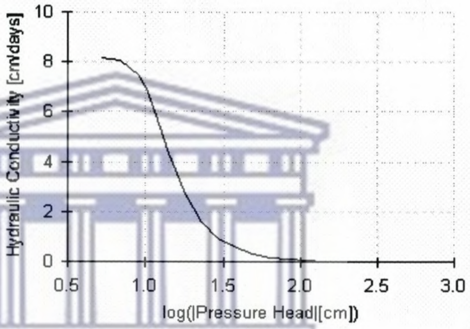

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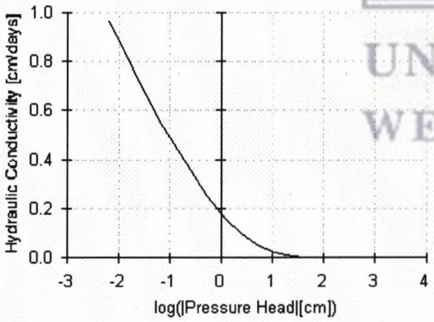

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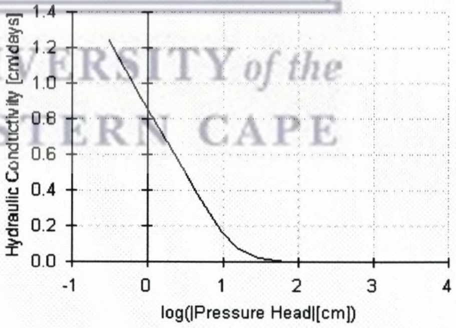

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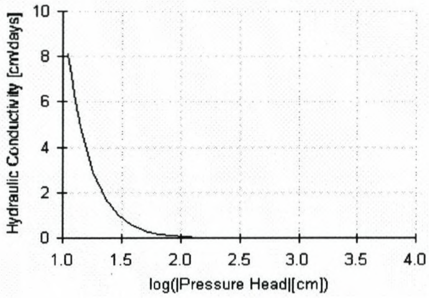

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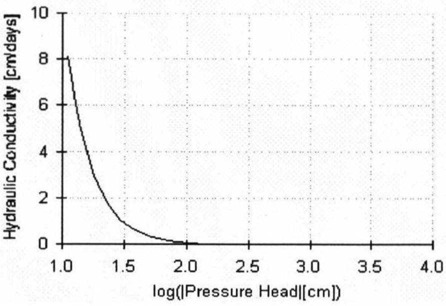
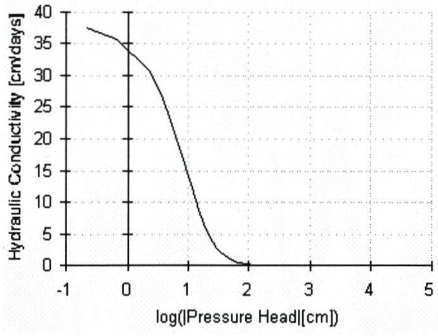


6

3m: Sandy Loam



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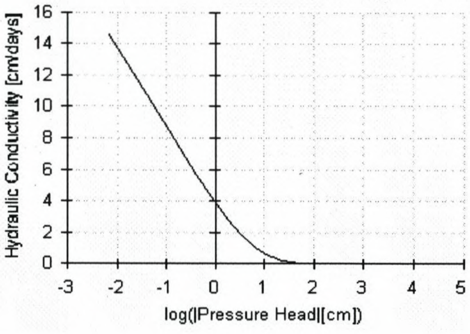

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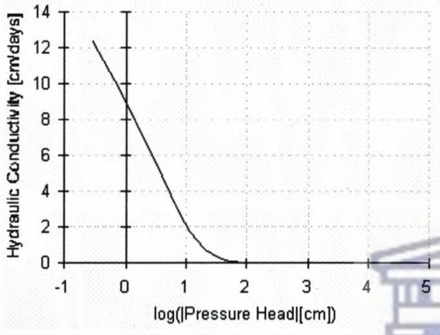

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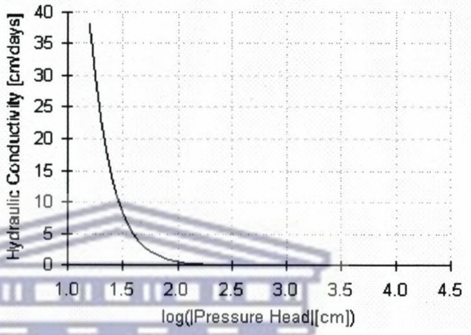

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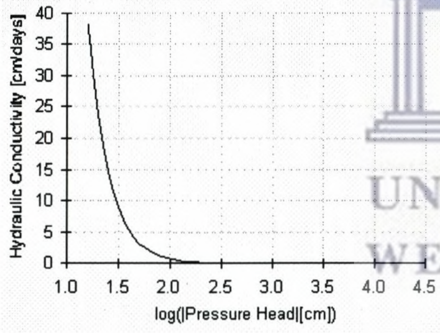
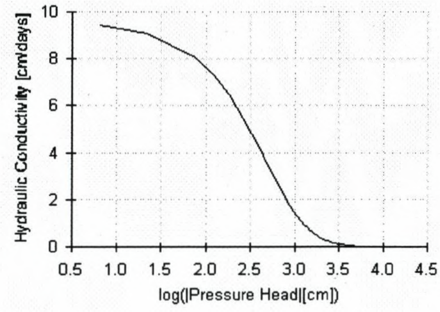


6

4m: Silty Clay



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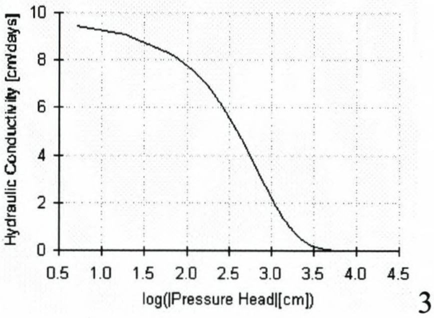

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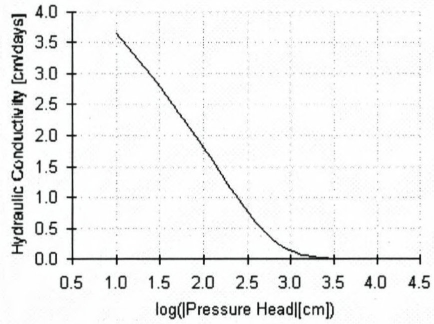

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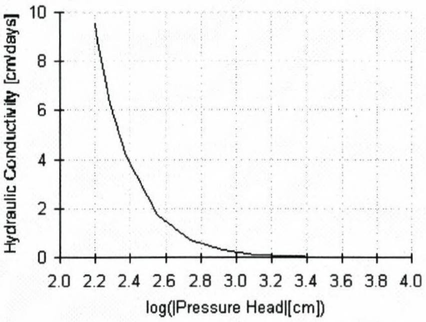

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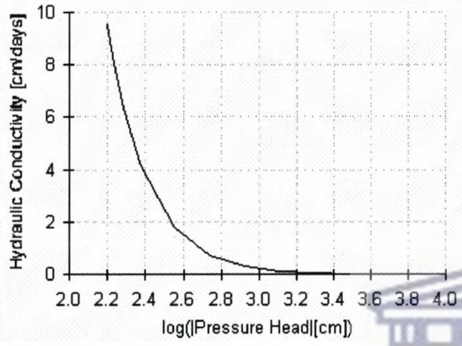
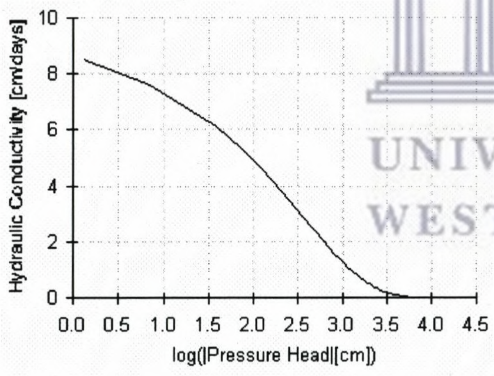


6

5m: Silty Clay



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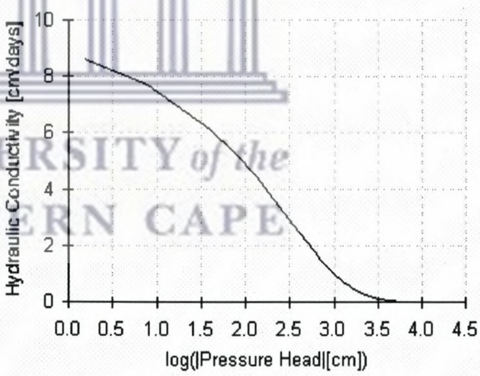

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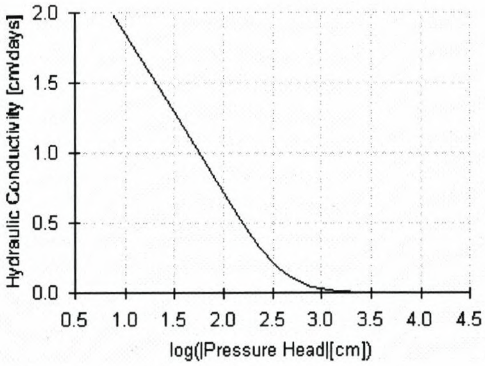

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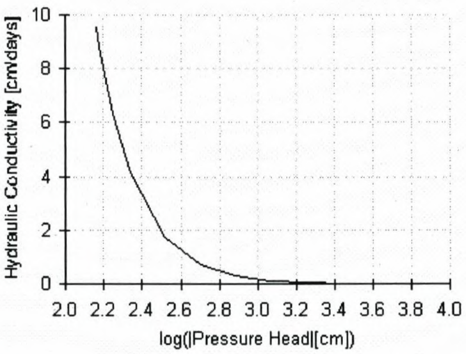

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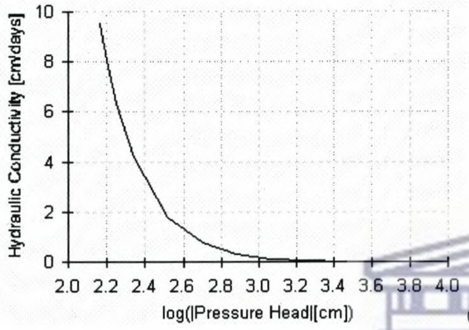
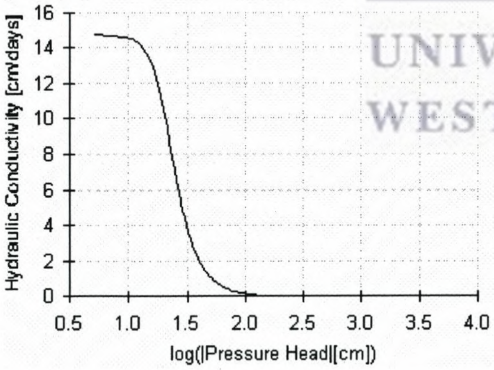


6

6m: Clay



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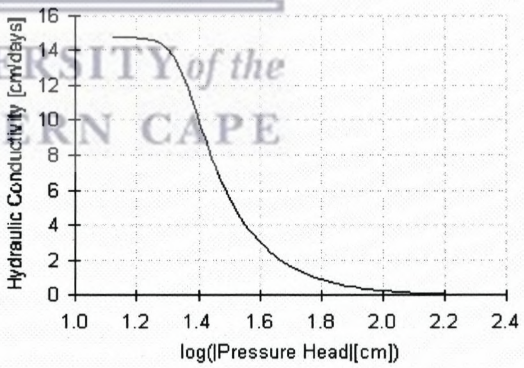

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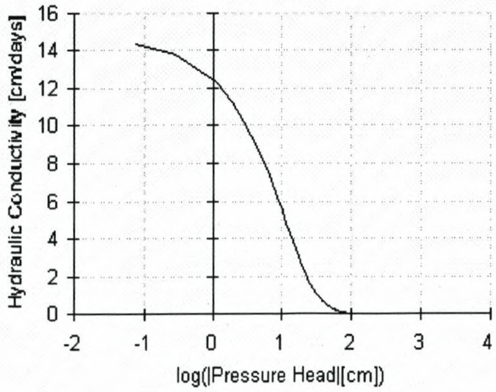

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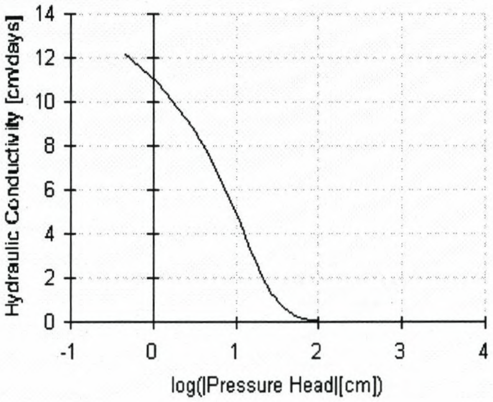

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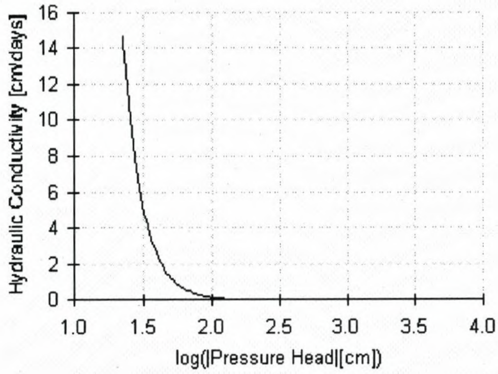

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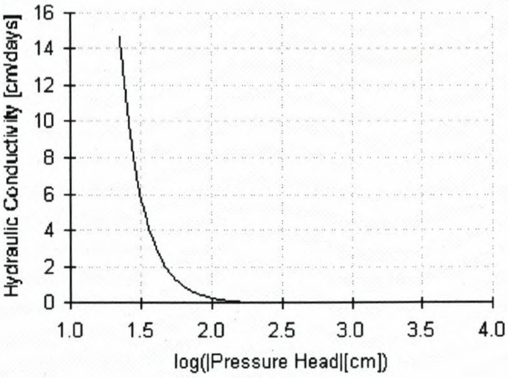
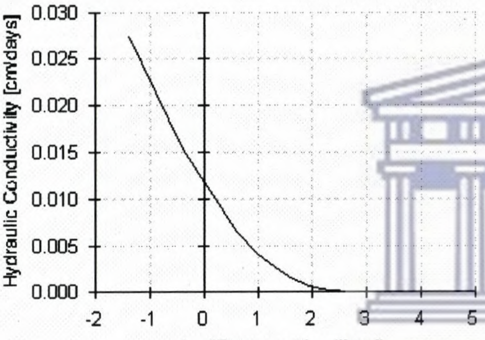


6

7m: Clay



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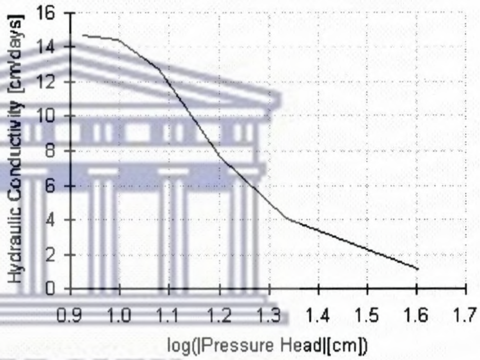

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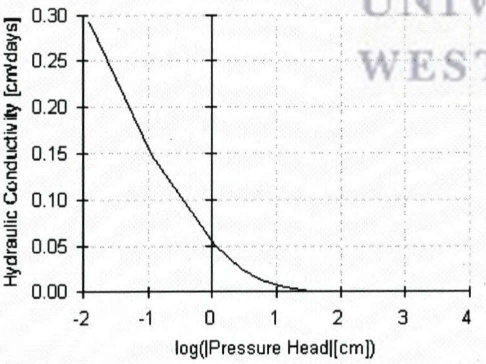

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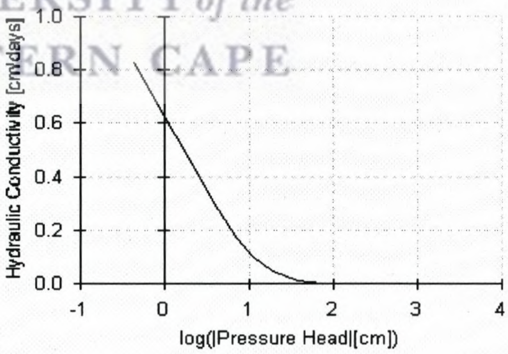

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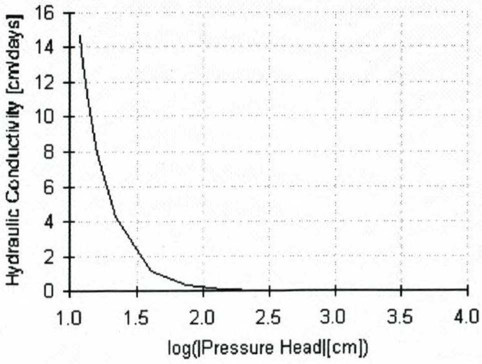

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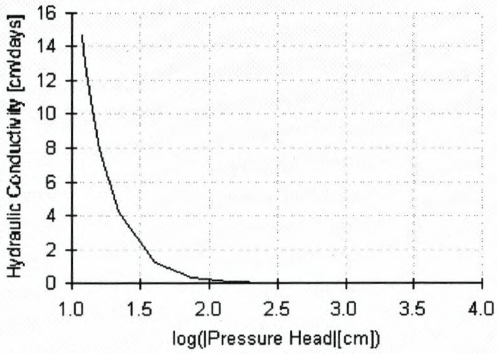
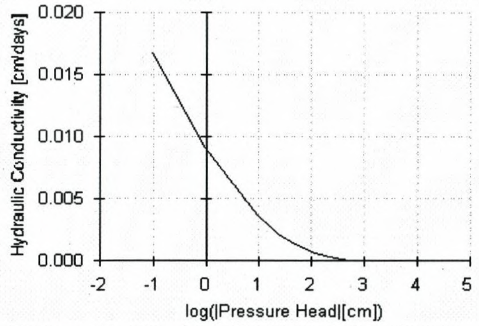


6

8.5m: Silty Clay



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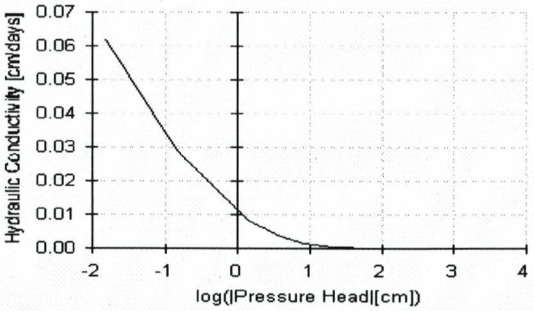

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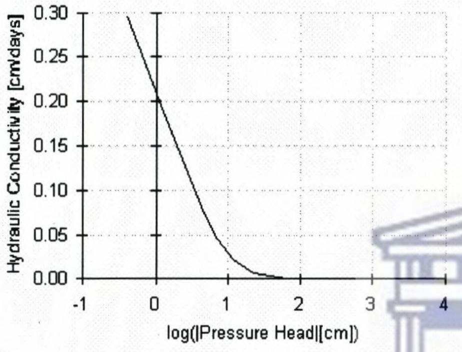

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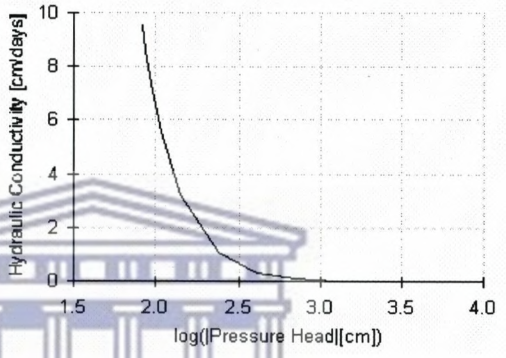

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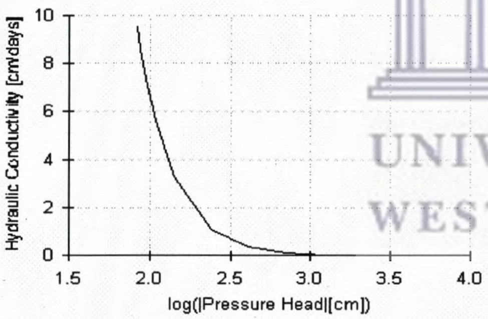

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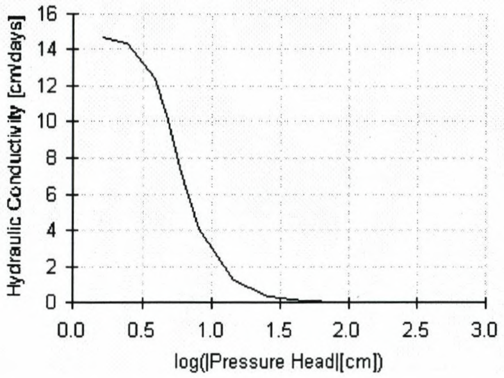
10m: Malmesbury Shale



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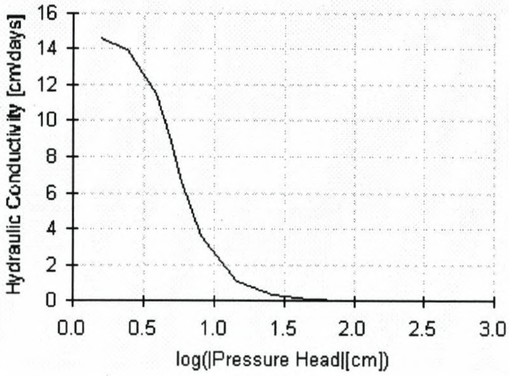

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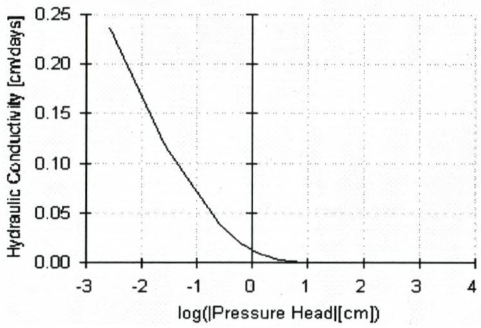

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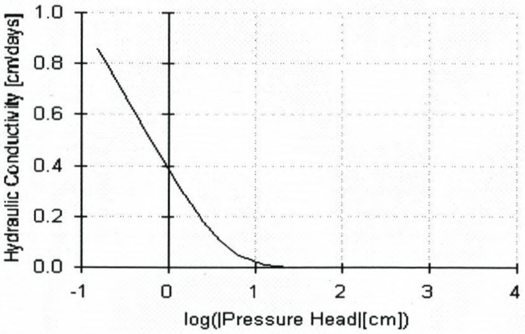

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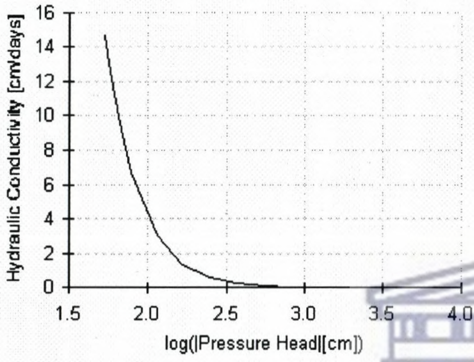
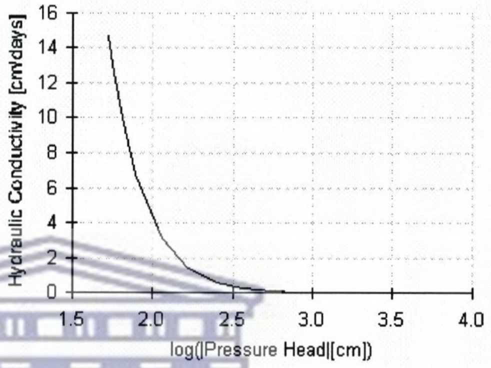
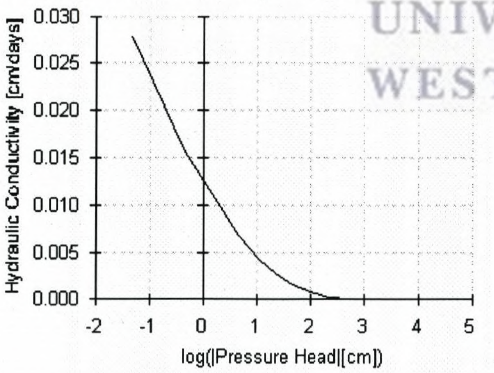




11.5m: Malmesbury Shale



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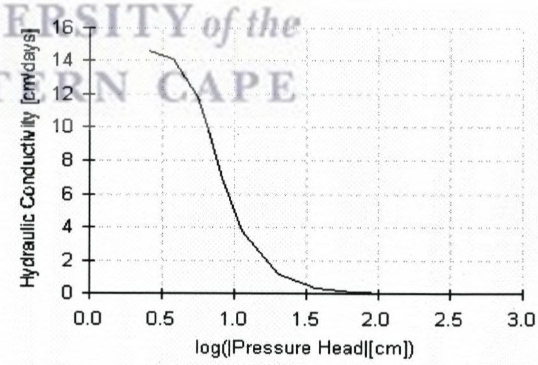

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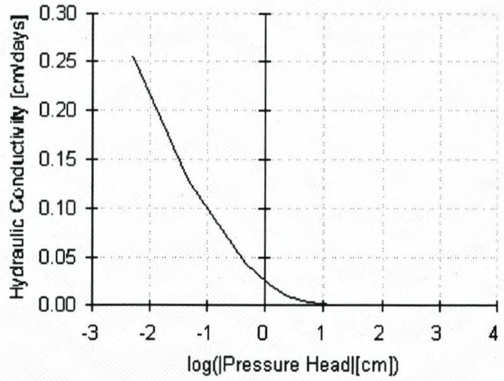

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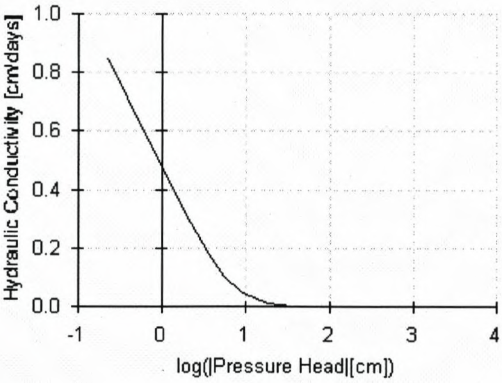

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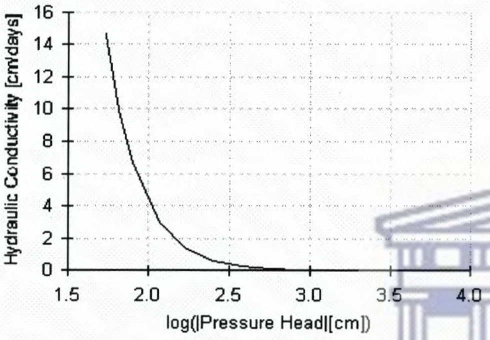

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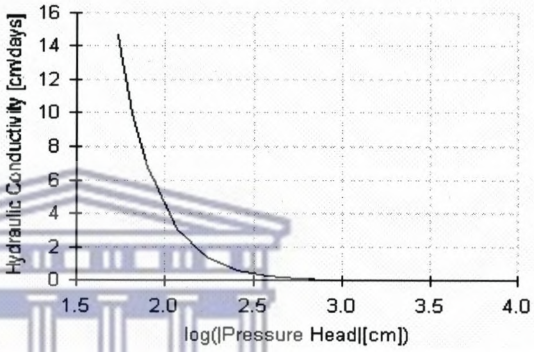
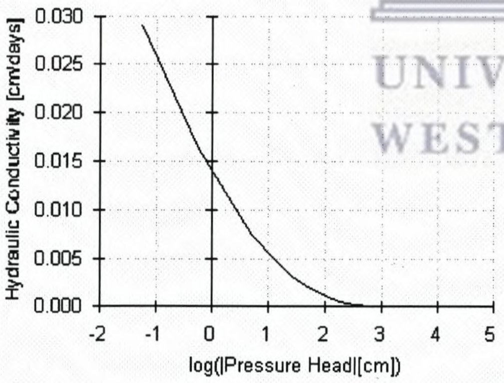


6

13m: Malmesbury Shale



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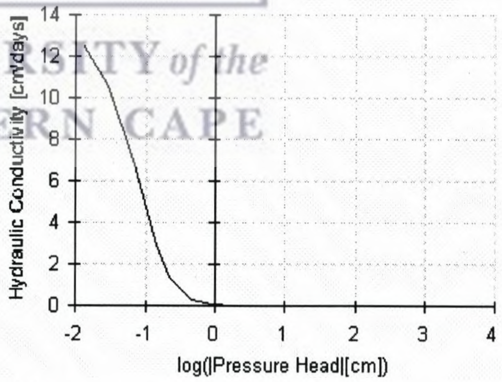

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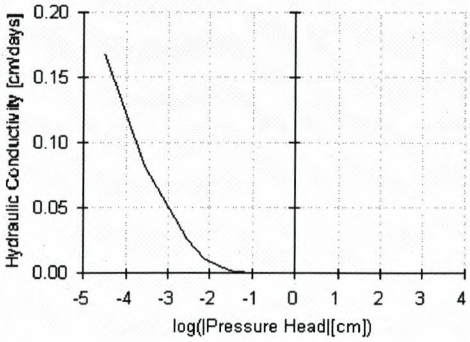

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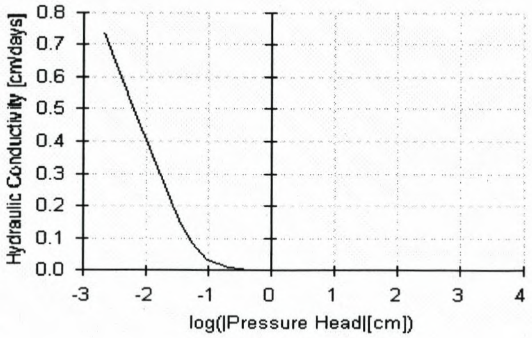

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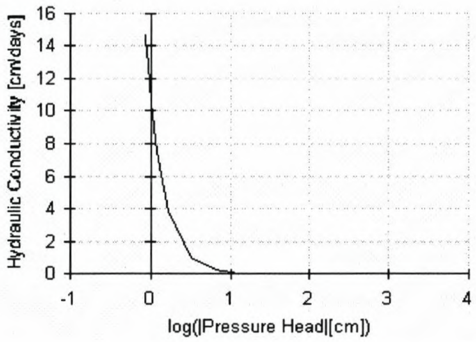

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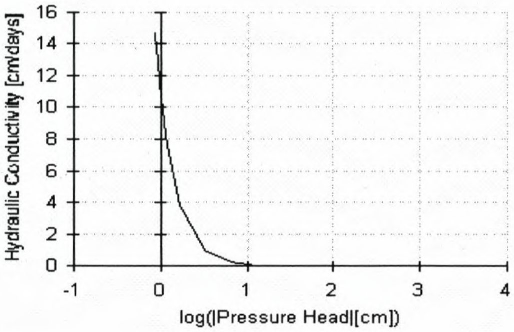

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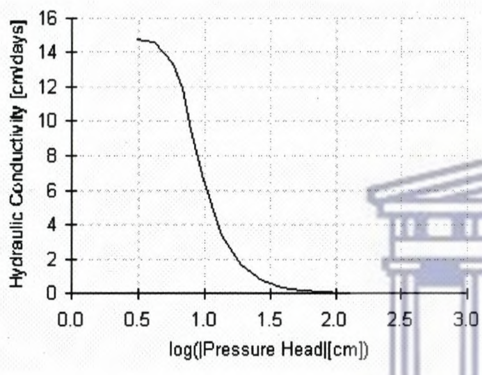
15.5m: Malmesbury Shale



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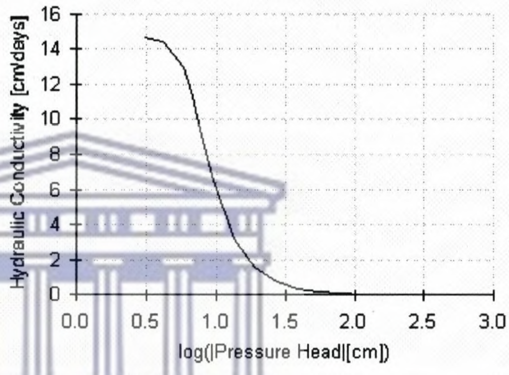

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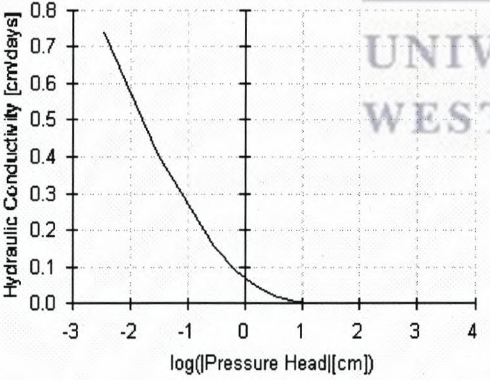

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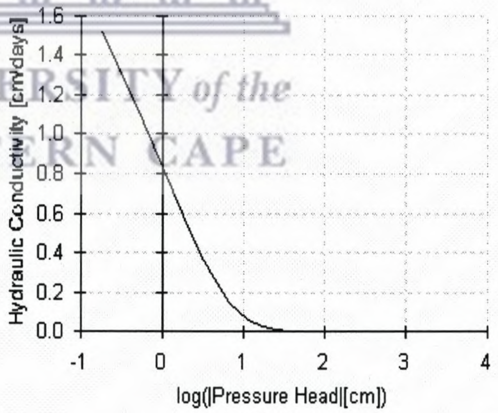

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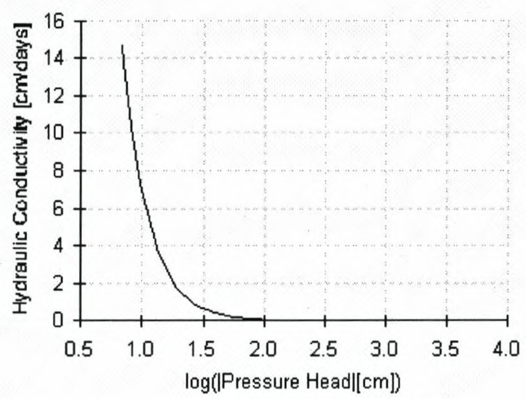

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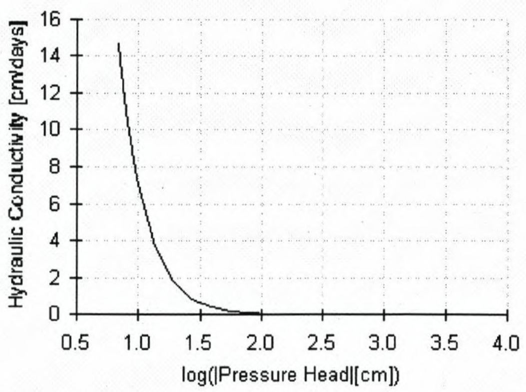

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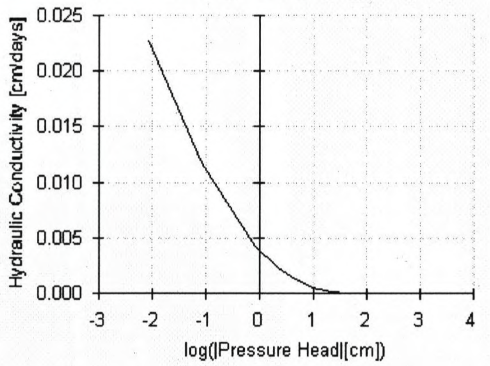
17m: Malmesbury Shale



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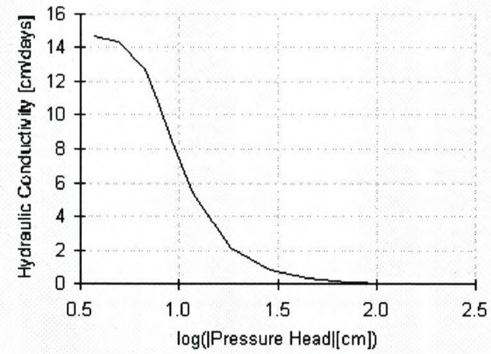

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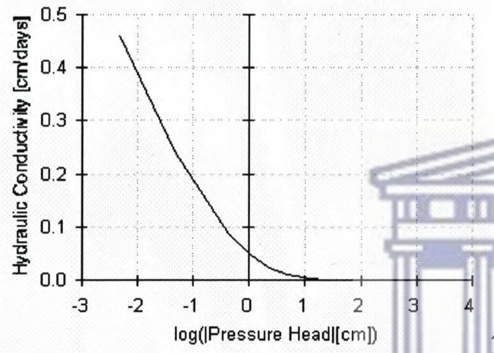

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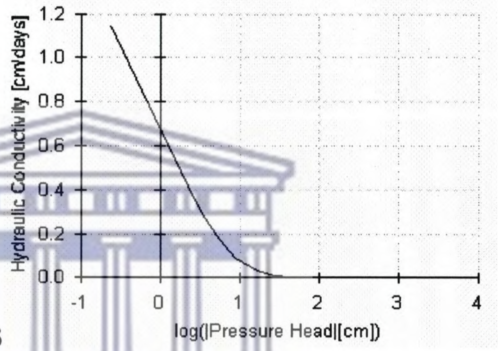

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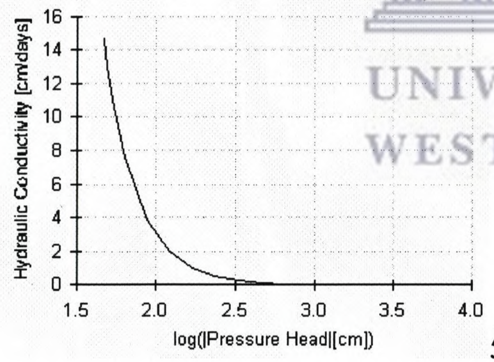

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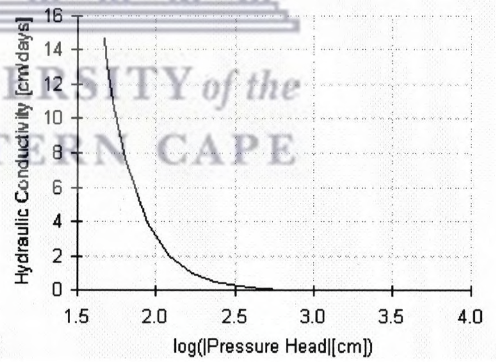

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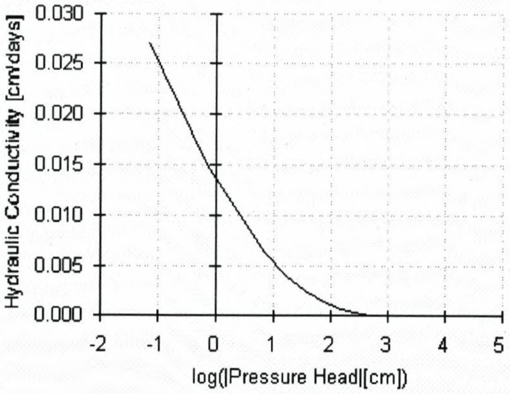
18.5m: Malmesbury Shale



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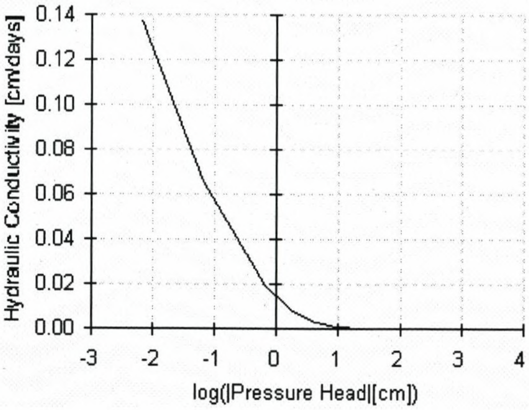

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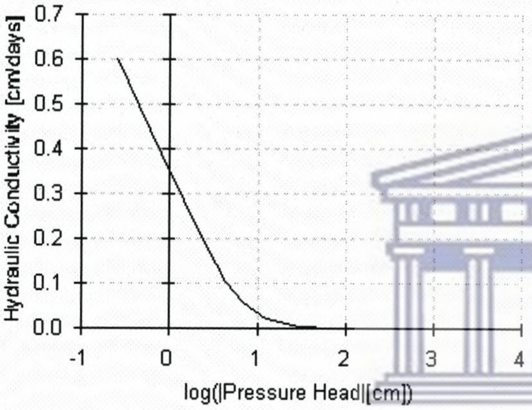

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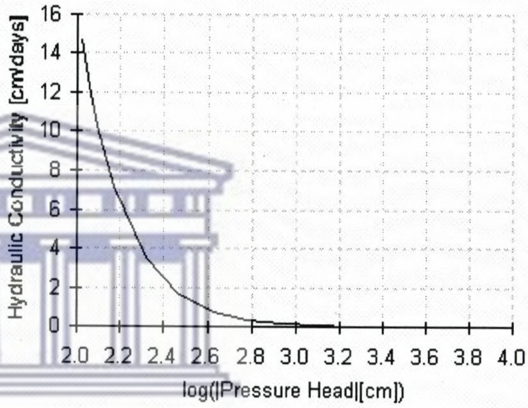

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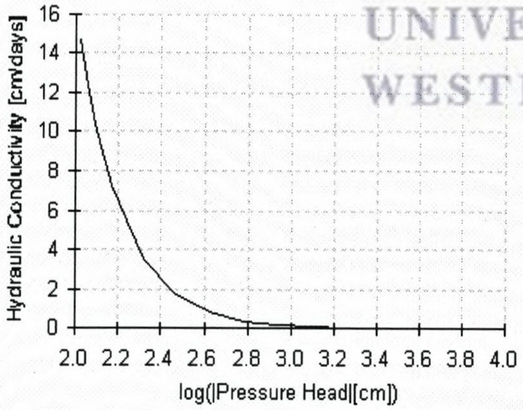
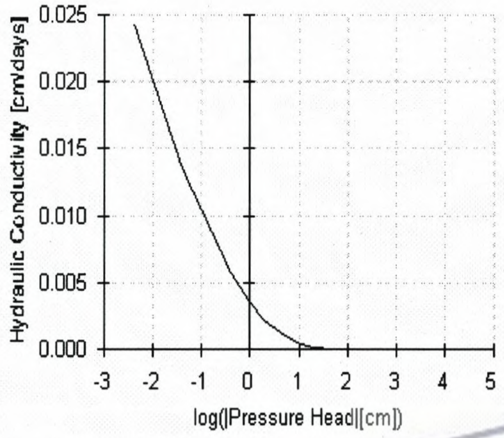


6

Bergriver site 1

Topsoil: Sandy Clay Loam



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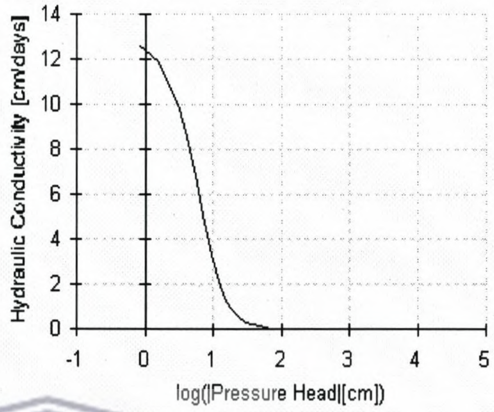

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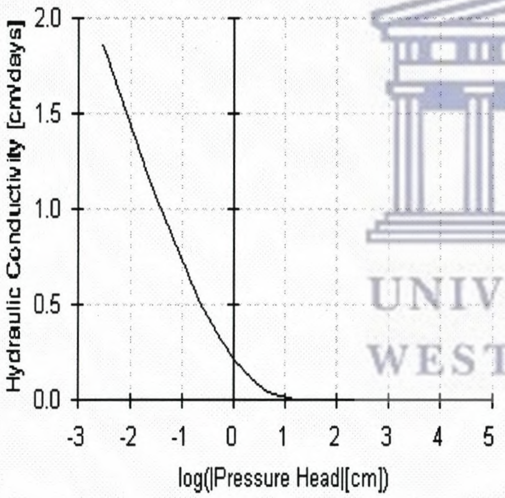

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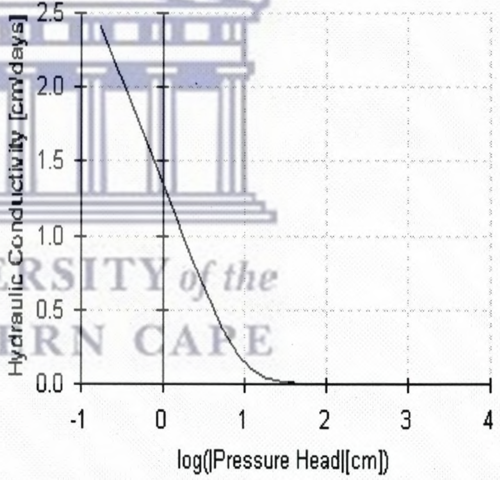

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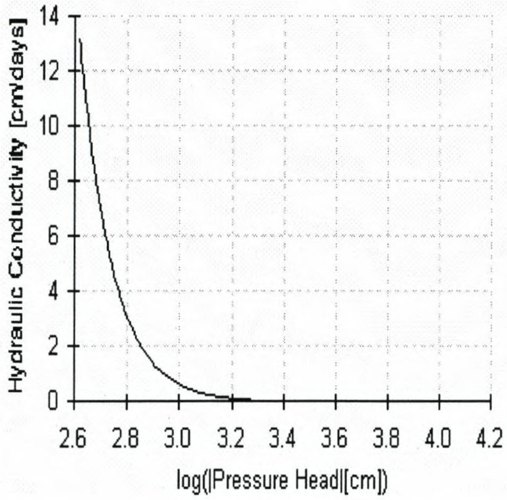

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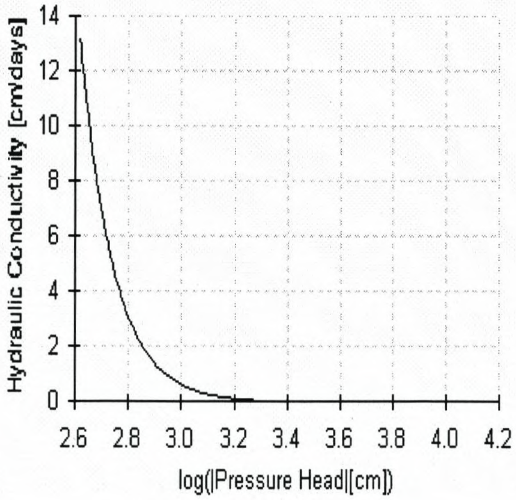

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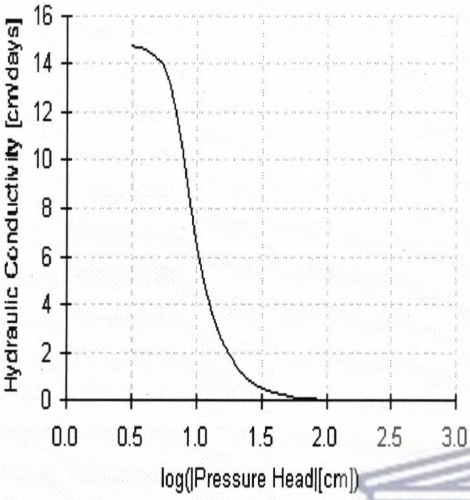
1m: Clay



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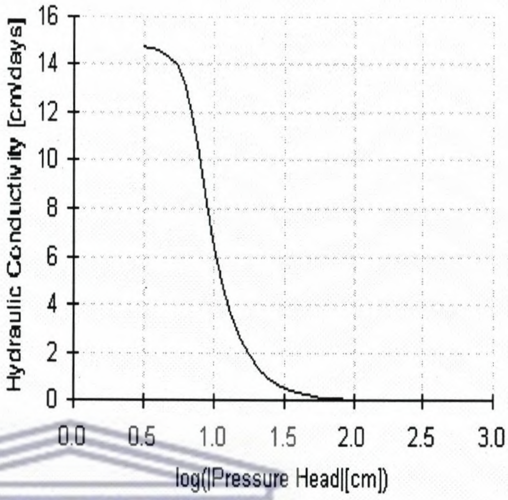

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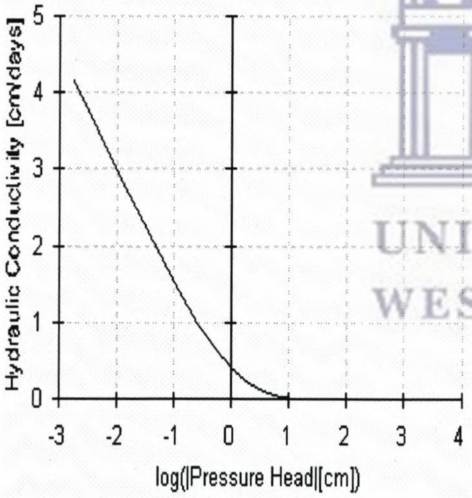

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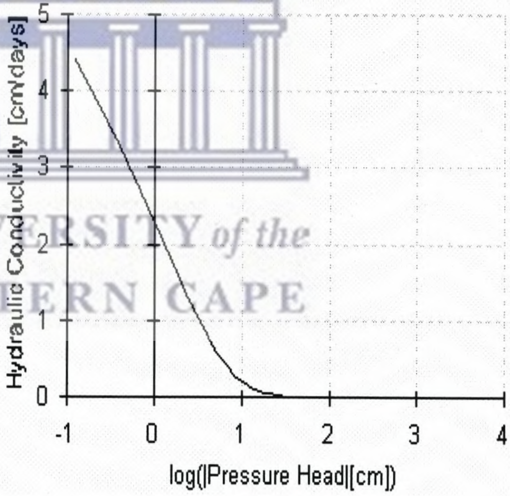

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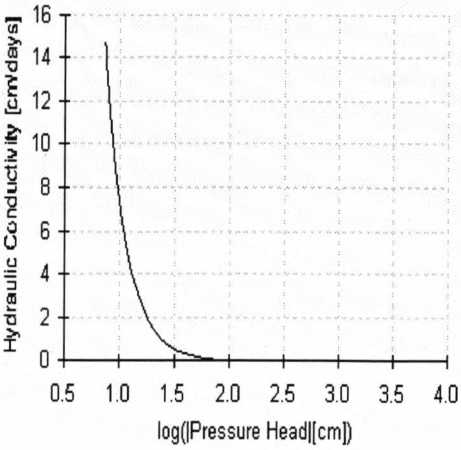

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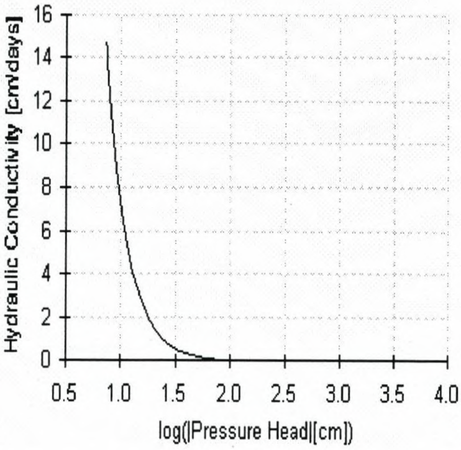
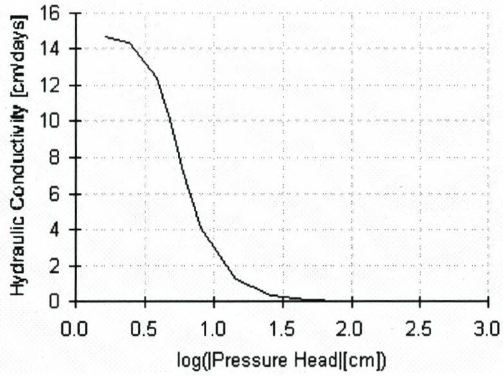


6

1.8m: Clay



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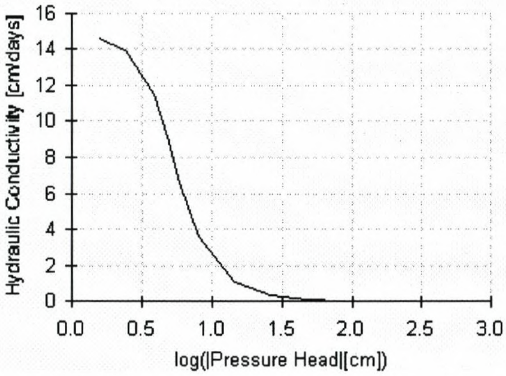

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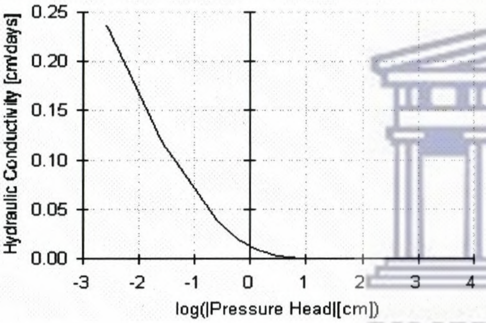

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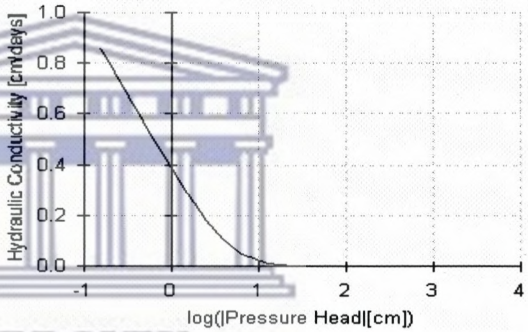

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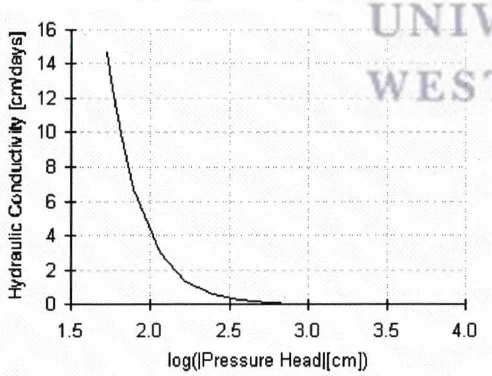

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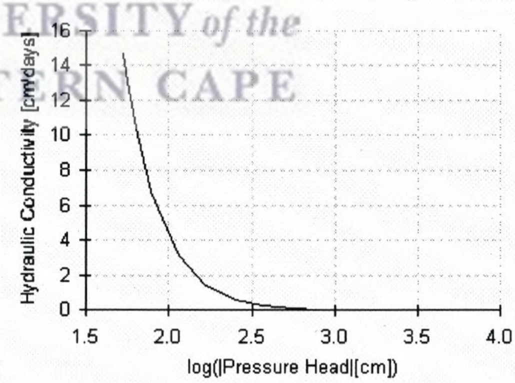

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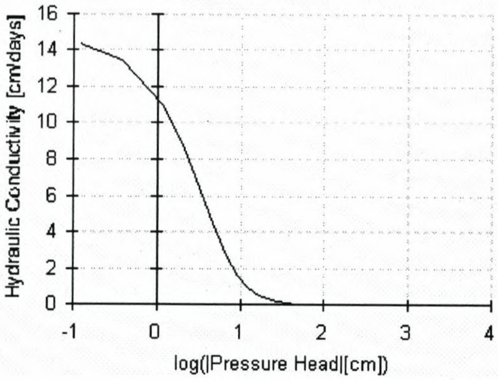
3.3m: Clay



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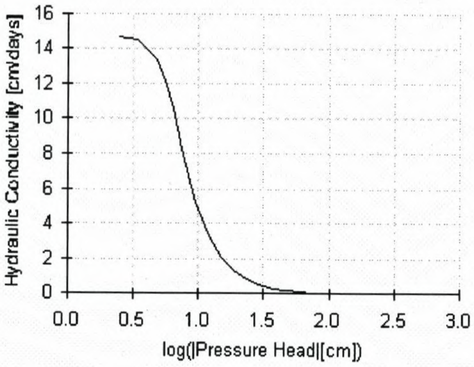

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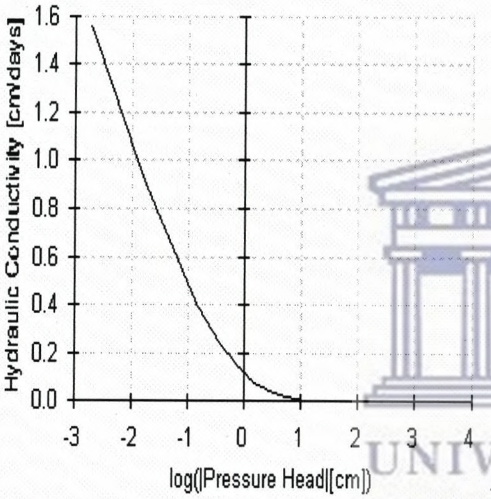

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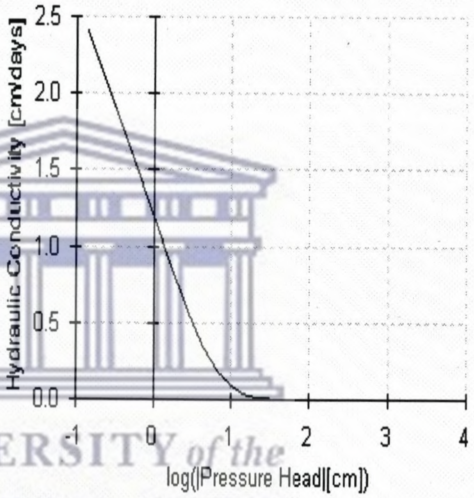

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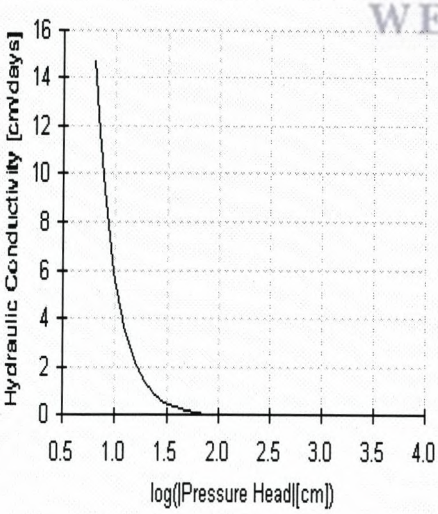

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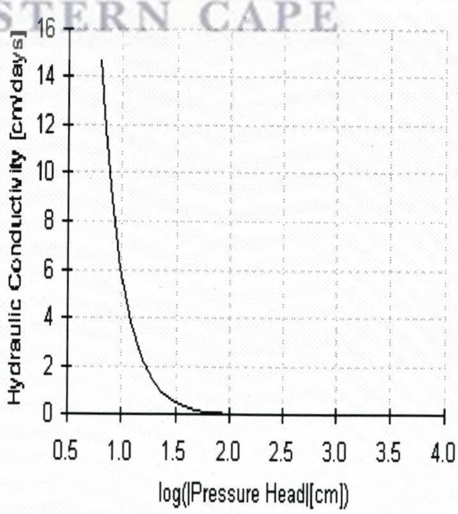

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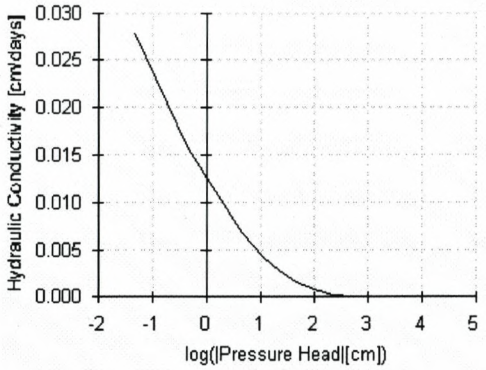
4.8m: Clay



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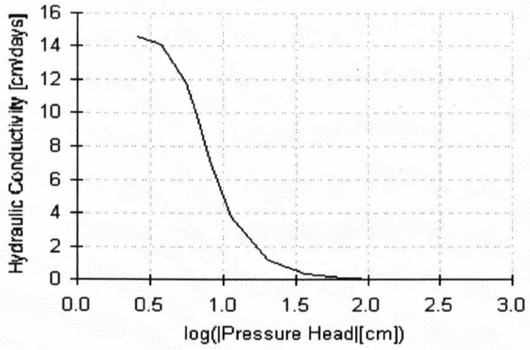

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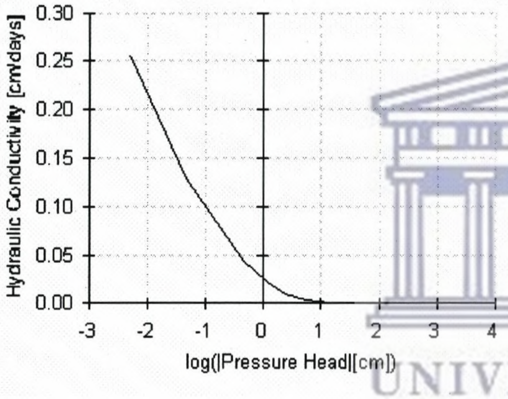

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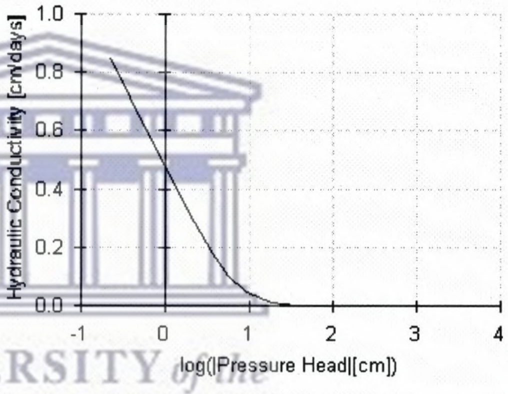

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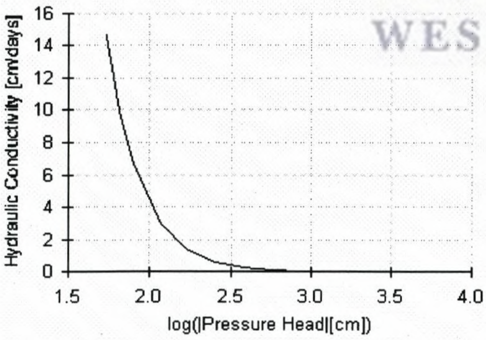

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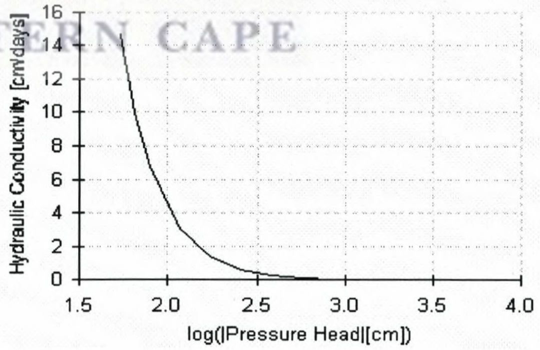

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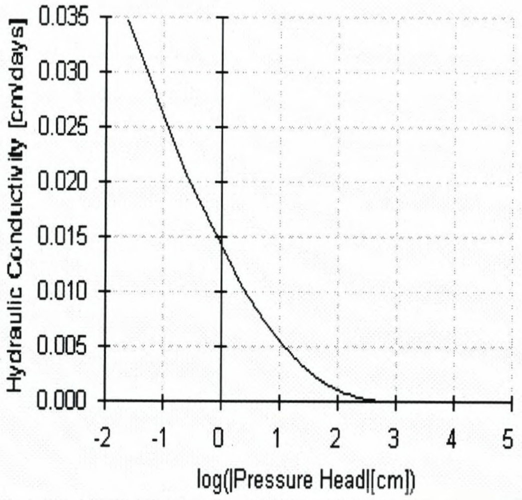
5.8m: Clay



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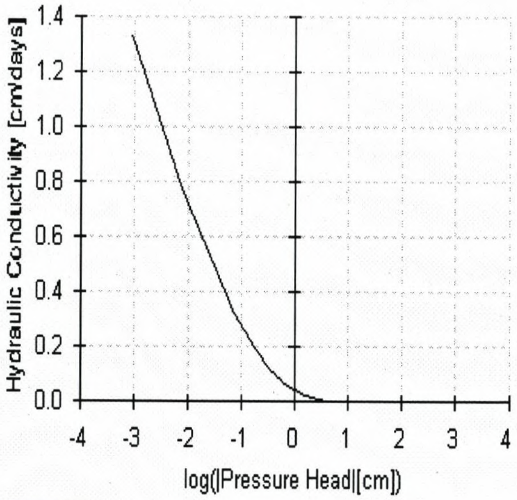

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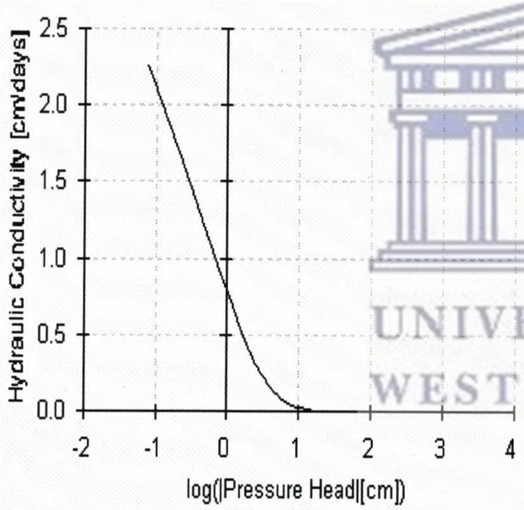

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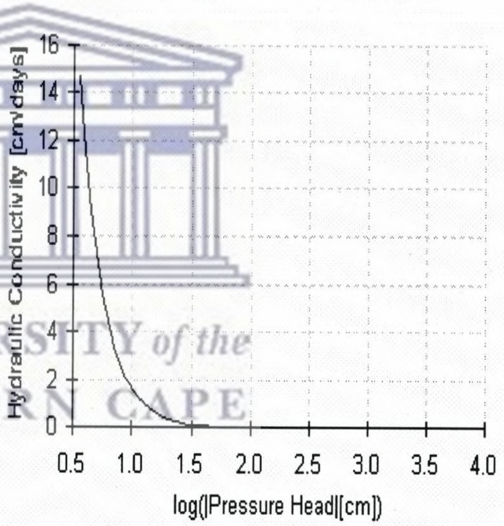

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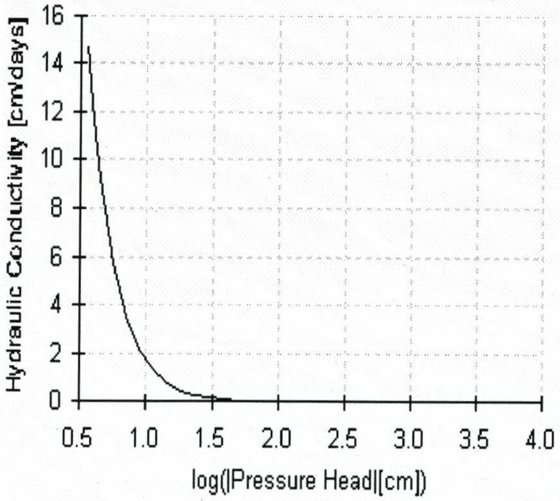

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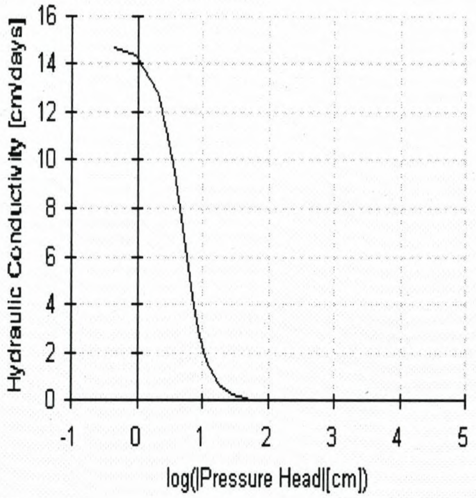
6.3m: Clay



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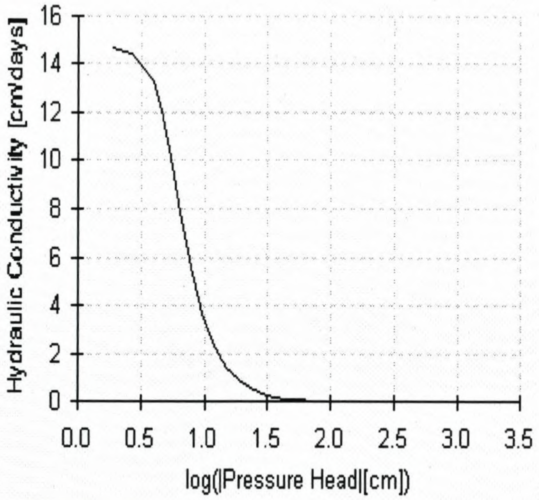

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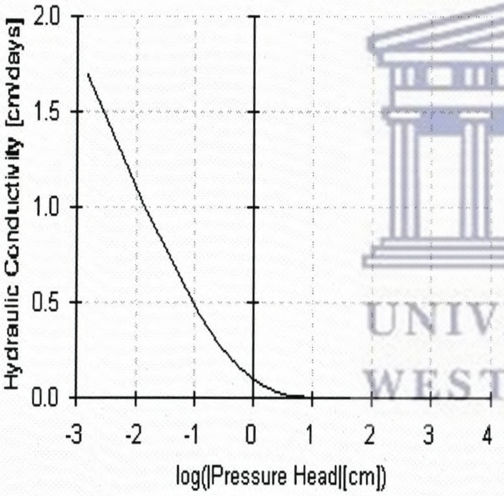

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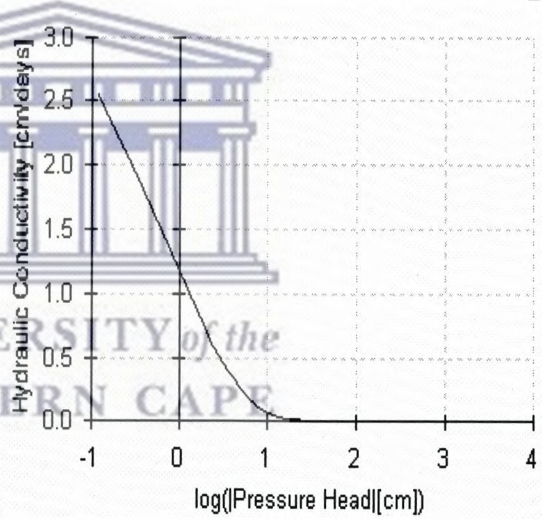

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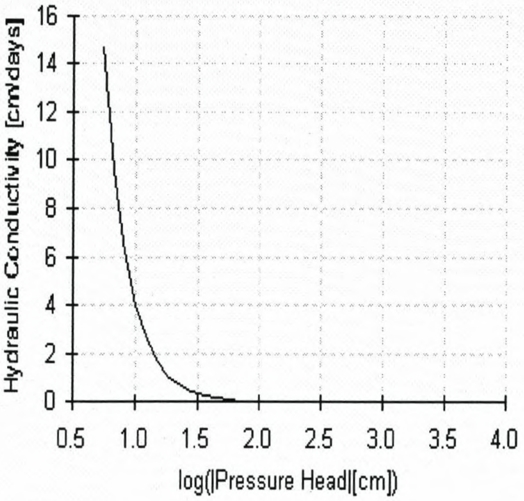

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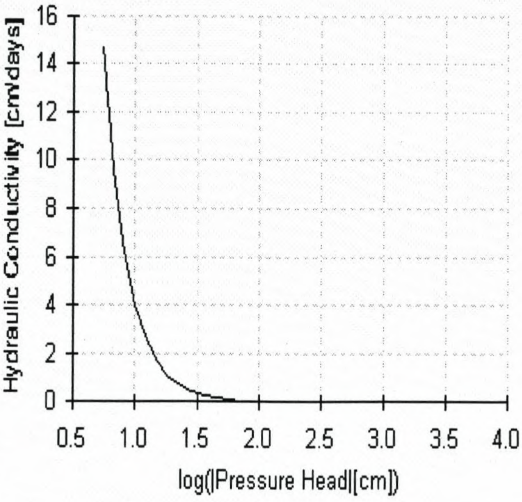

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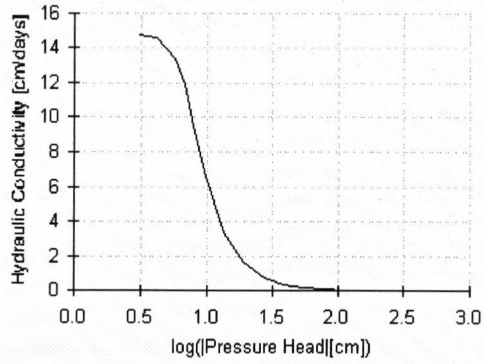
7m: Malmesbury Shale



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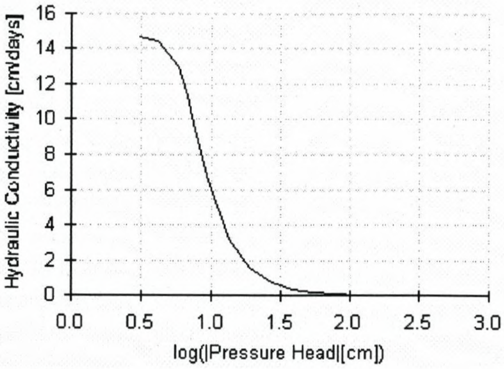

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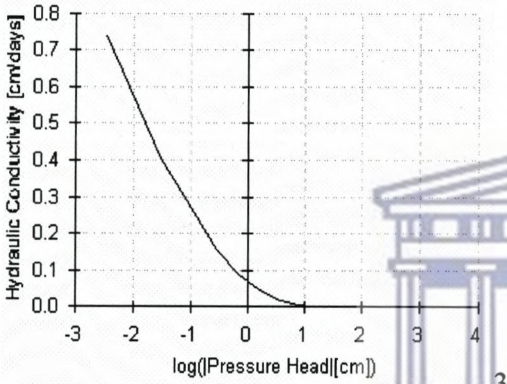

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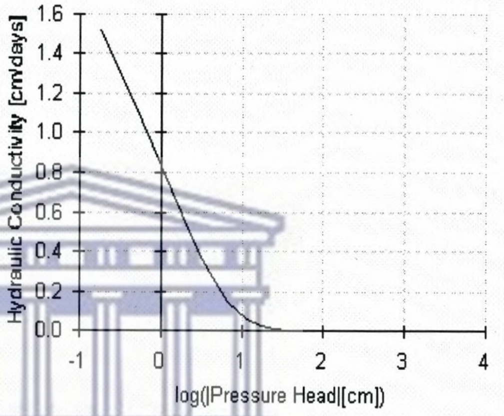

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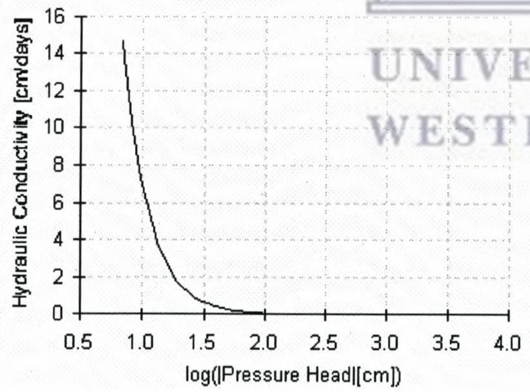

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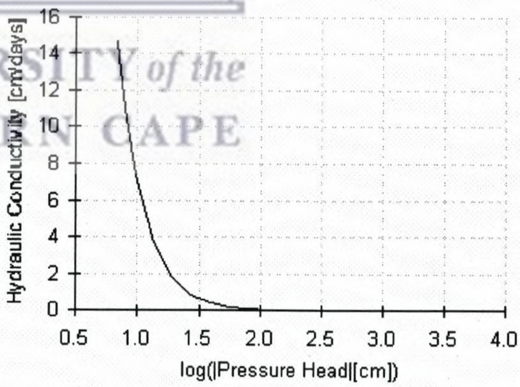

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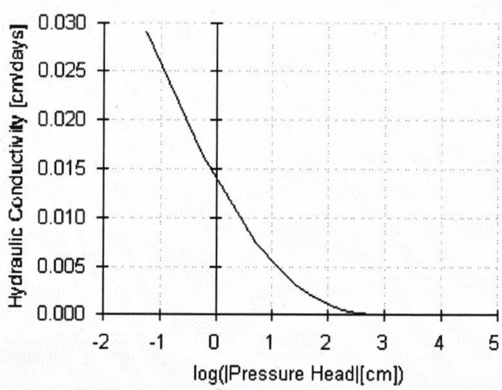
8.5m: Malmesbury Shale



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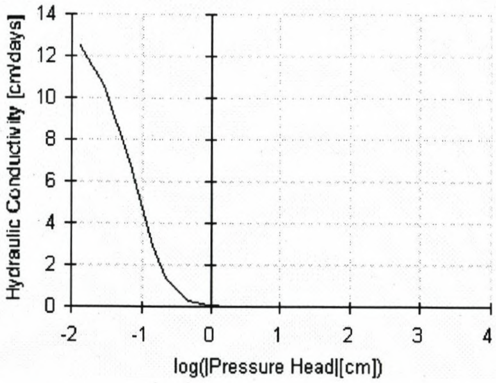

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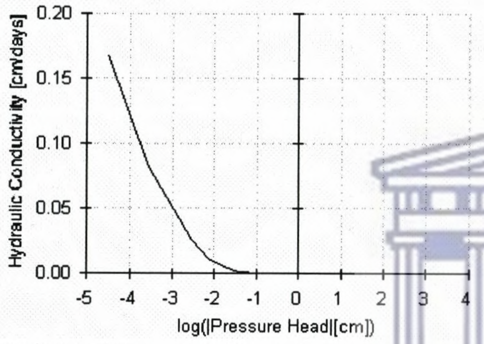

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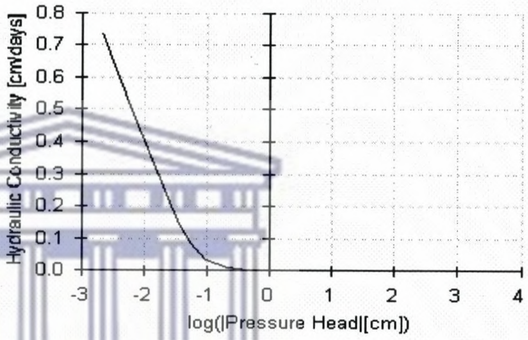

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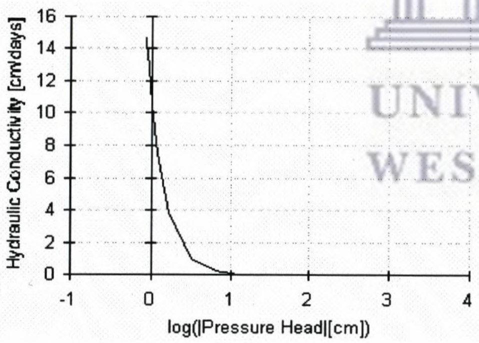

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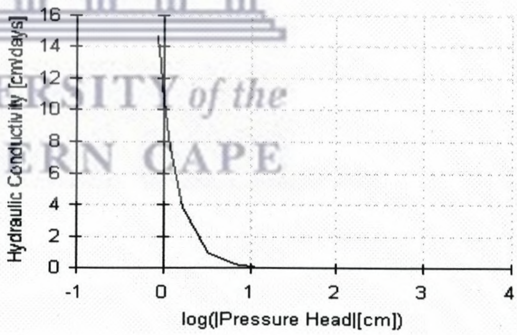
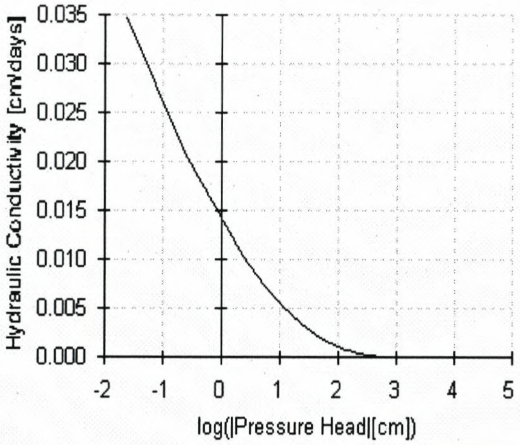


6

10.5m: Malmesbury Shale



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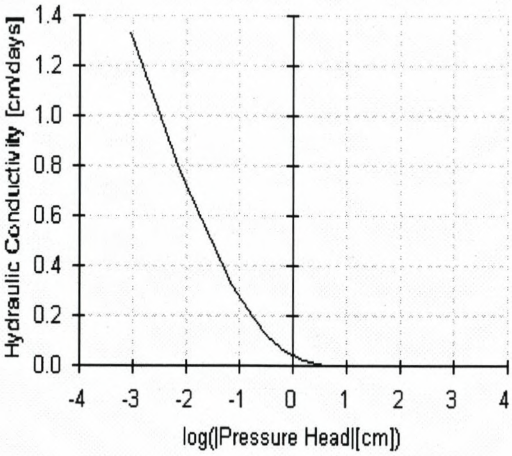

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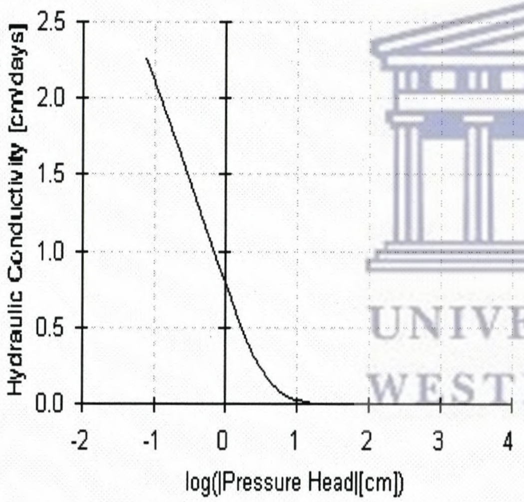

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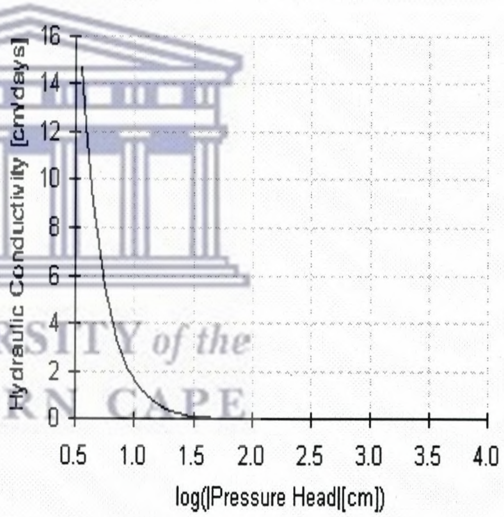

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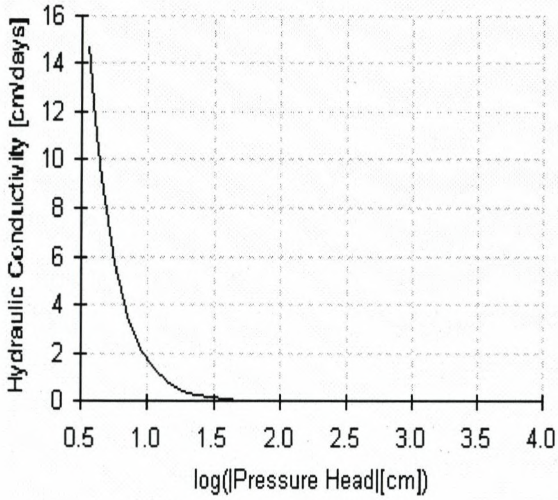

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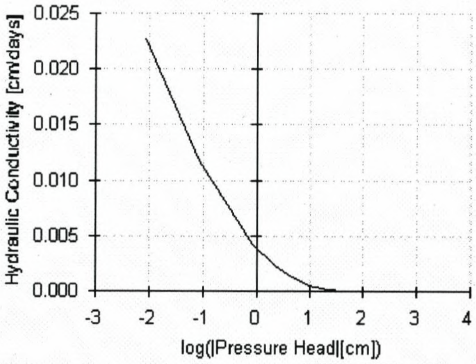
11.5m: Malmesbury Shale



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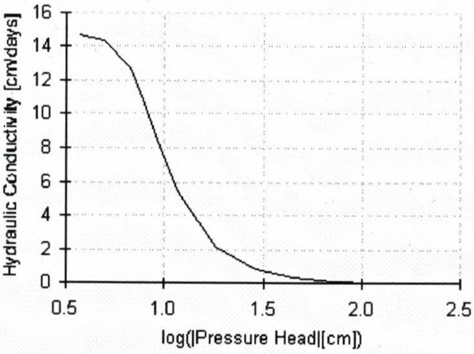

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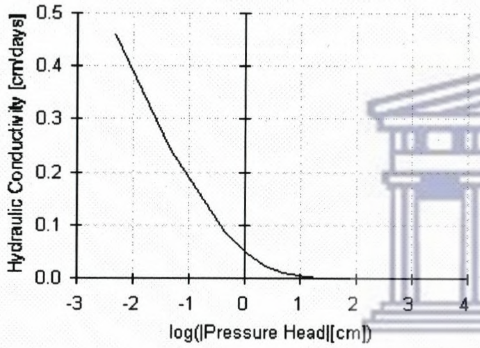

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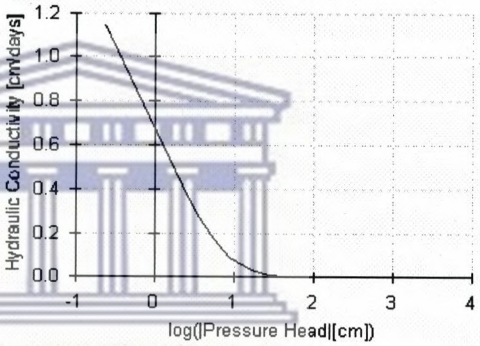

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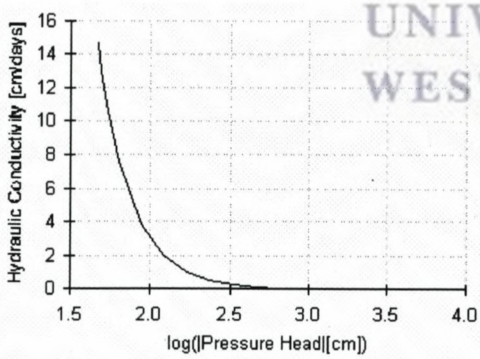

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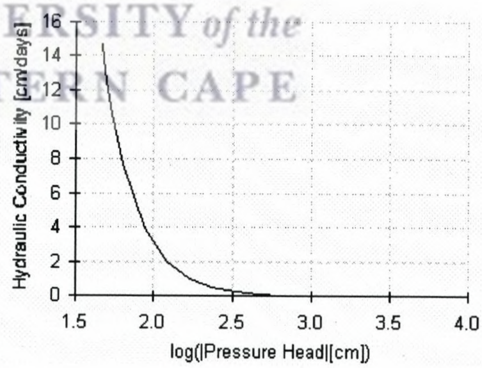

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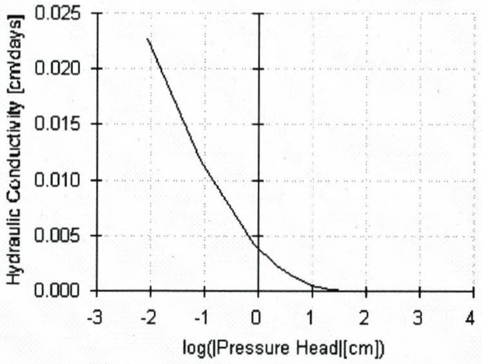
13.8m: Malmesbury Shale



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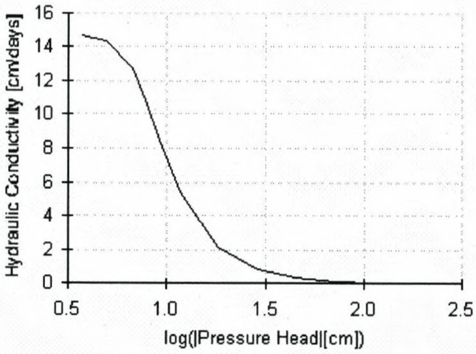

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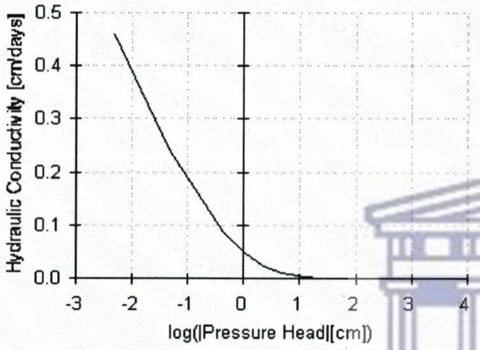

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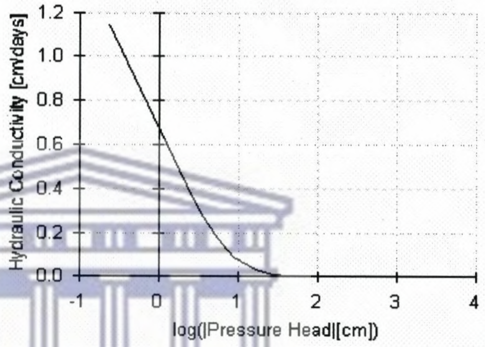

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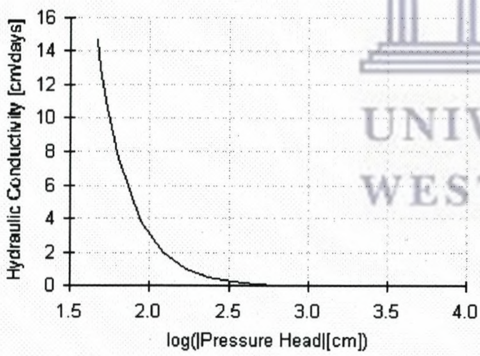

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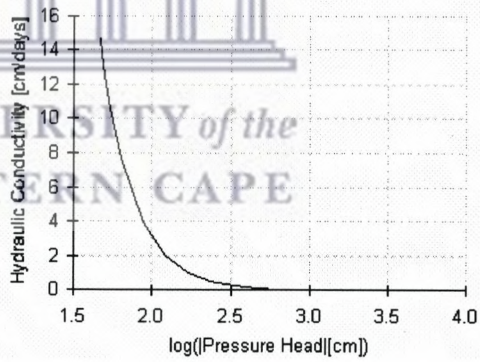

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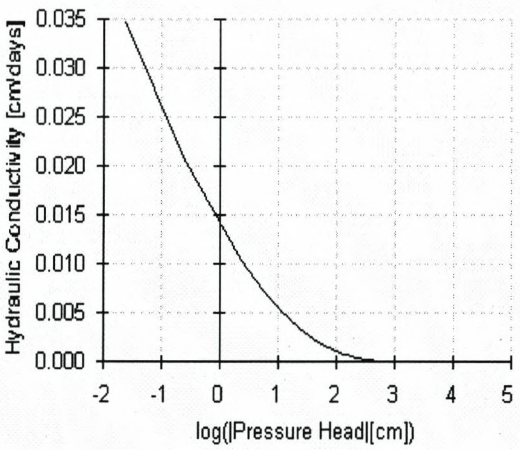
15.3m: Malmesbury Shale



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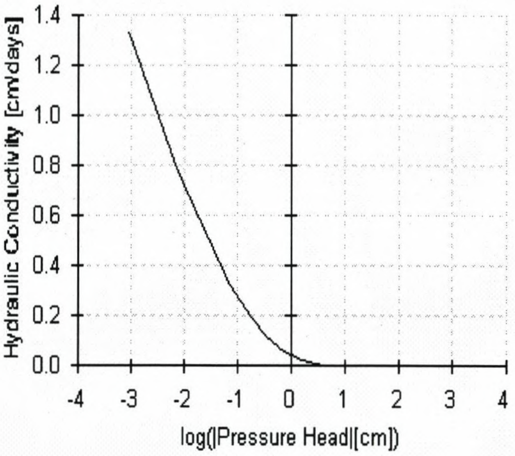

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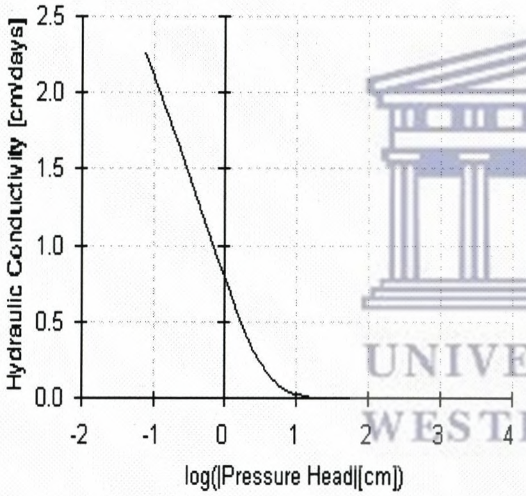

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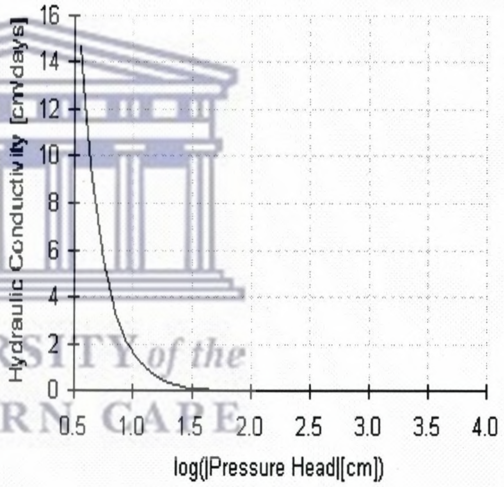

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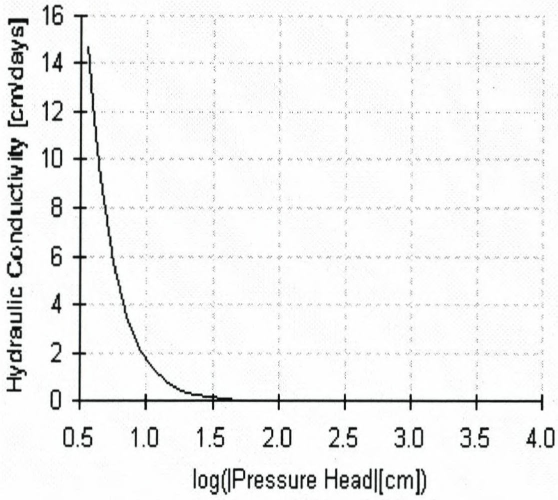

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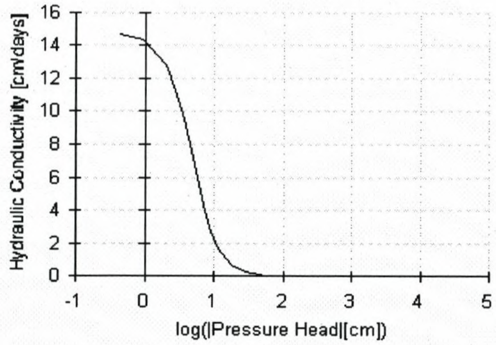
16.5m: Malmesbury Shale



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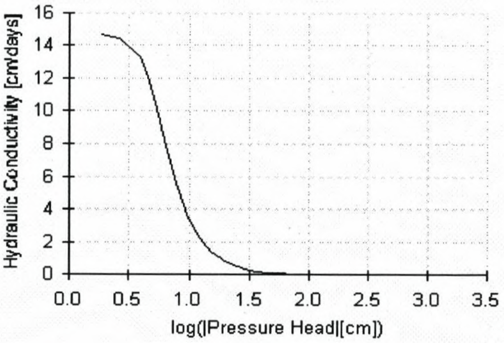

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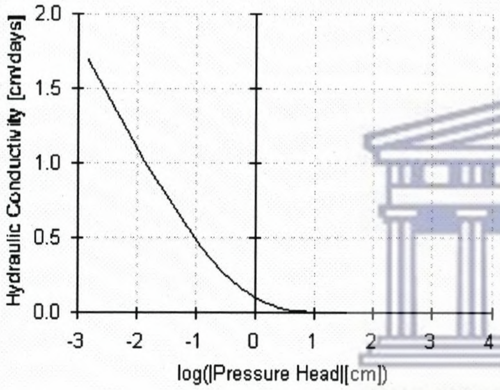

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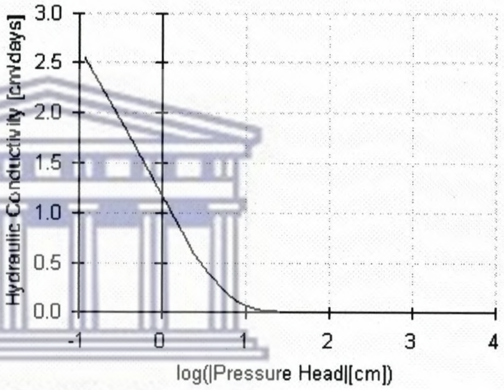

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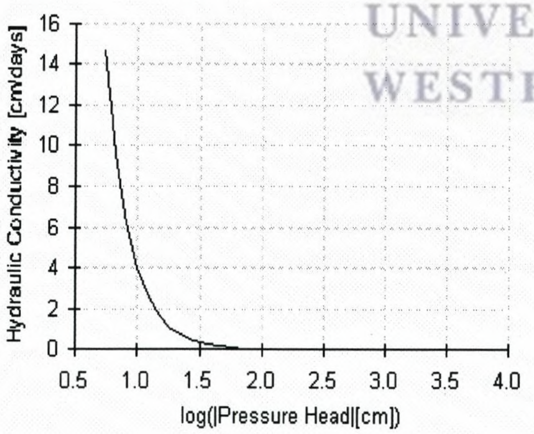

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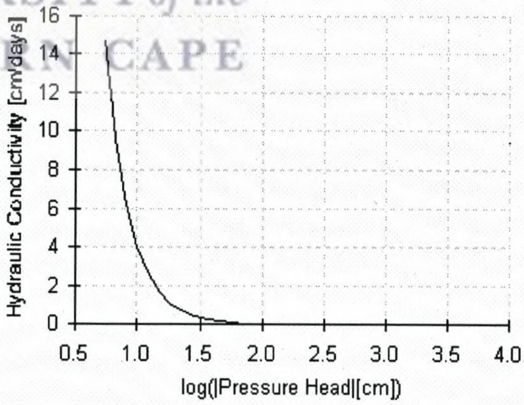

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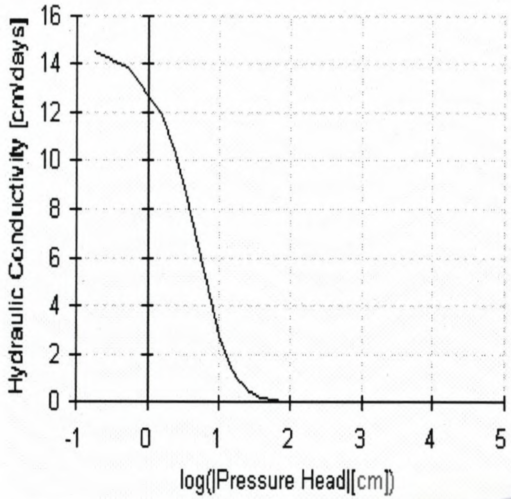
17.7m: Malmesbury Shale



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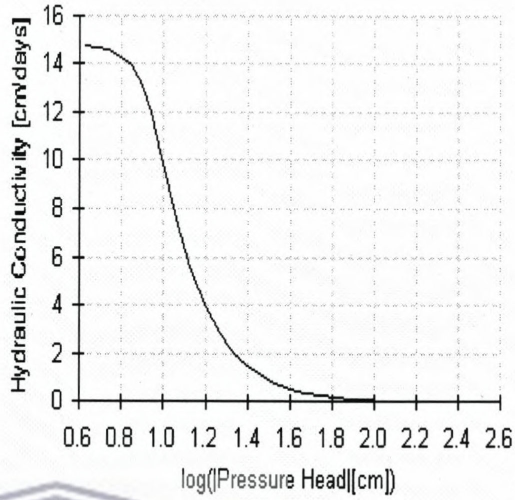

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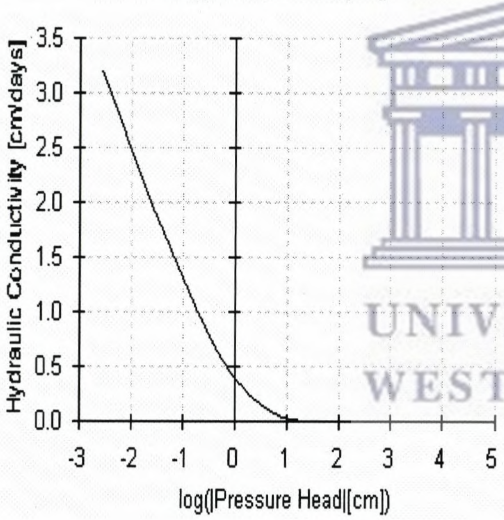

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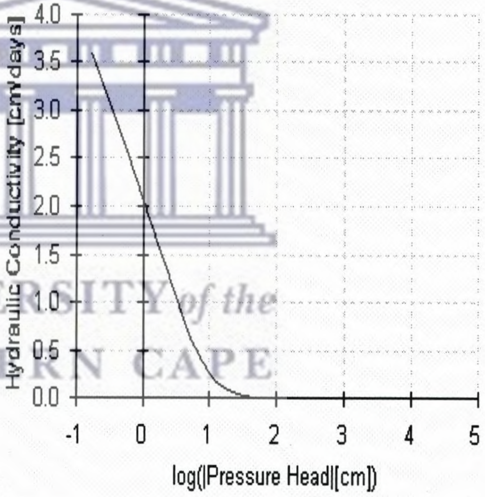

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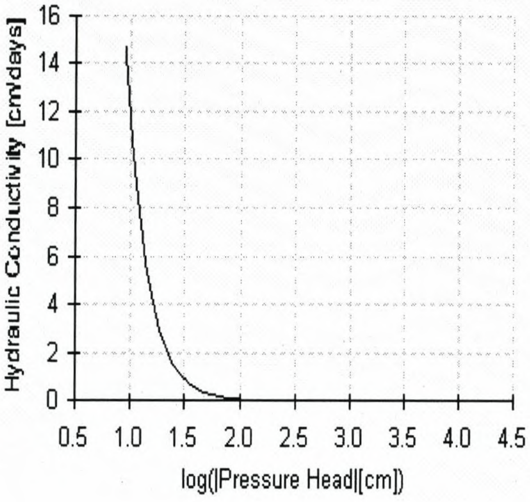

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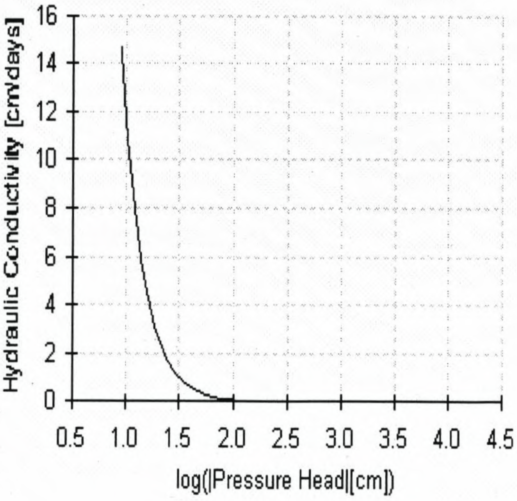

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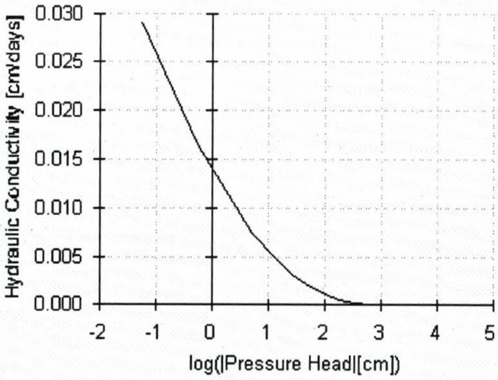
18.5m: Malmesbury Shale



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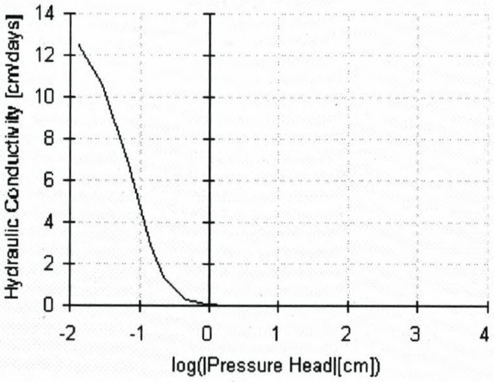

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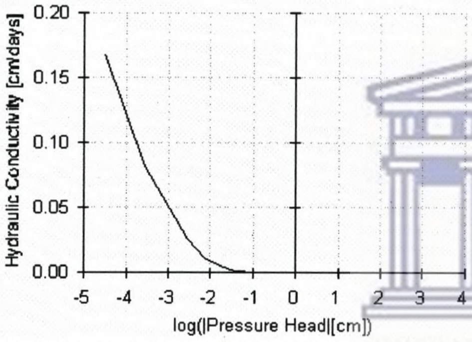

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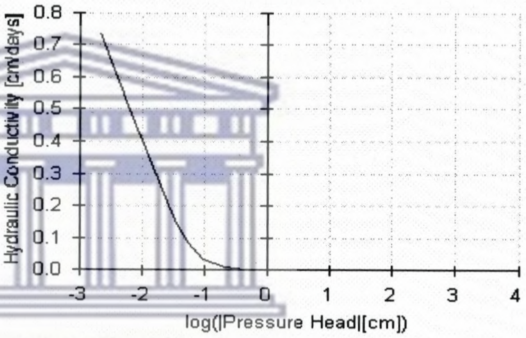

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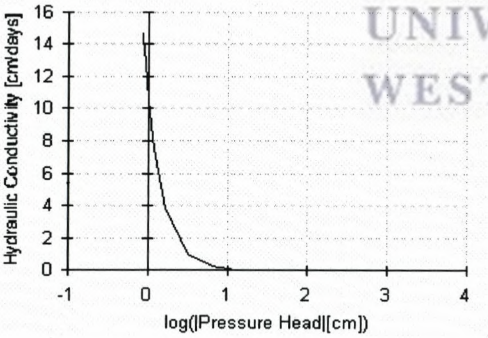

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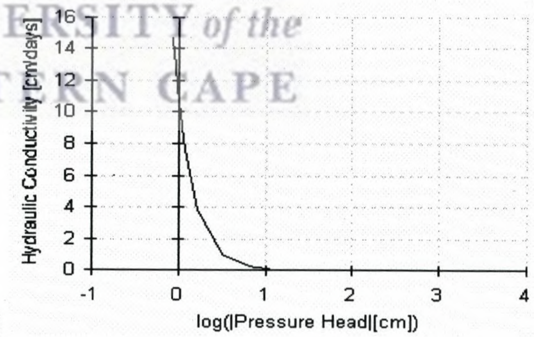
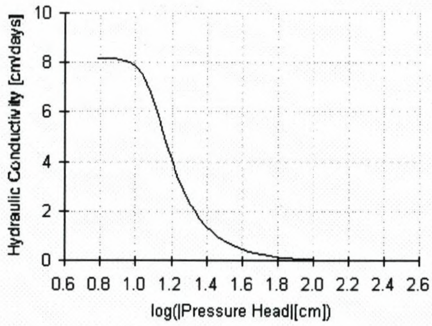


6

Bergriver site 2

Topsoil: Clay Loam



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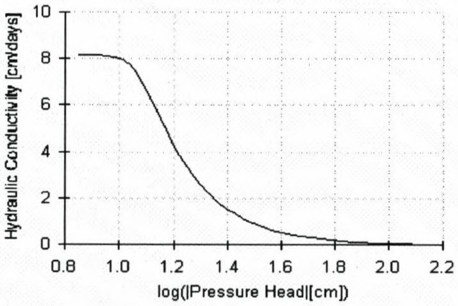

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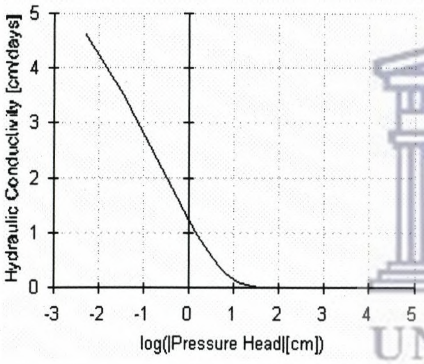

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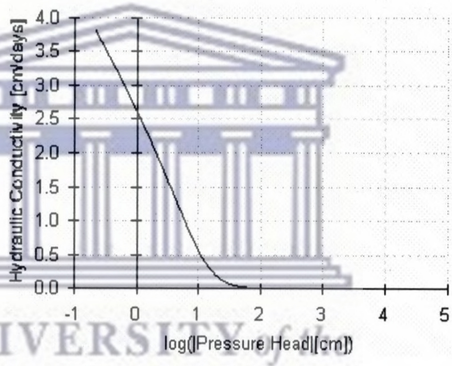

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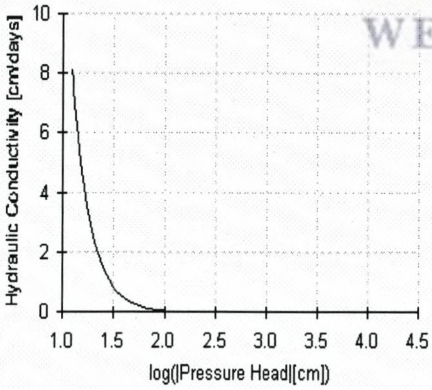

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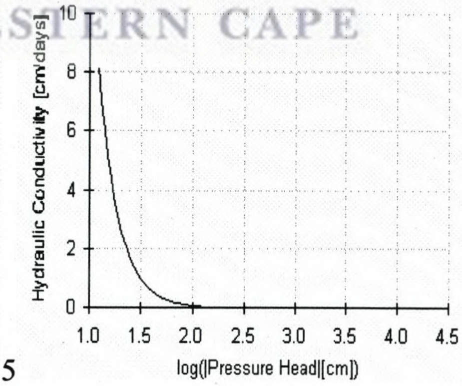

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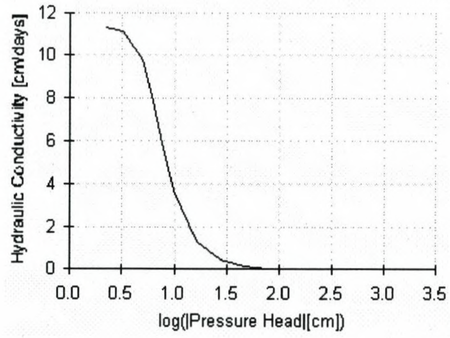
0.9m: Sandy Clay



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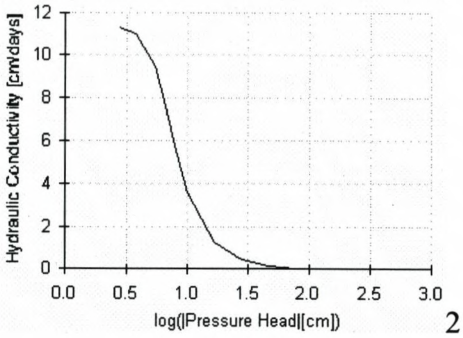

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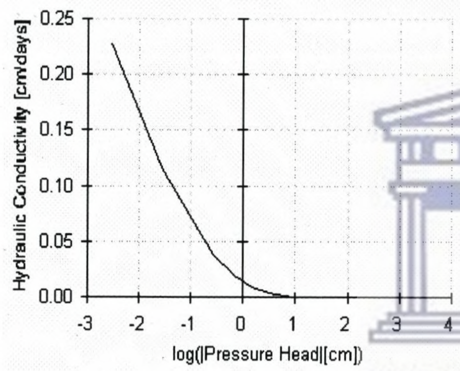

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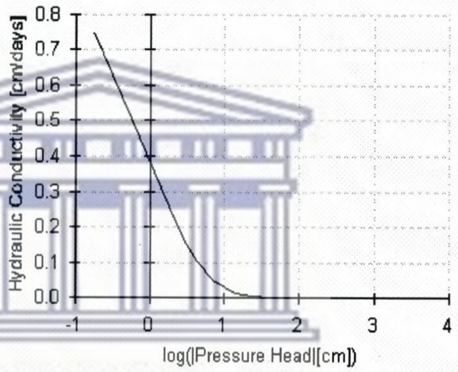

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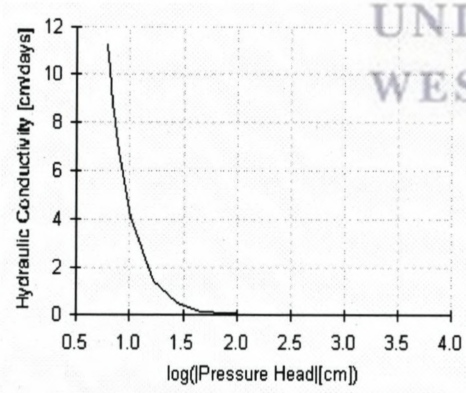

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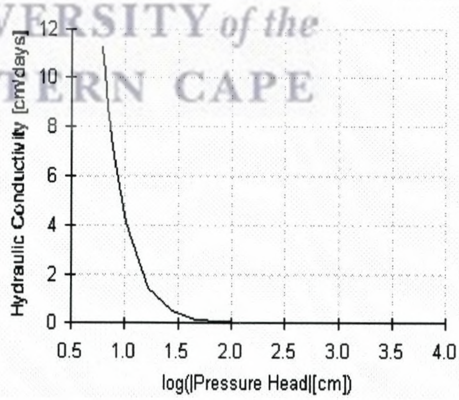

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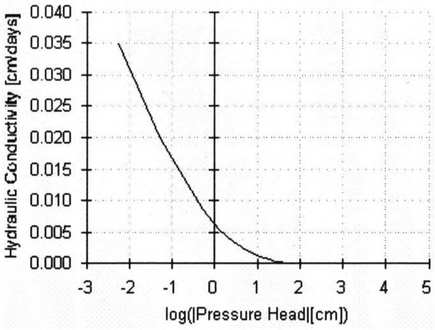
2.2m: Silt Loam



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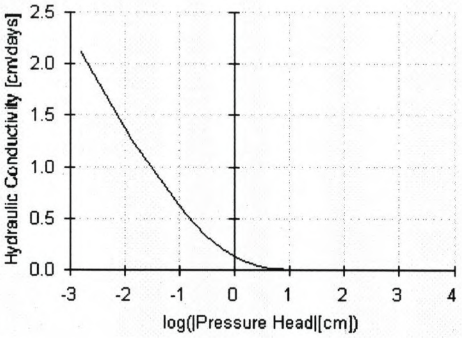

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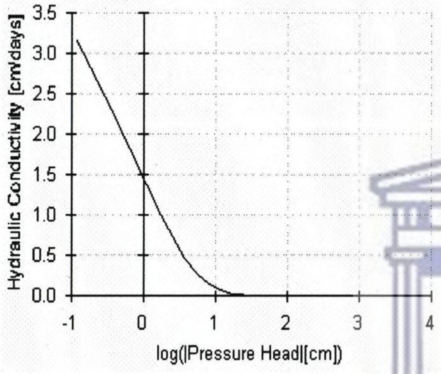

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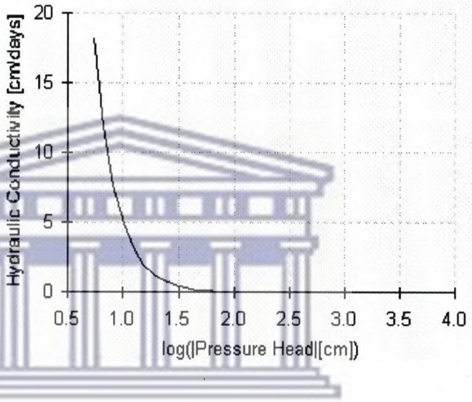

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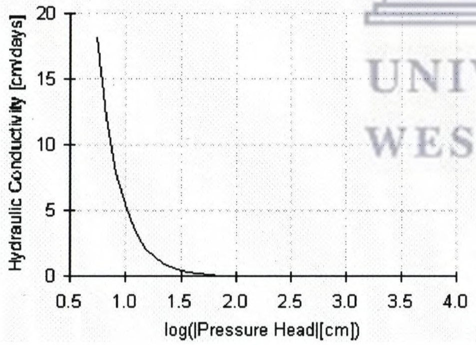

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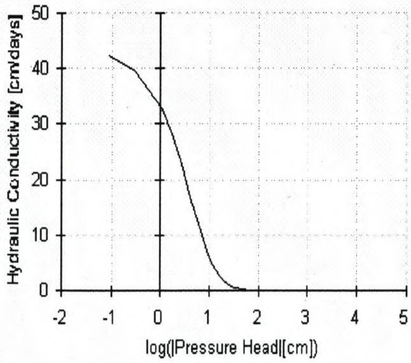

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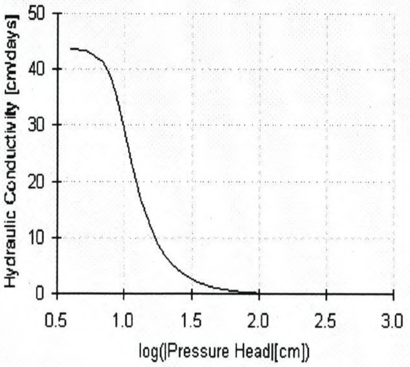

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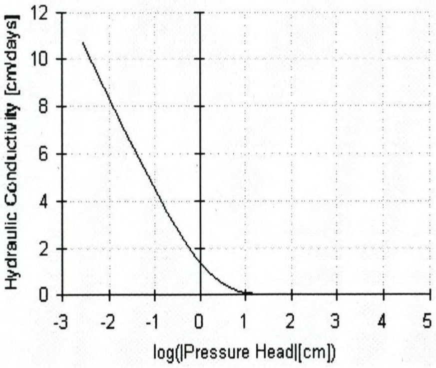

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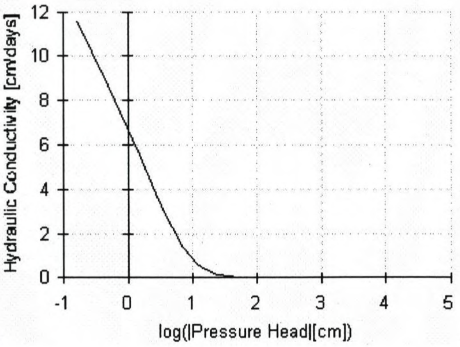

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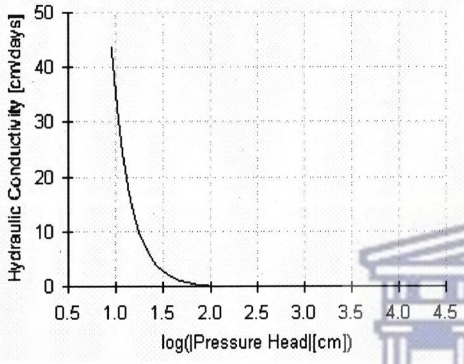

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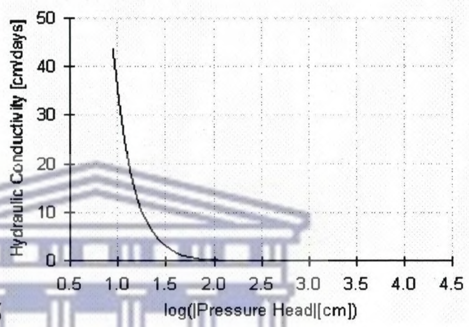

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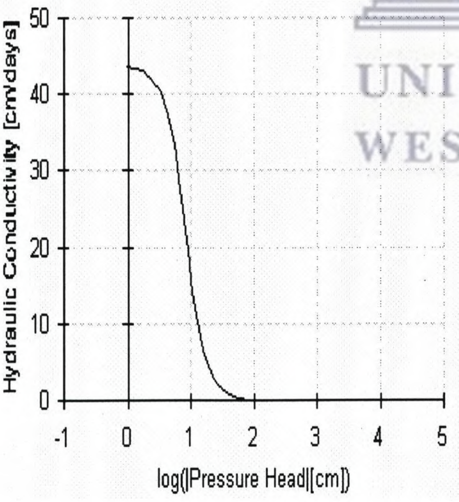

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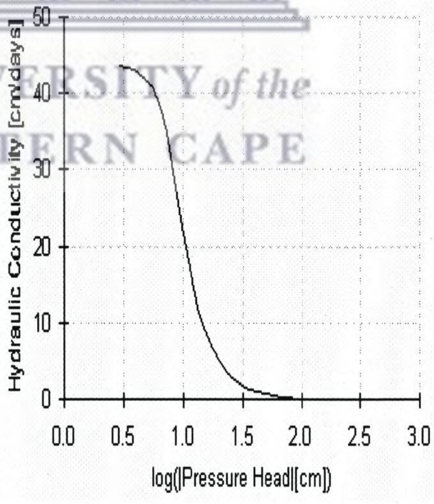

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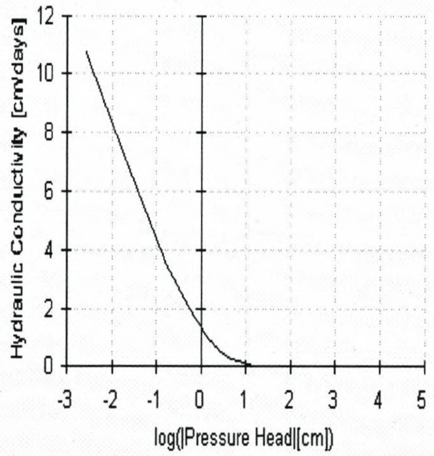

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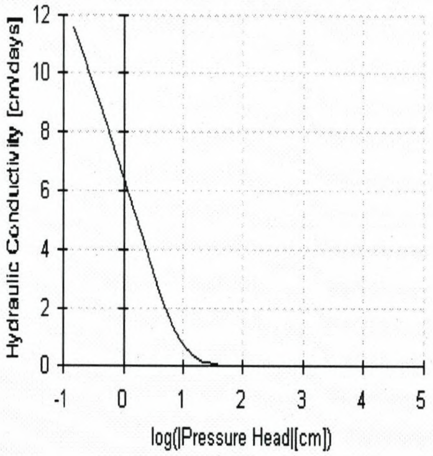

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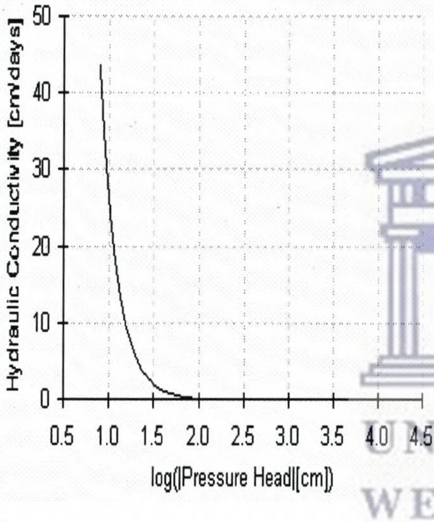

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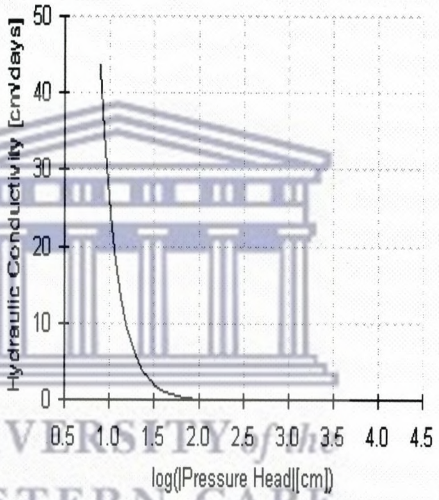

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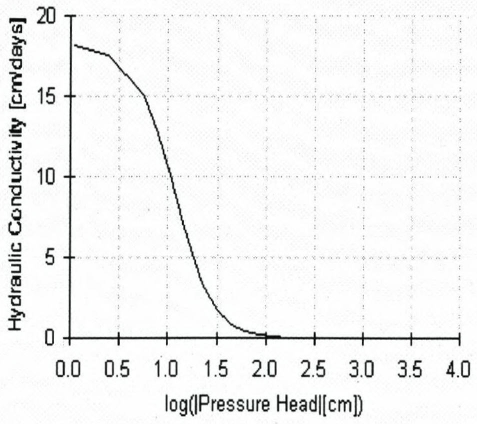
5m: Silt Loam



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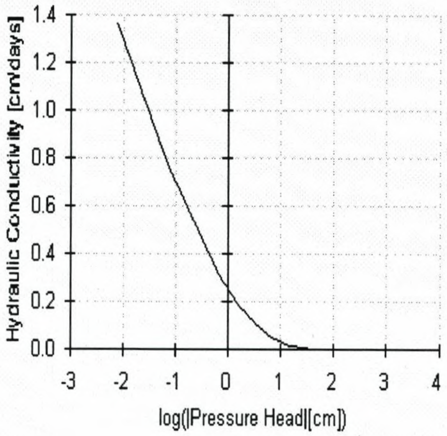

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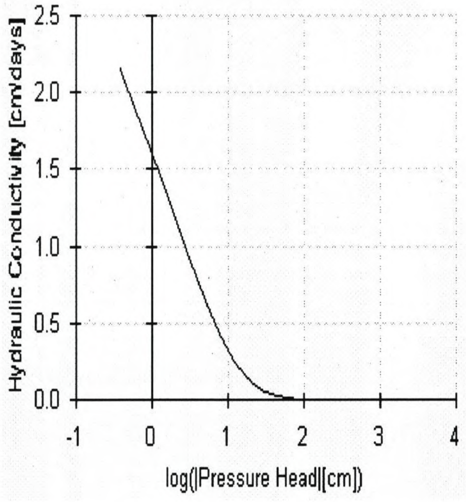

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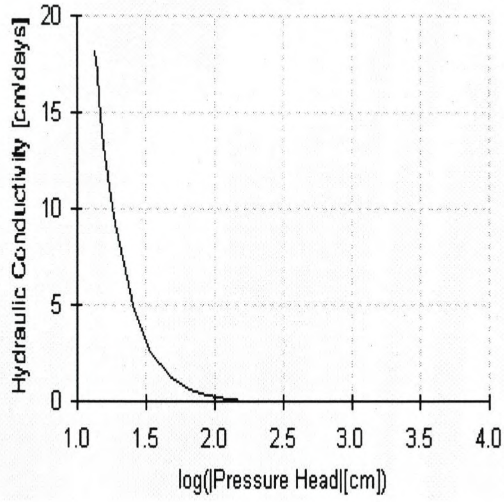

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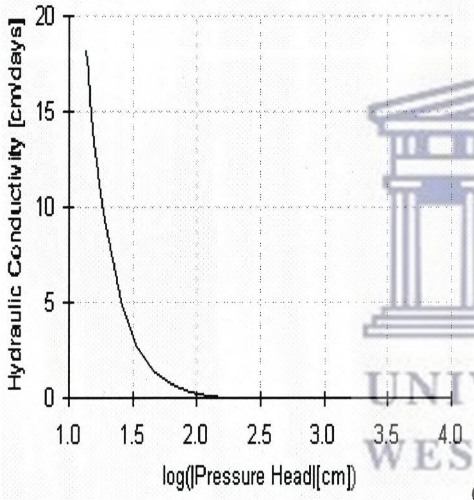
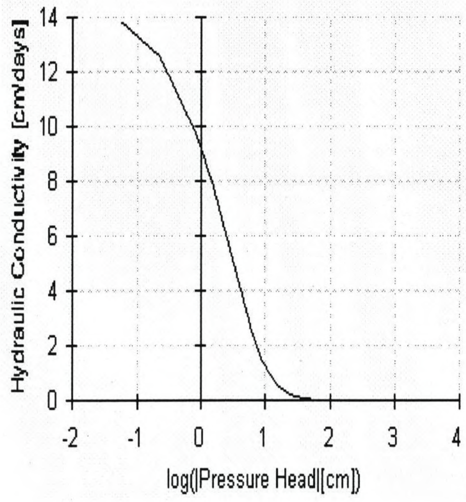


6

6.5m: Clay



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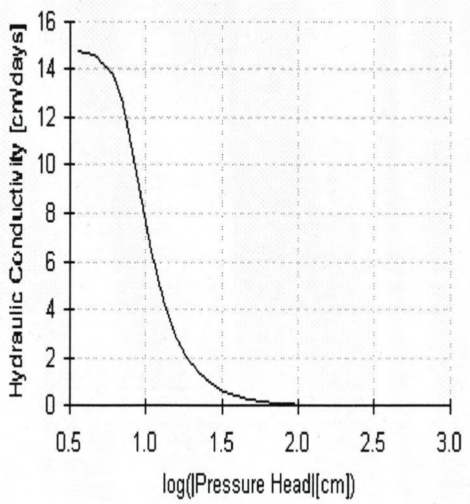

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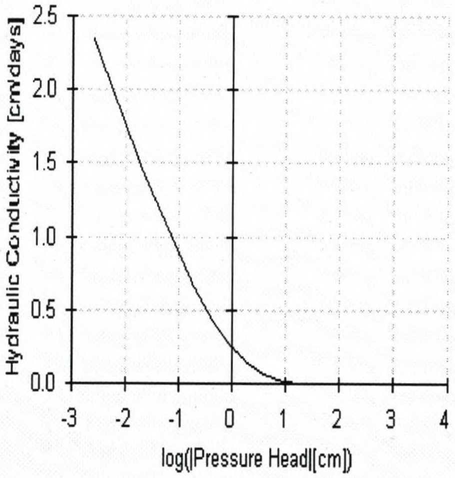

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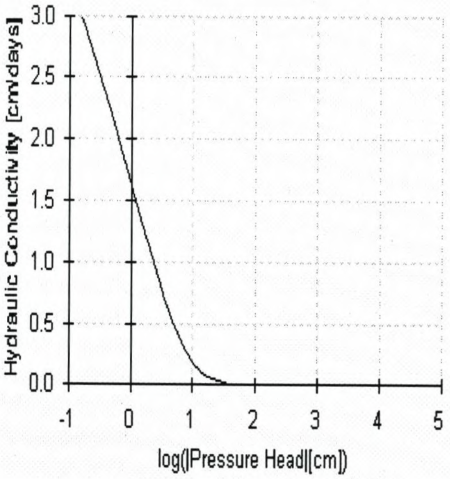

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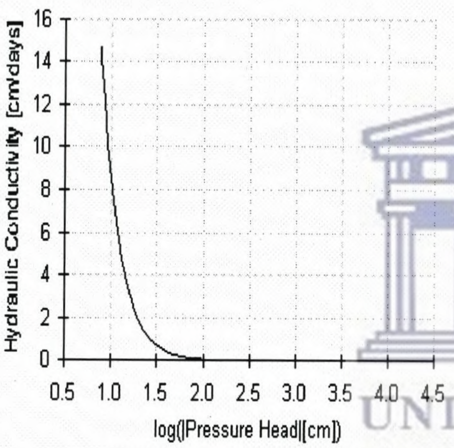

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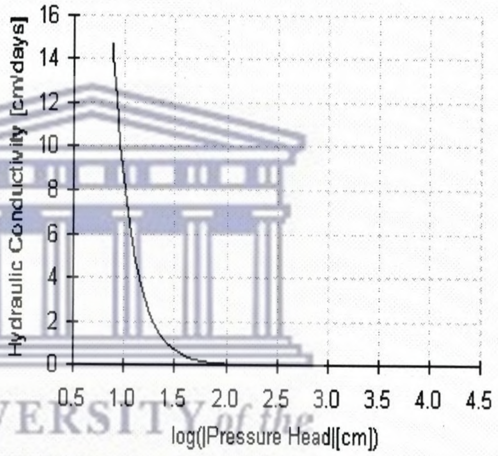
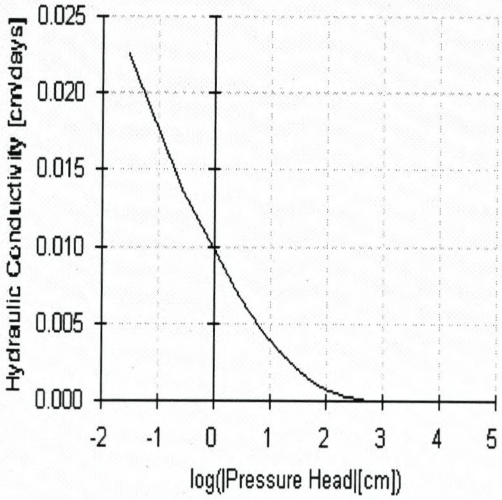


6

7.5m: Silty Clay



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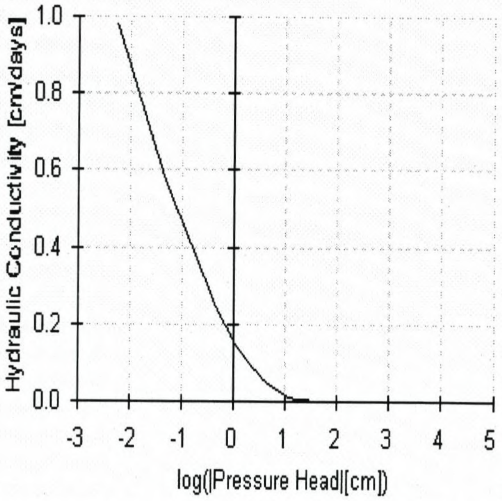

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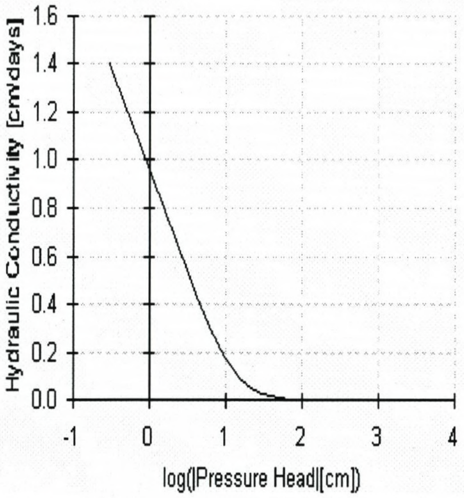
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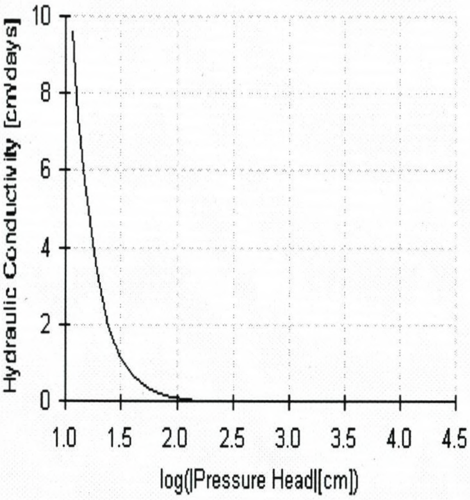
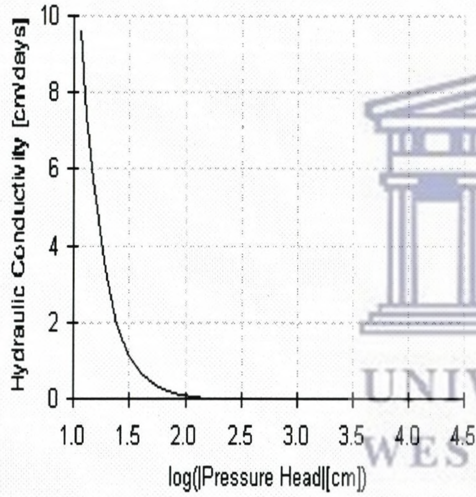
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-1
0
1
2
3
4
log(|Pressure Head|[cm])

4

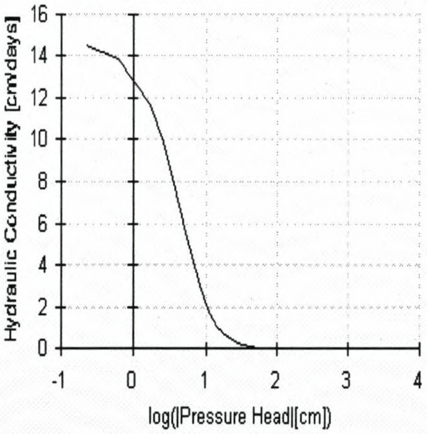

Hydraulic Conductivity [cm/days]
10
8
6
4
2
0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
log(|Pressure Head|[cm])

5


Hydraulic Conductivity [cm/days]
10
8
6
4
2
0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
log(|Pressure Head|[cm])

6

8.2m : Clay



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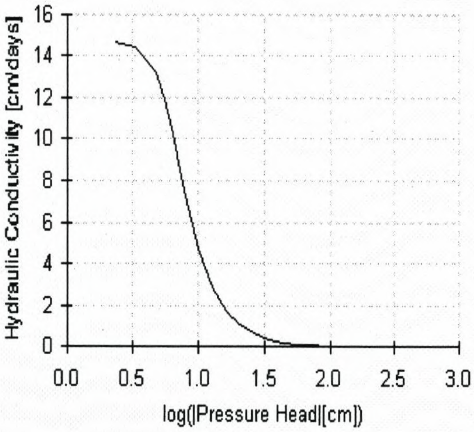

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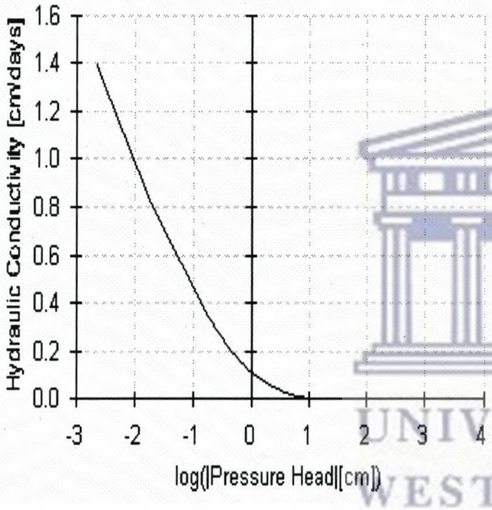

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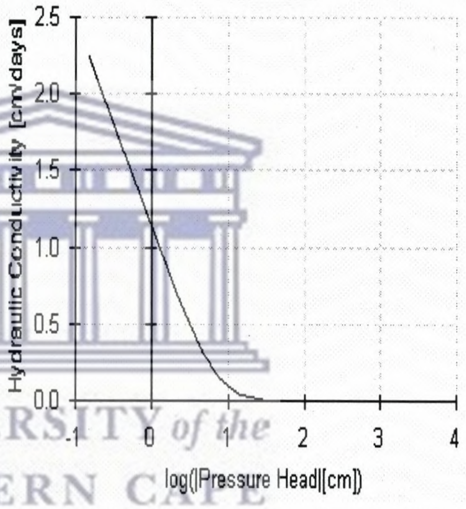

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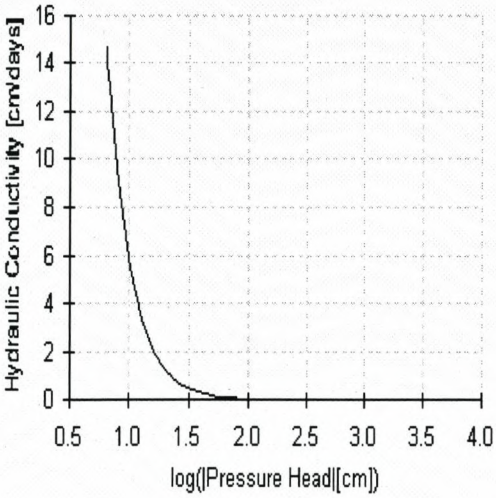

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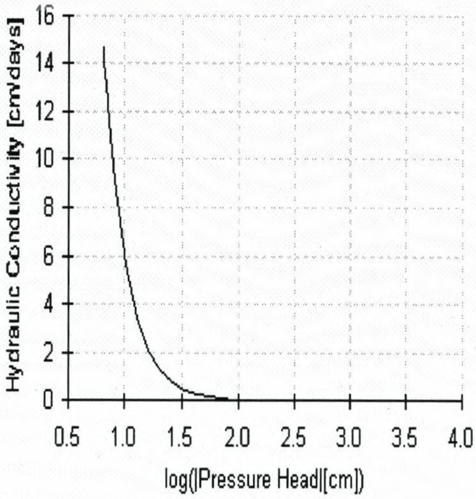
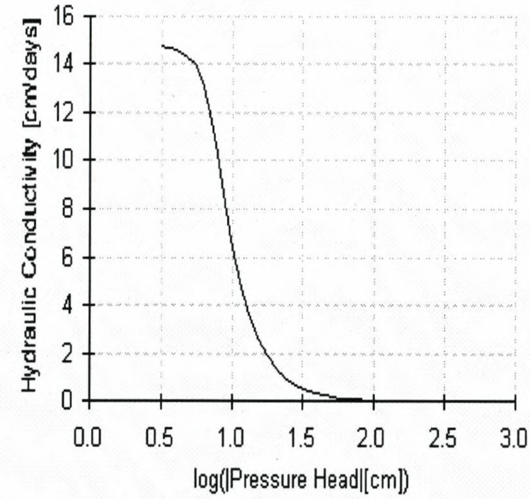


6

10m: Malmesbury Shale



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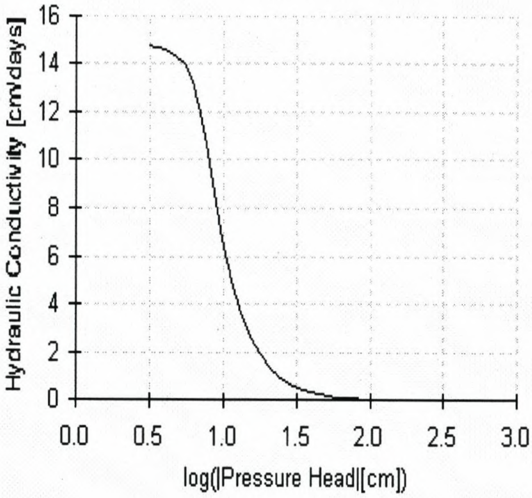

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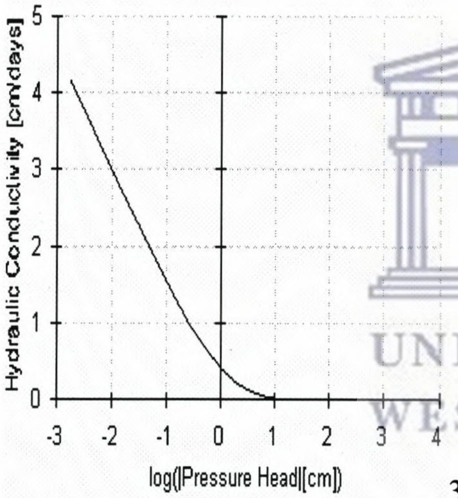

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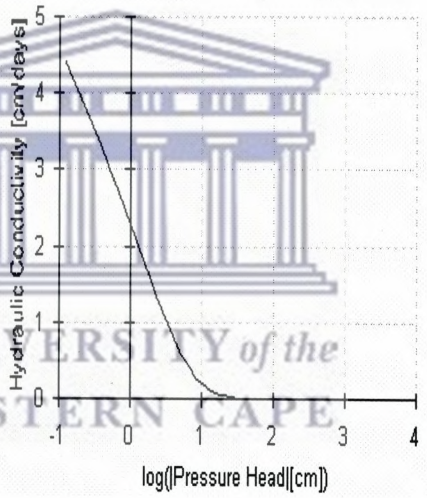

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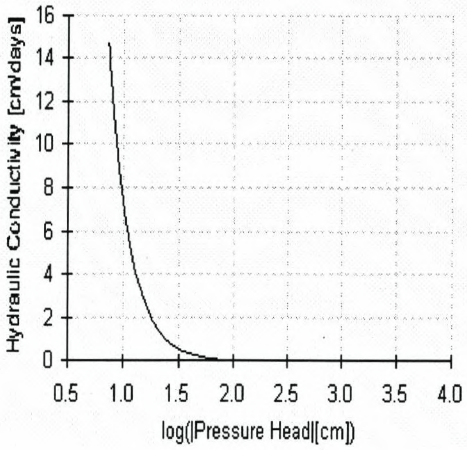

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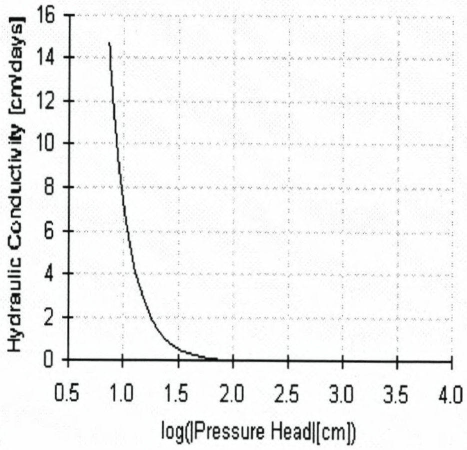
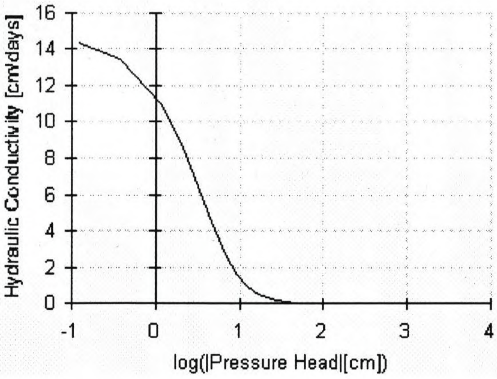


6

10.8m: Malmesbury Shale



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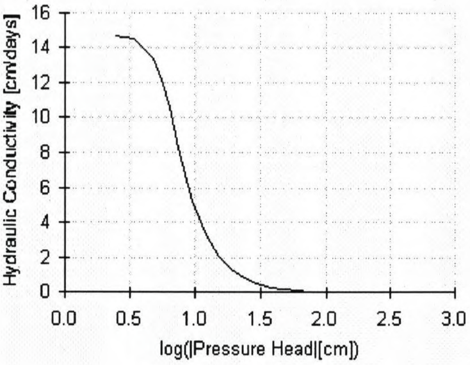

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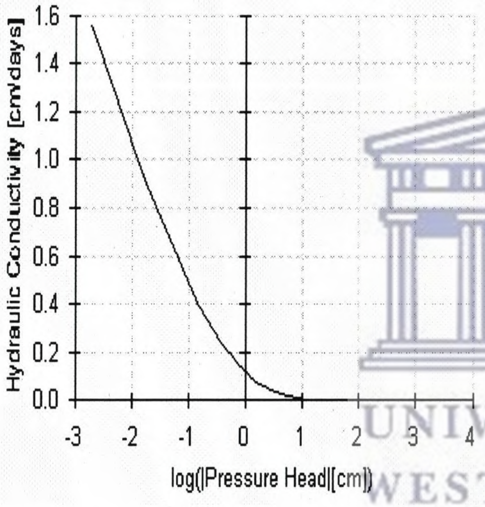

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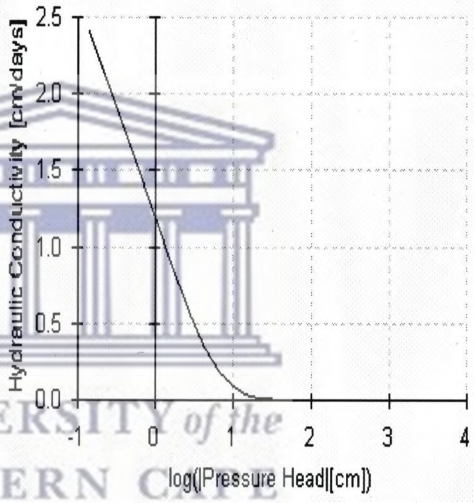

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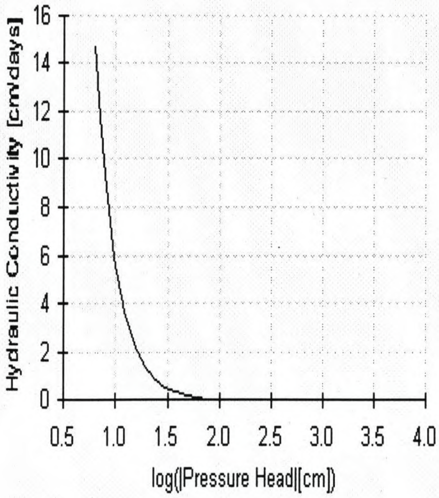

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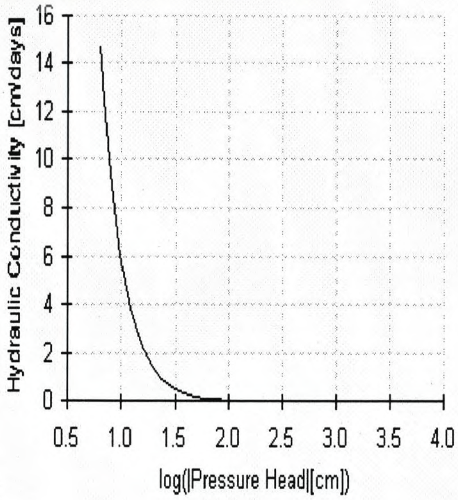
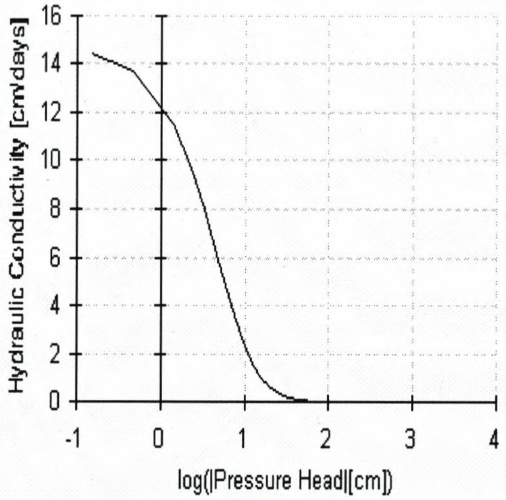


6

11.5m: Malmesbury Shale



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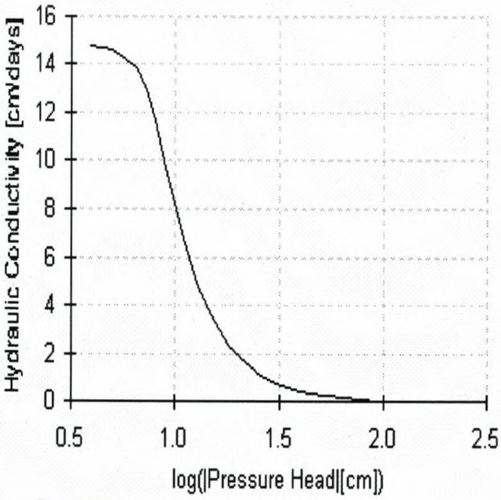

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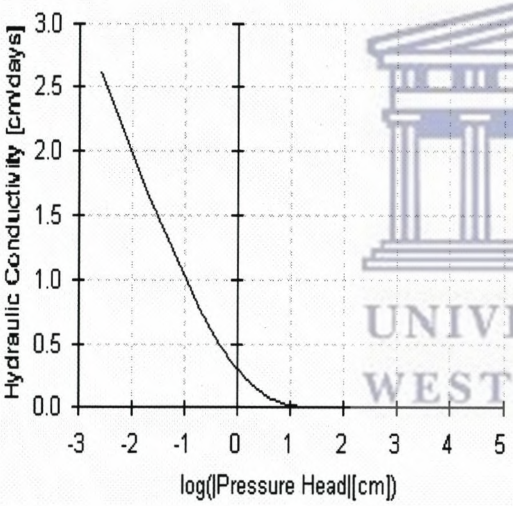

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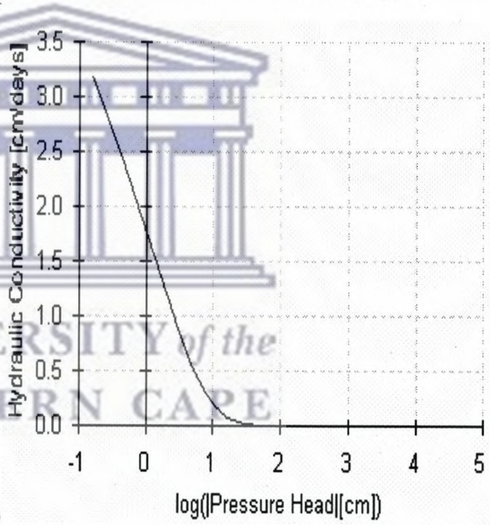

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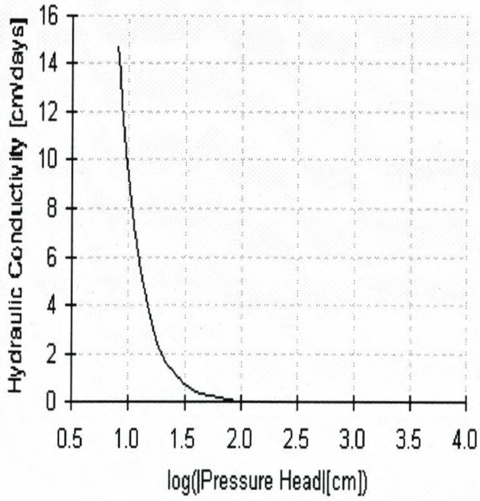

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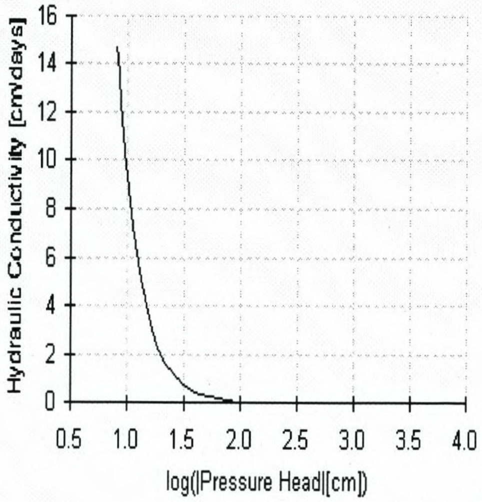

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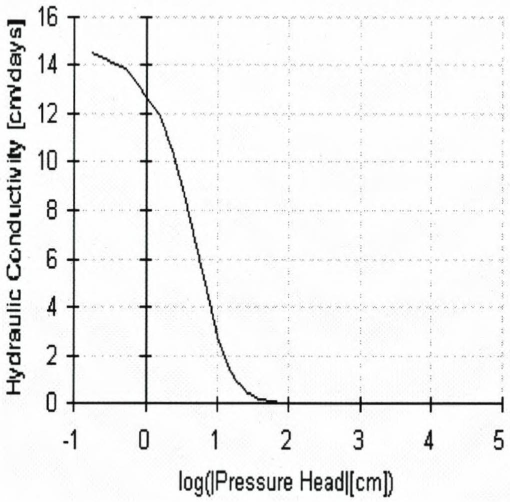
12.5m: Malmesbury Shale



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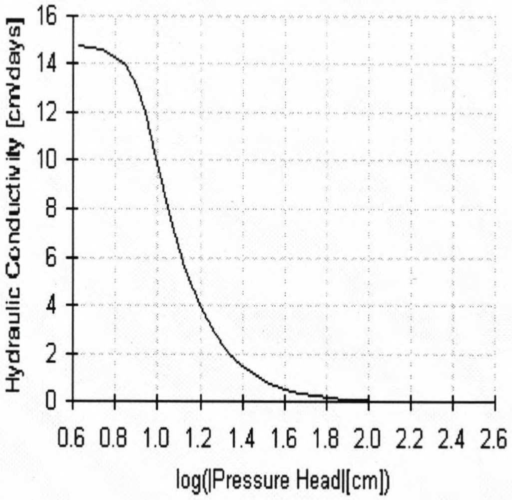

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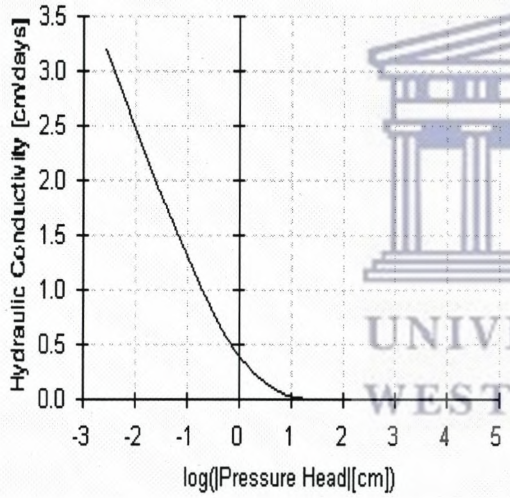

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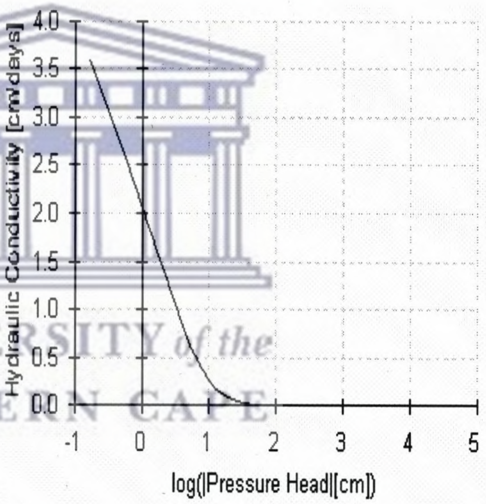

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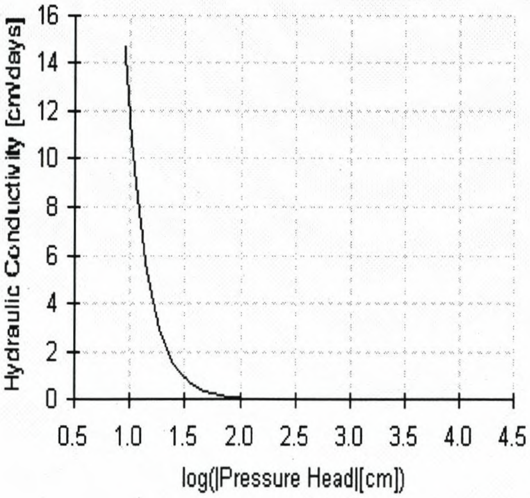

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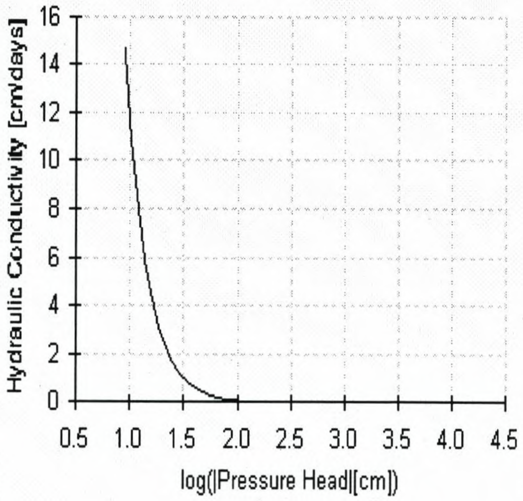
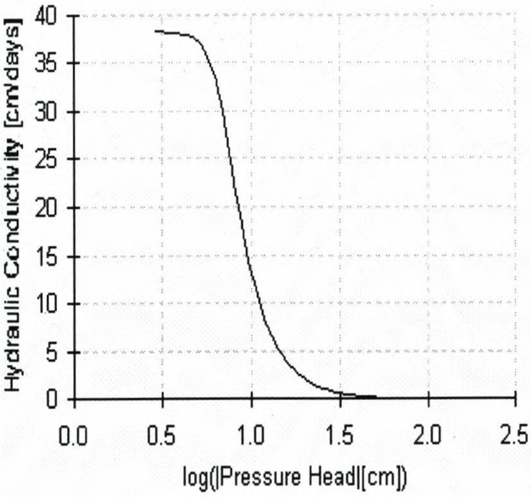


6

15m: Sandy Loam



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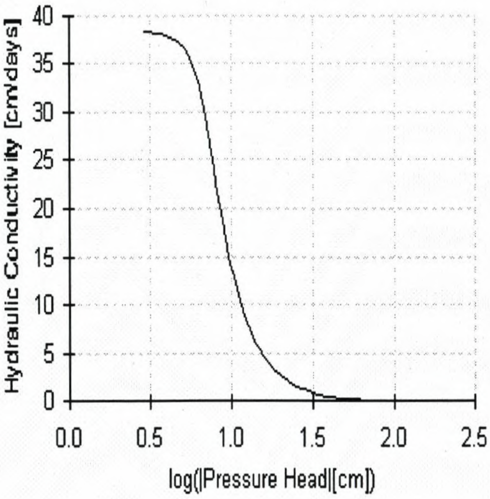

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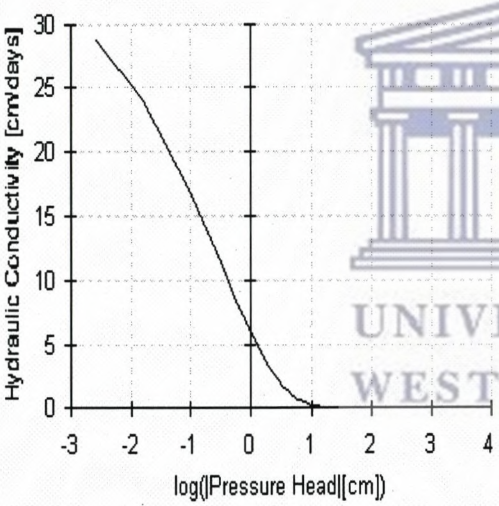

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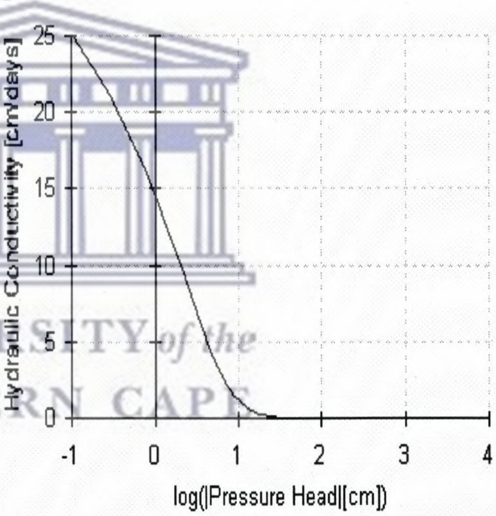

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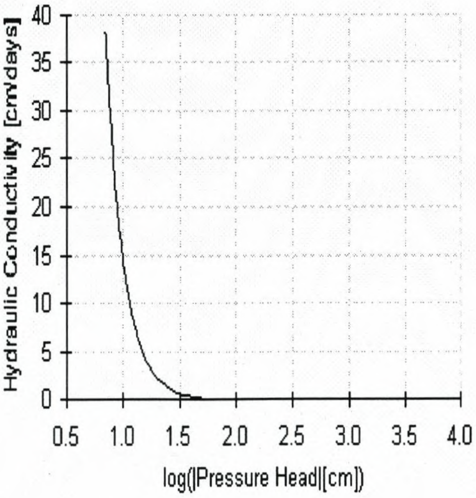

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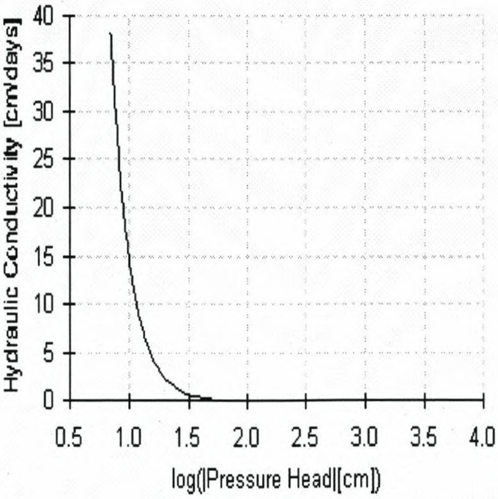
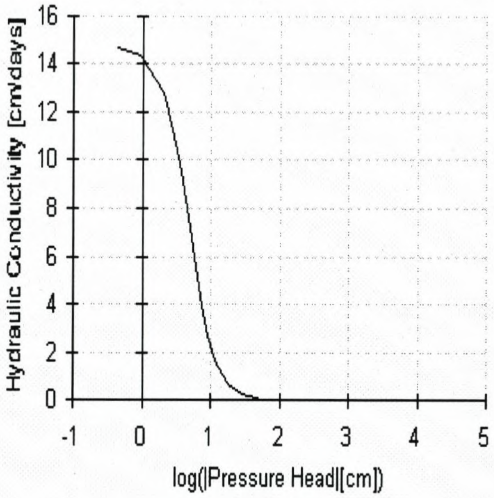


6

16.2m: Malmesbury Shale



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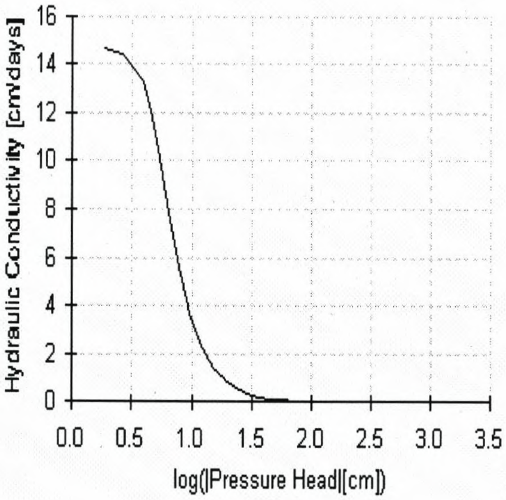

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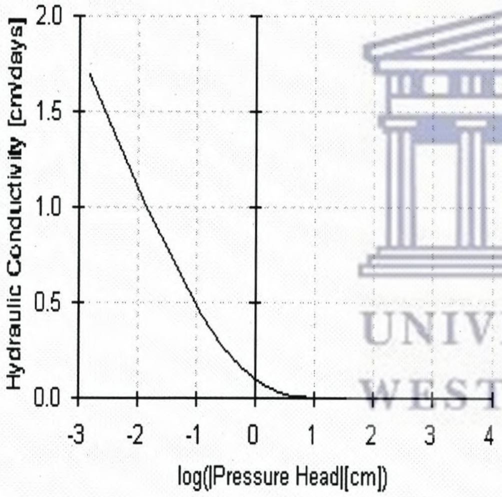

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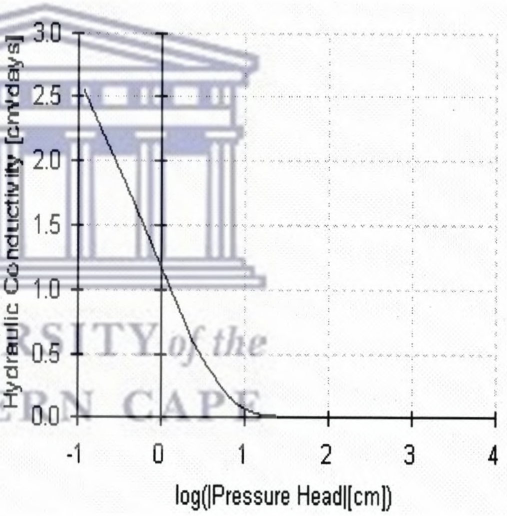

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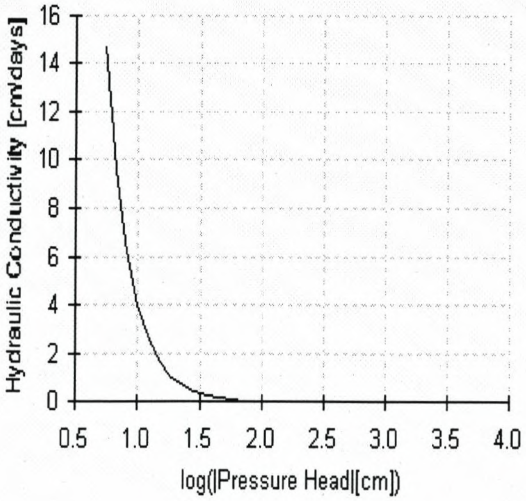

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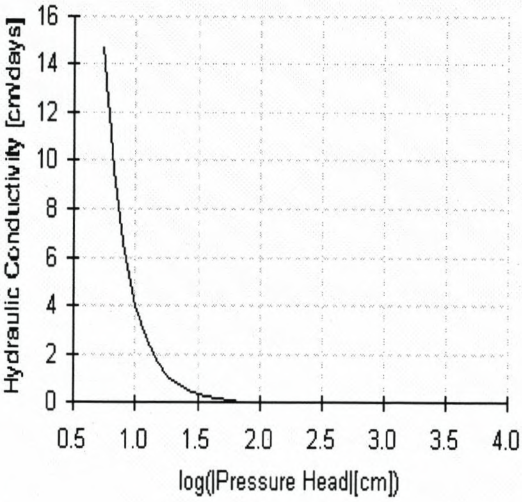
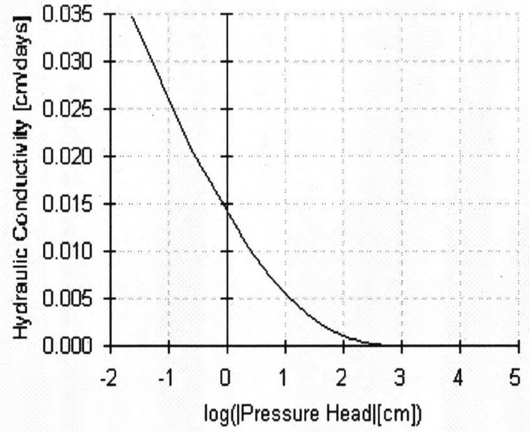


6

17.5m: Malmesbury Shale



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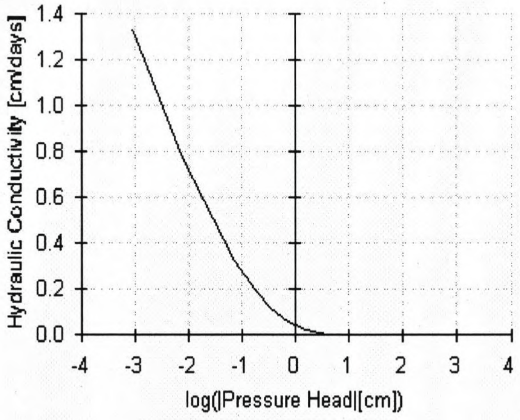

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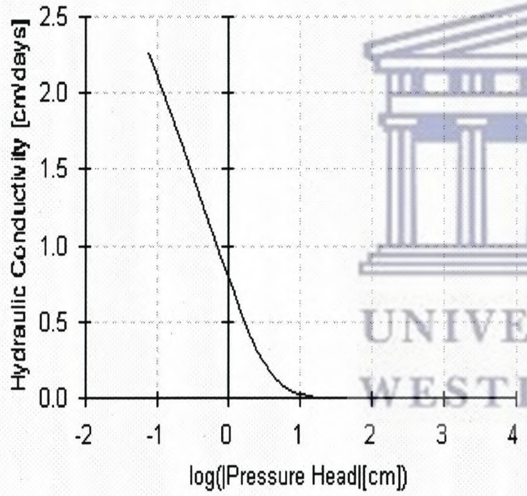

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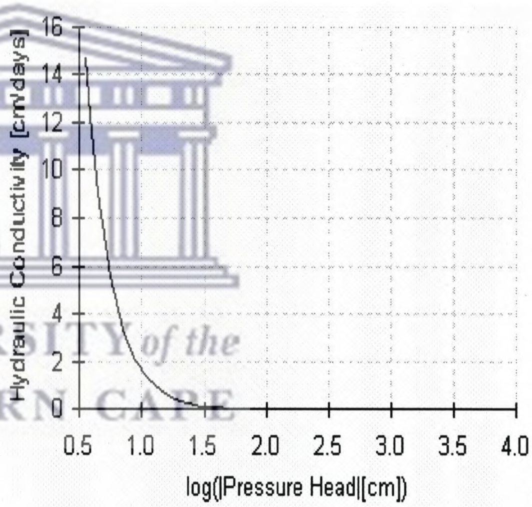

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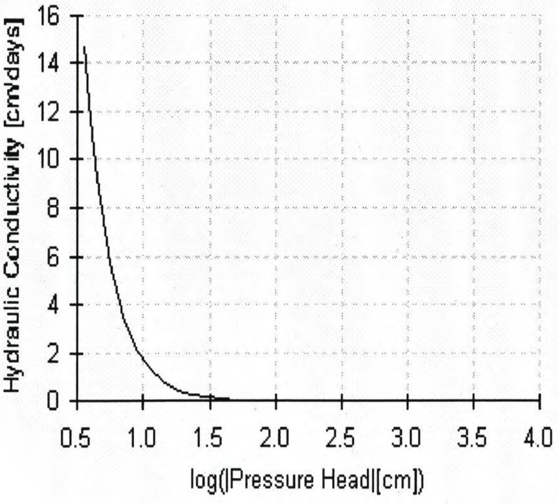

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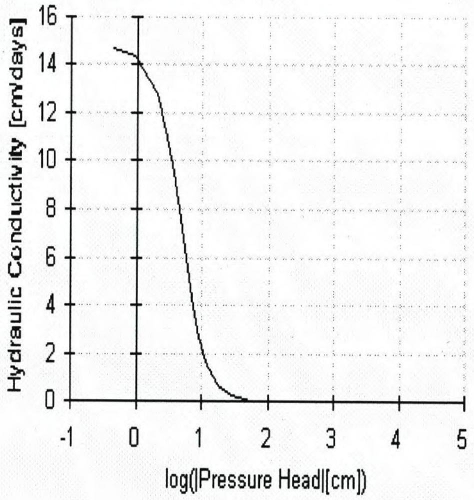
18.5m: Malmesbury Shale



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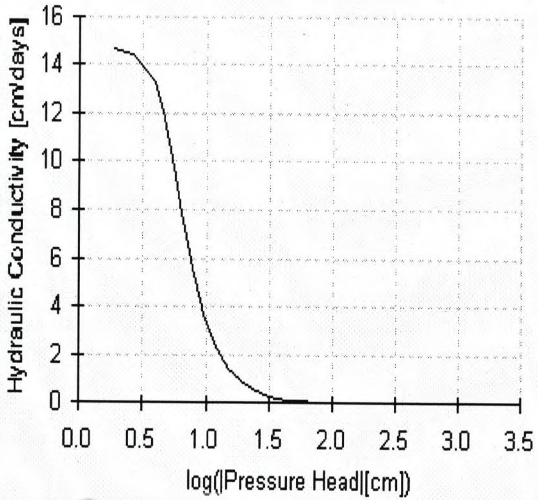

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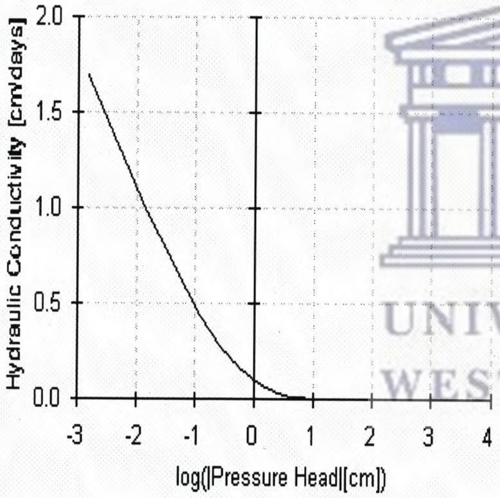

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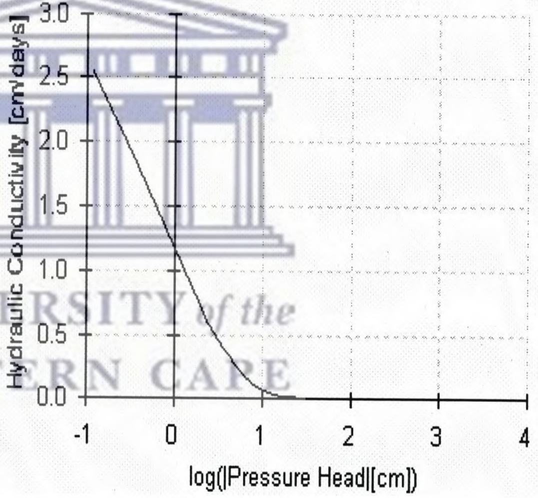

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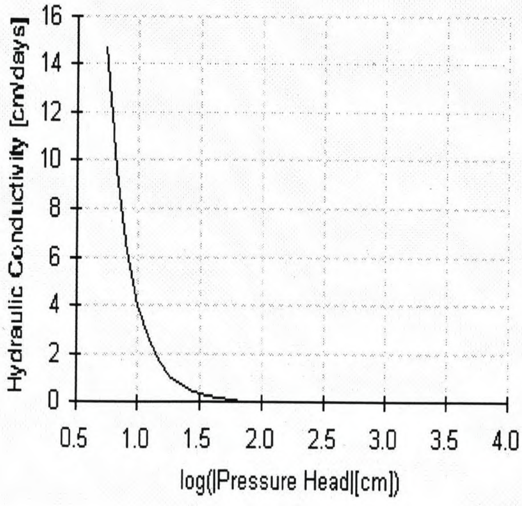

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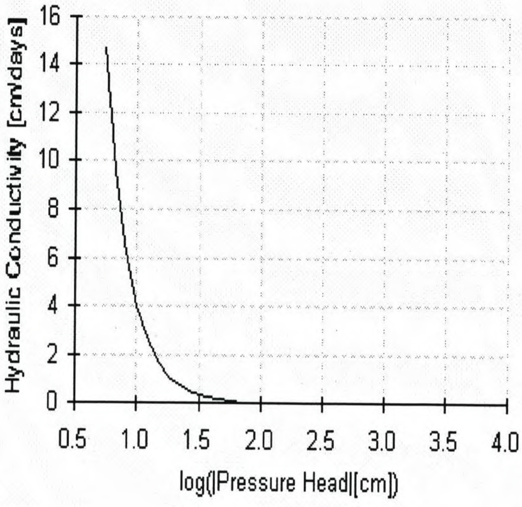

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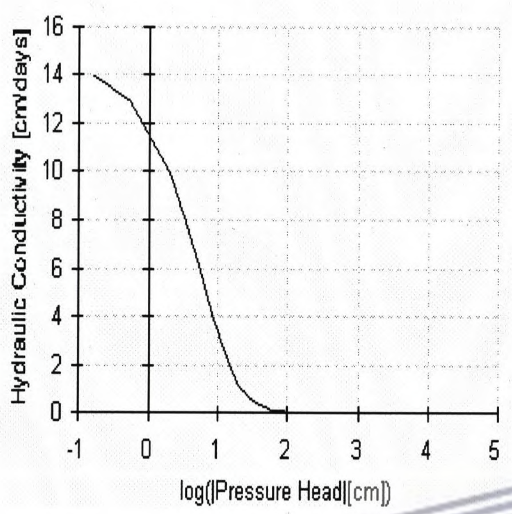
20m: Malmesbury Shale



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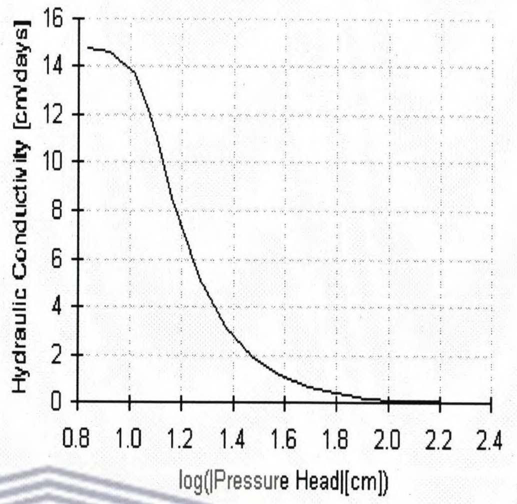

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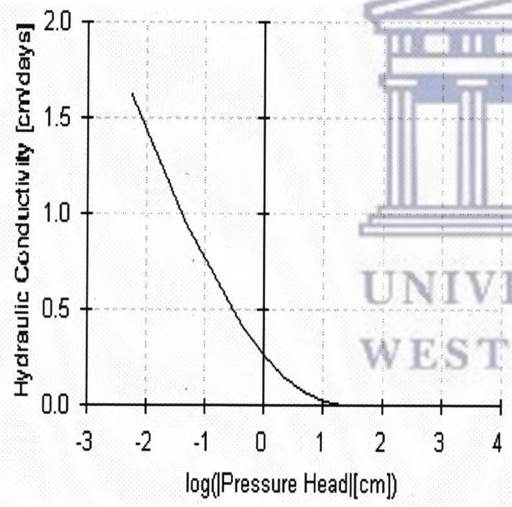

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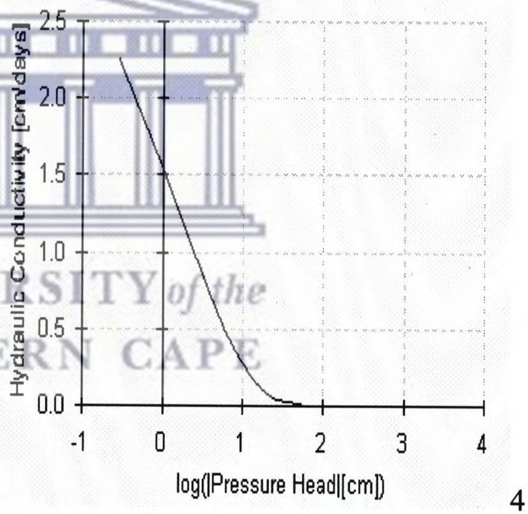

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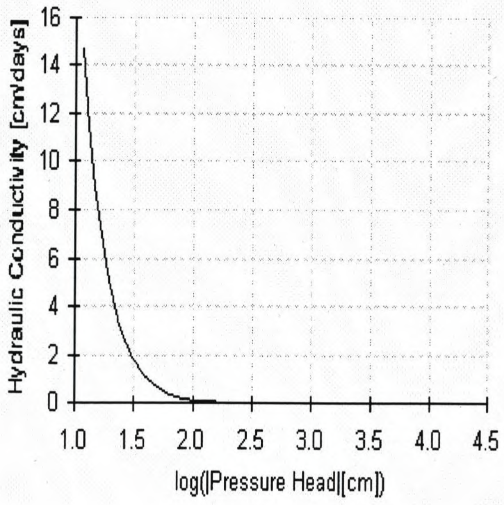

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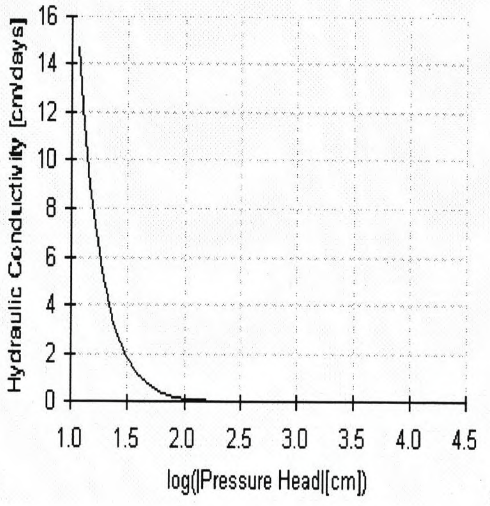
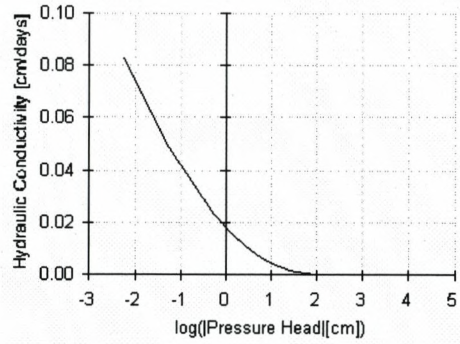


6

Bergriver site 3

Topsoil: Sandy Loam



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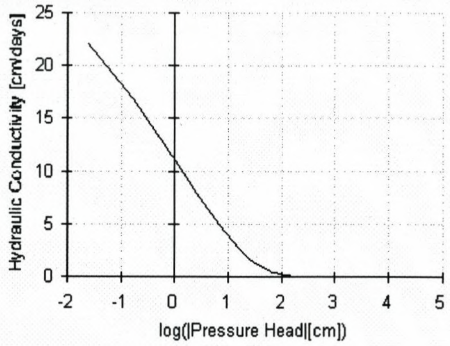

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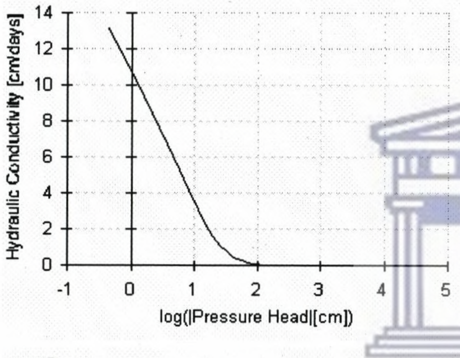

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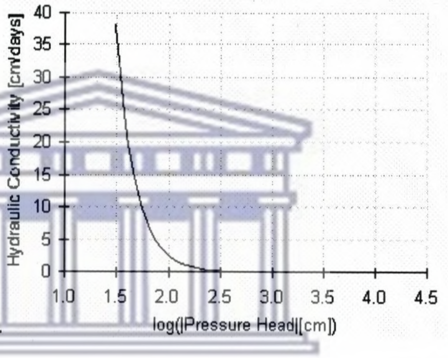

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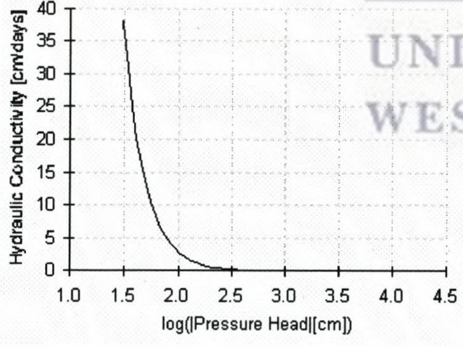

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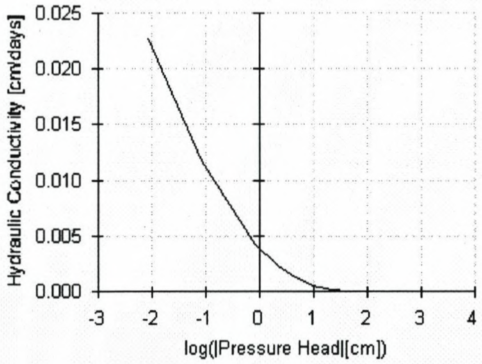

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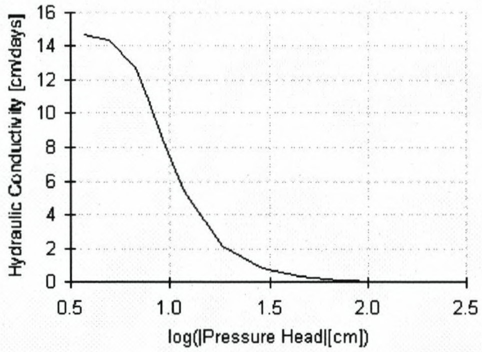

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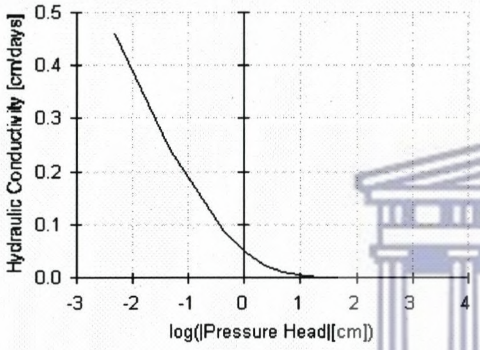

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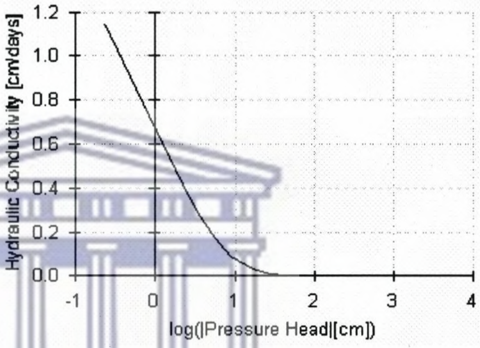

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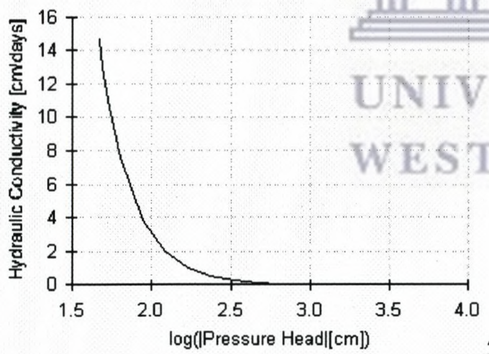

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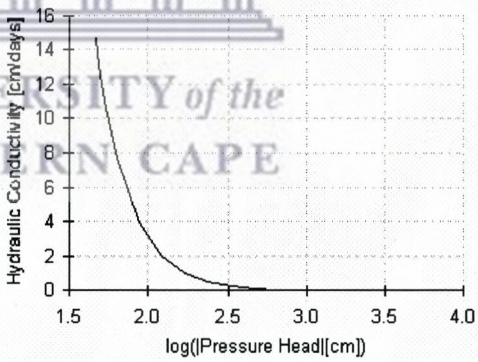

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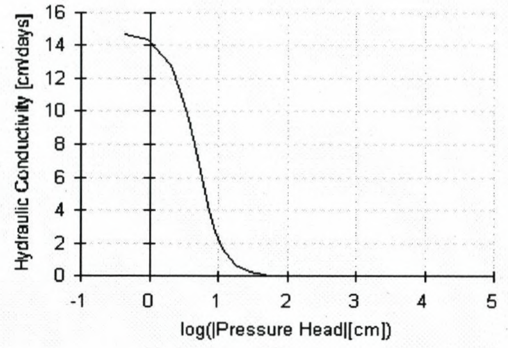

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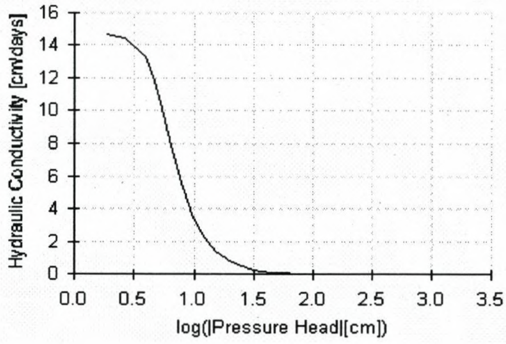

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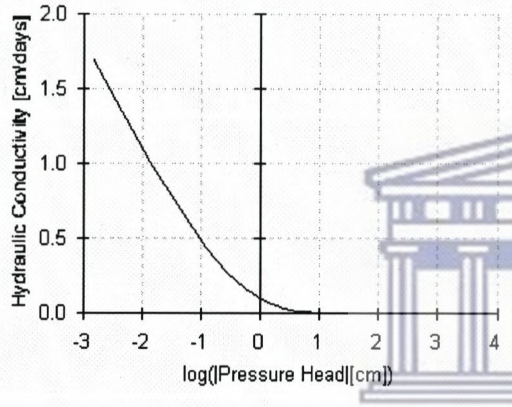

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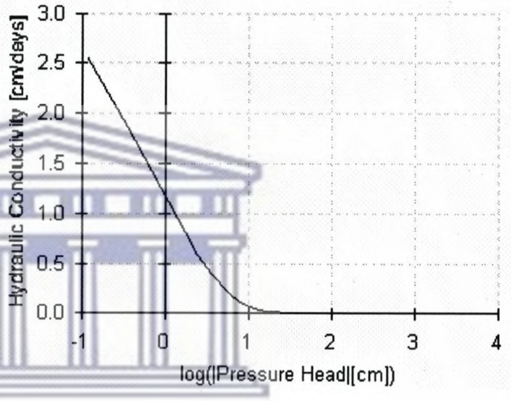

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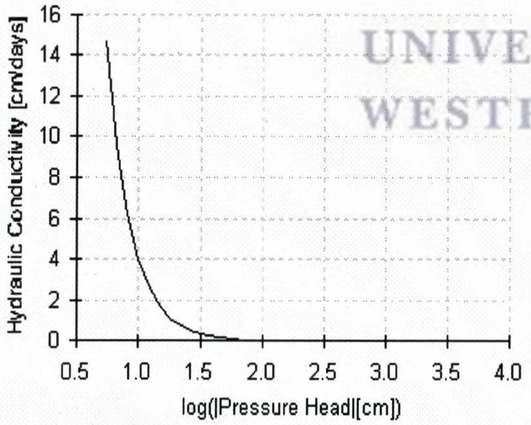

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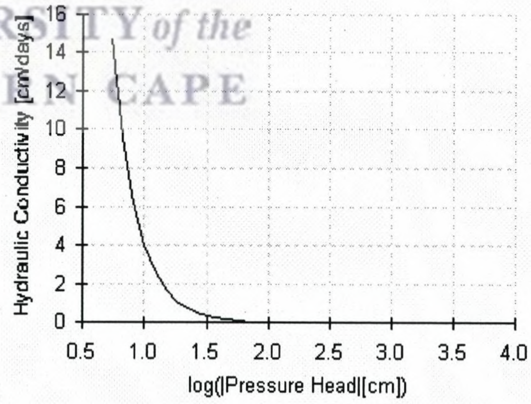

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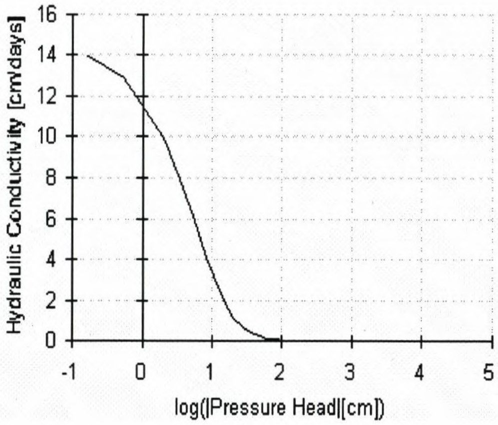

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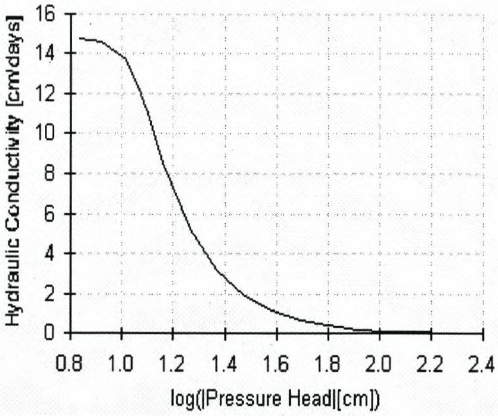

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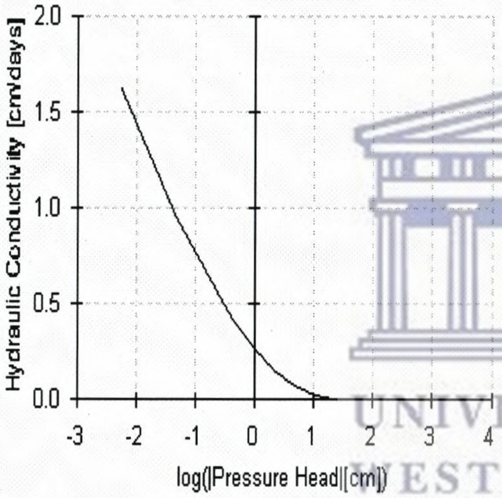

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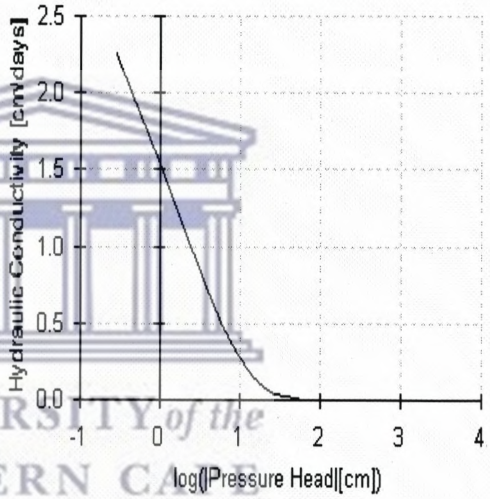

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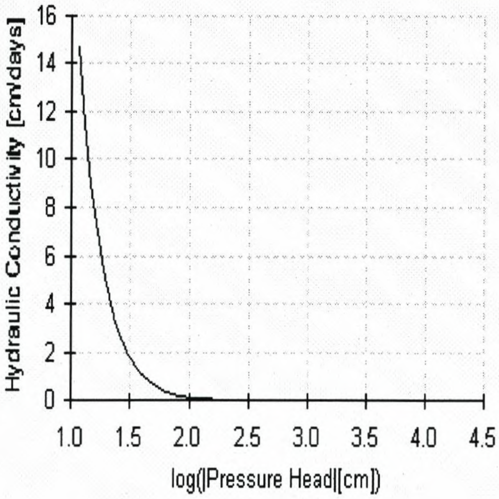

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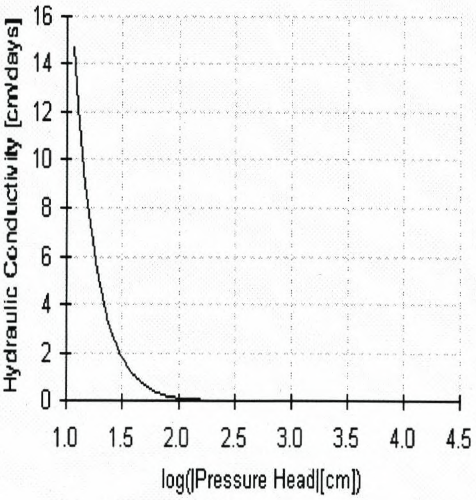

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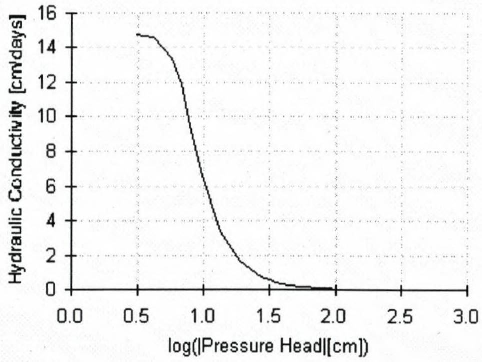

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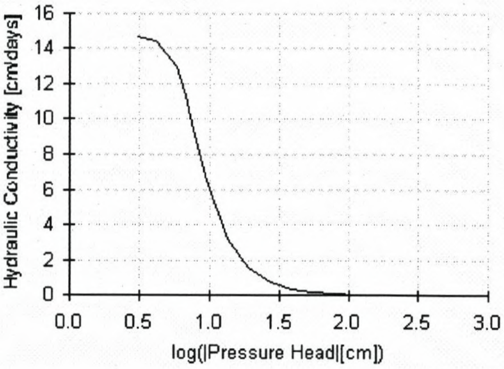

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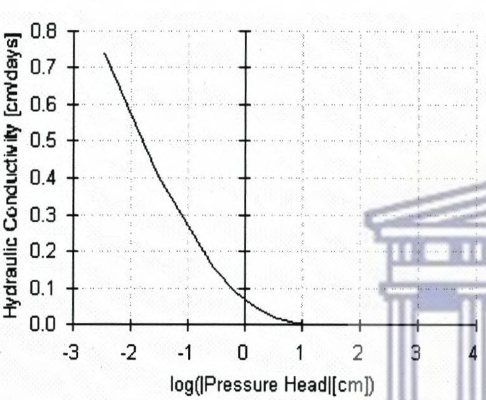

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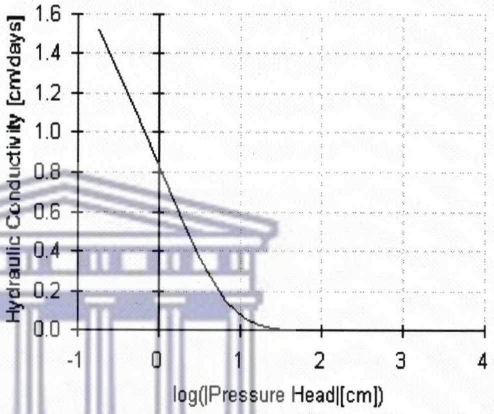

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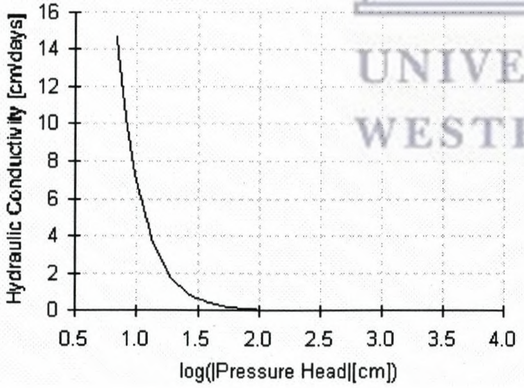

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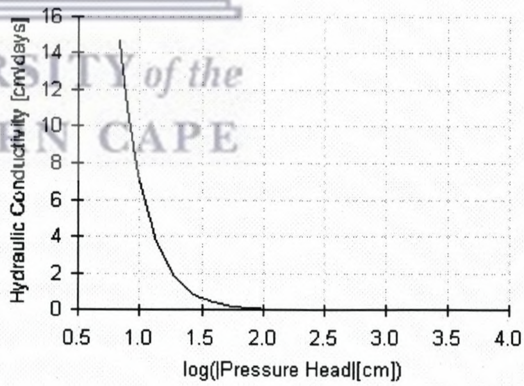

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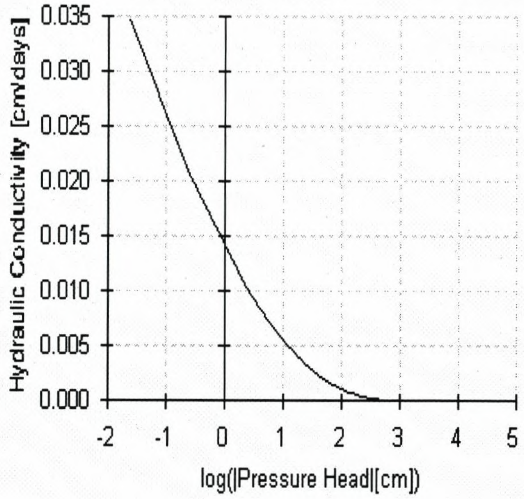

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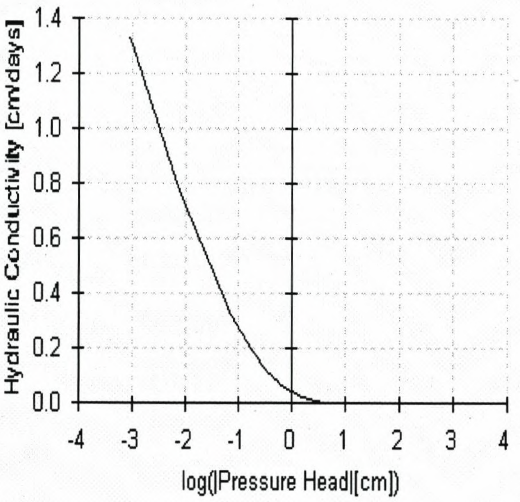

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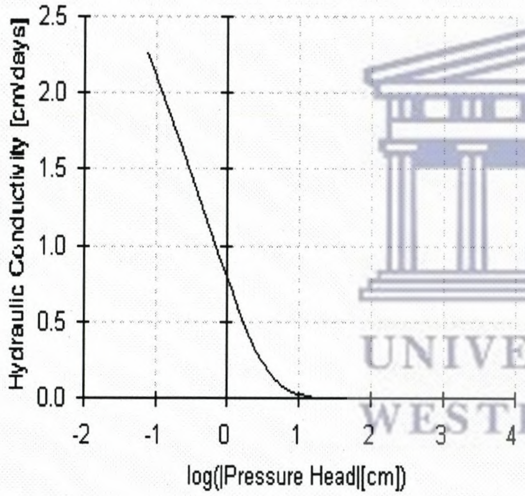

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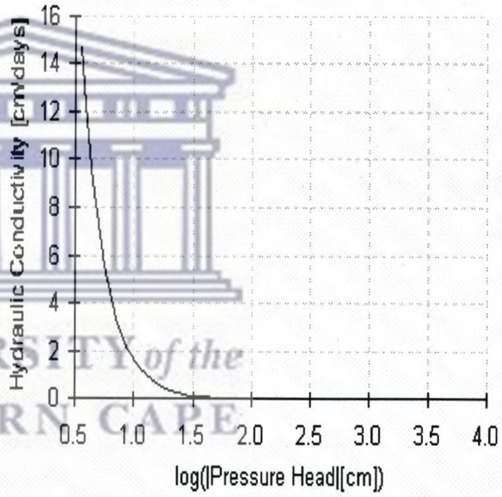

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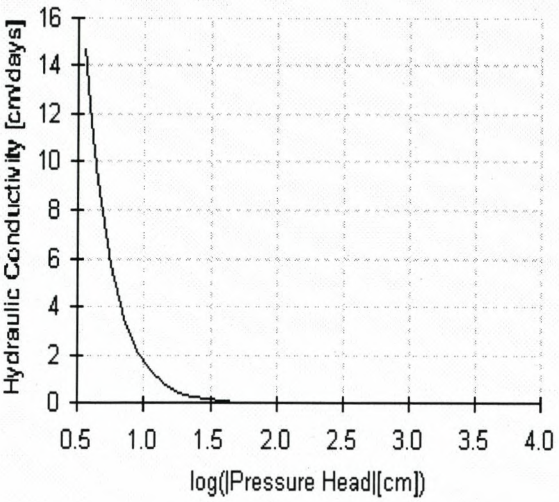

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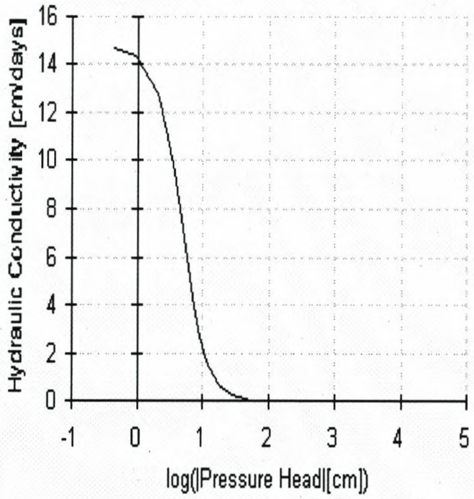

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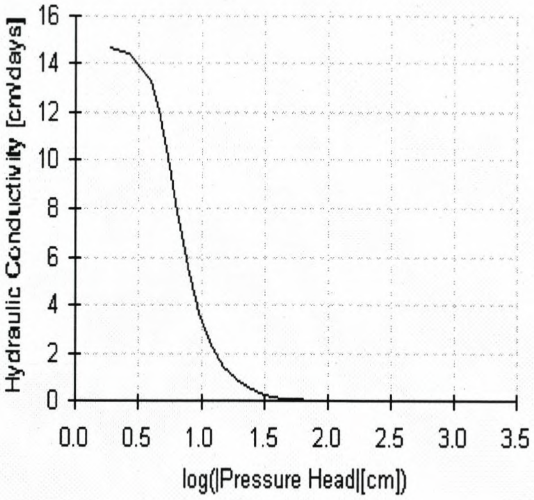

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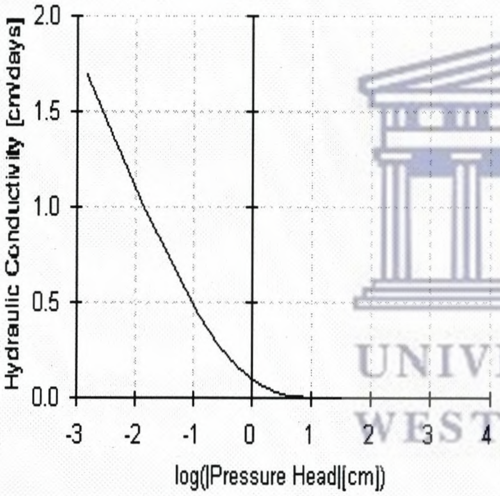

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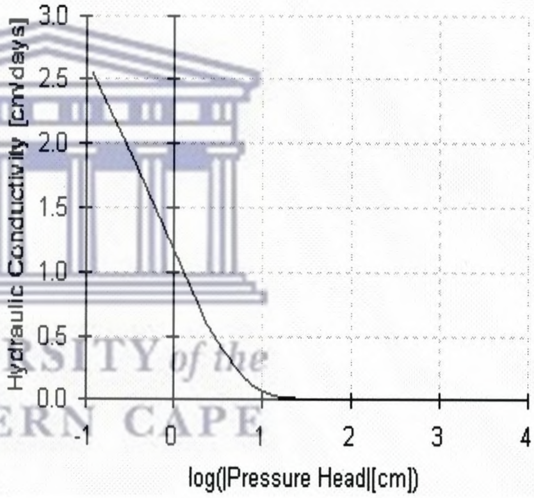

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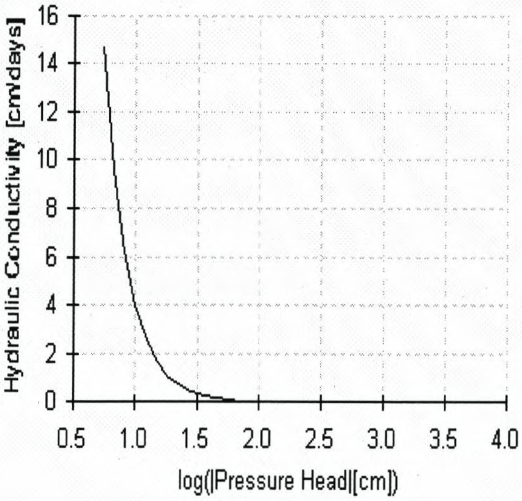

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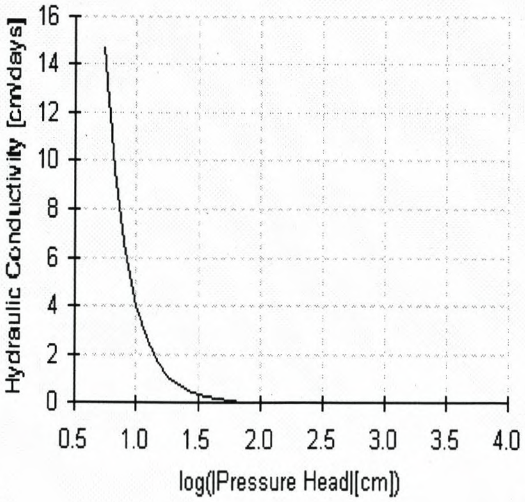

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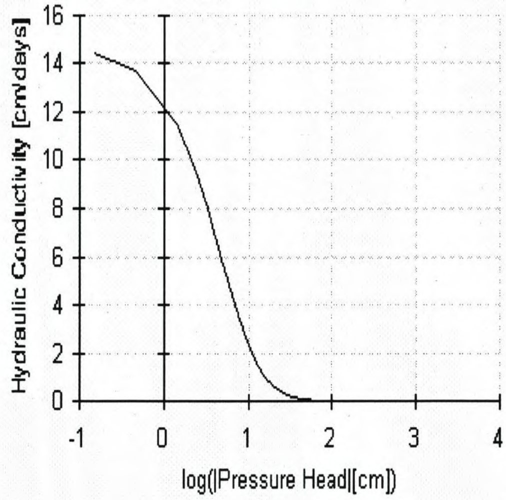

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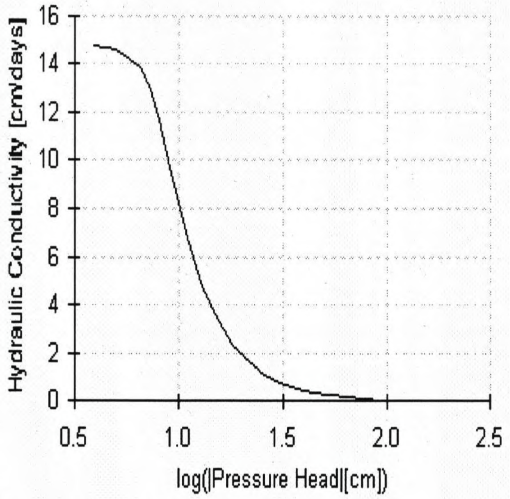

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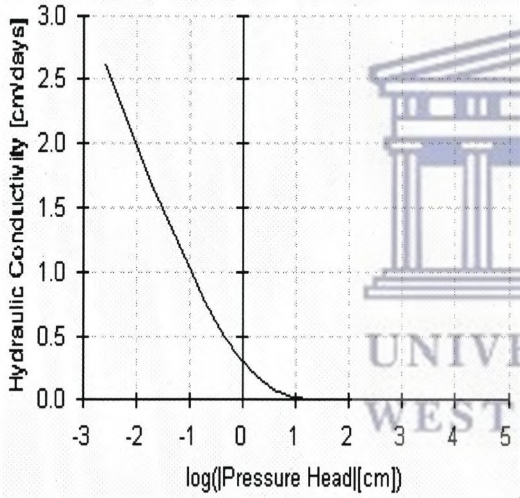

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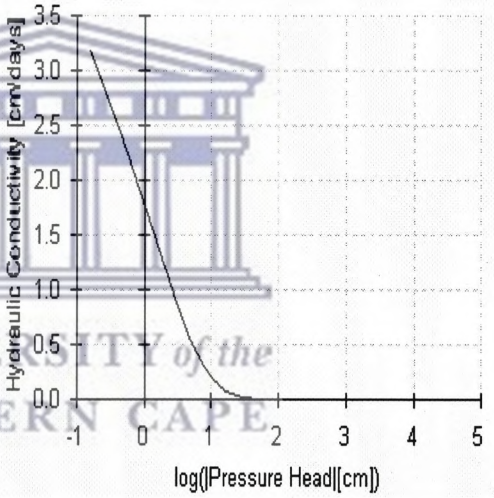

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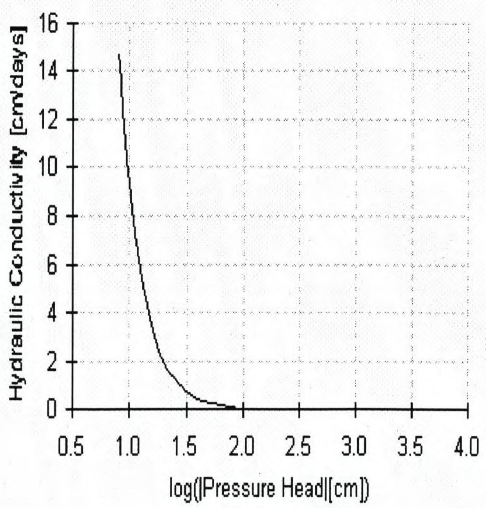

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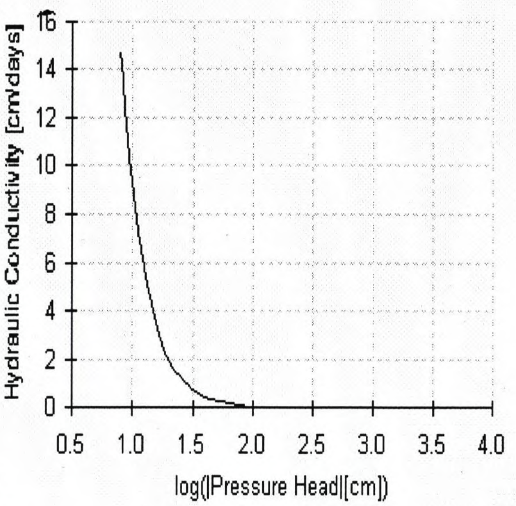

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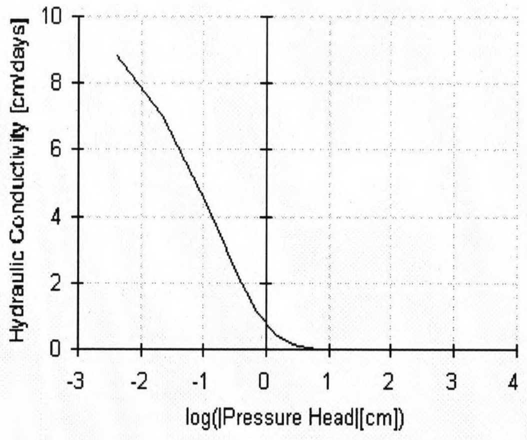

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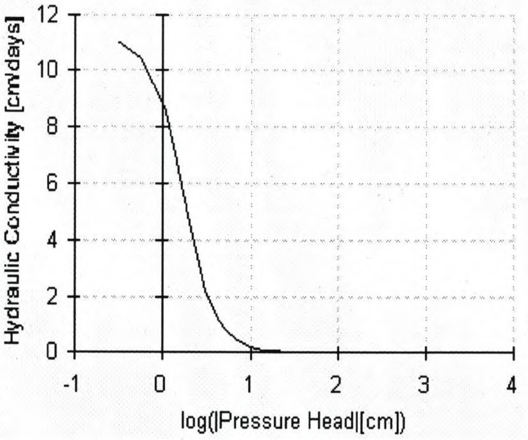

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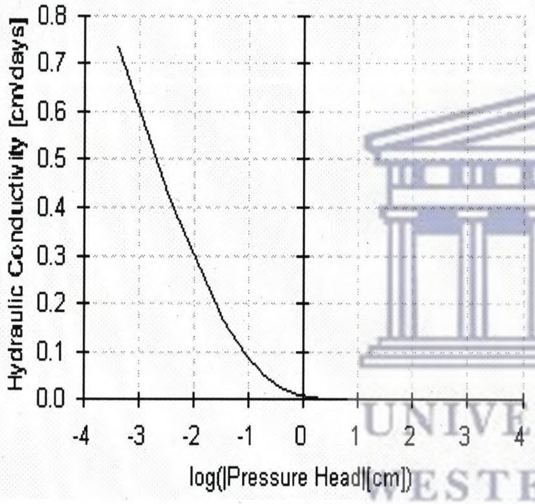

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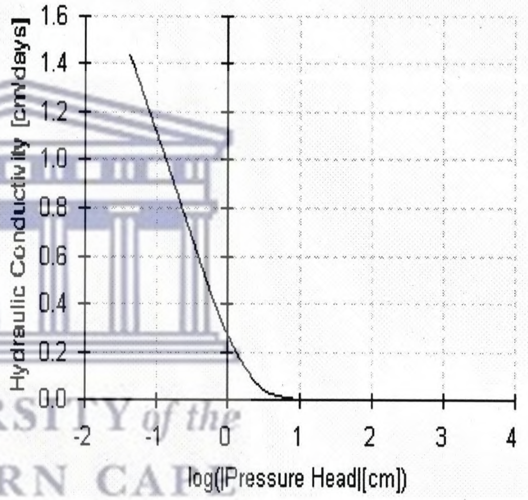

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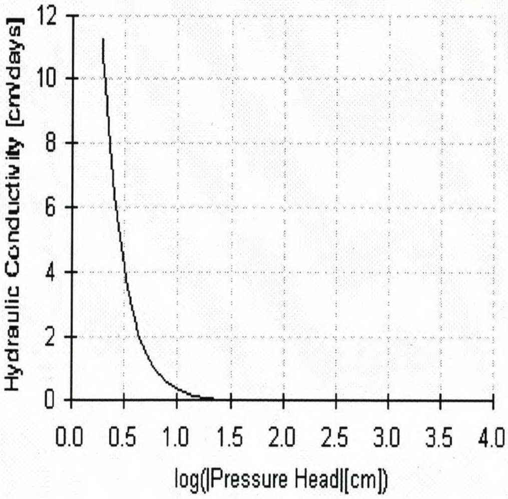

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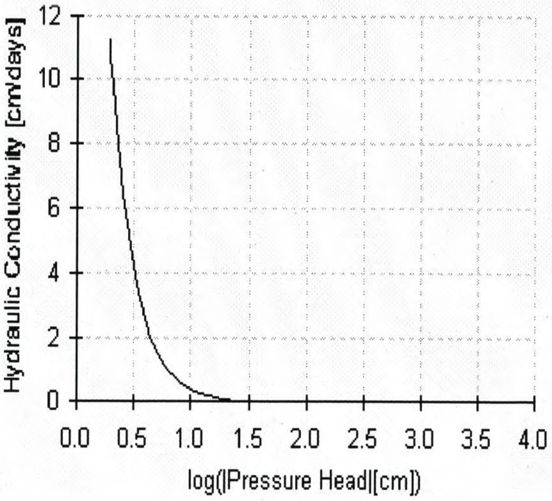

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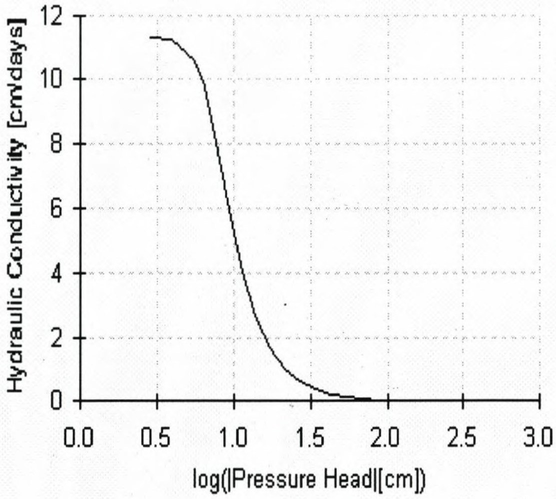

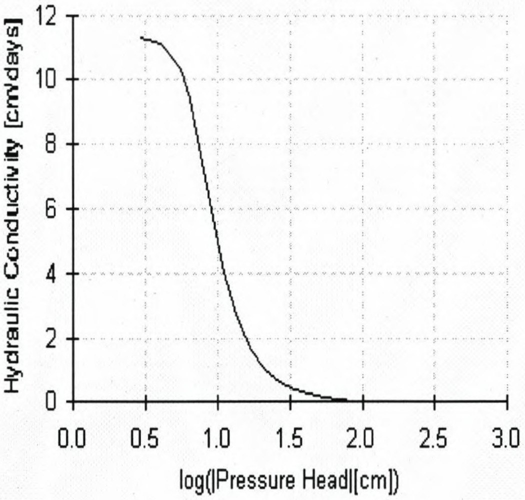

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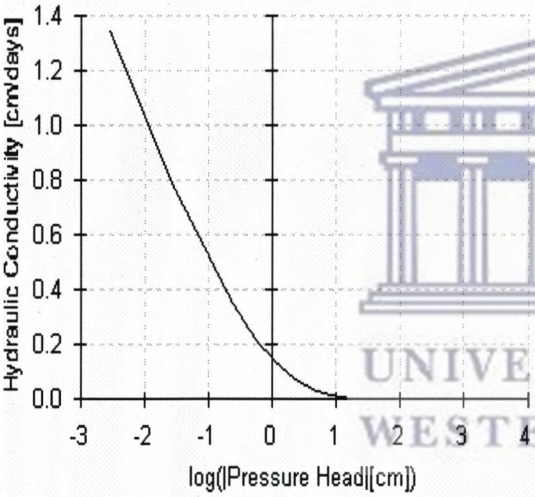

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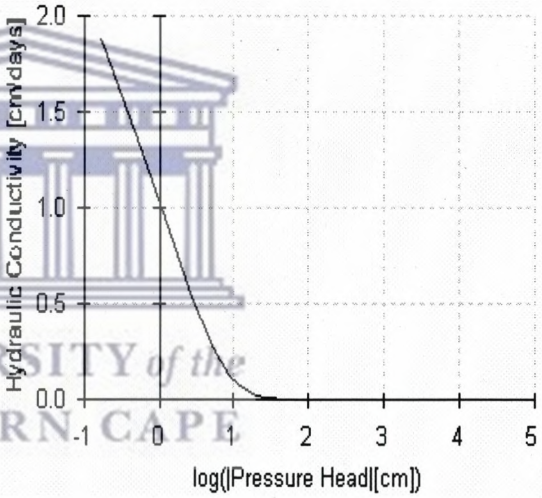

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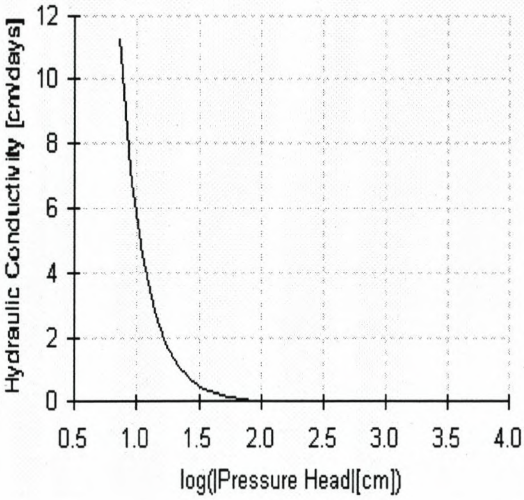

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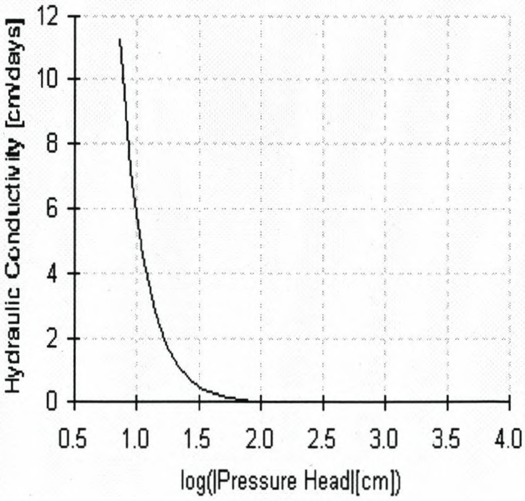

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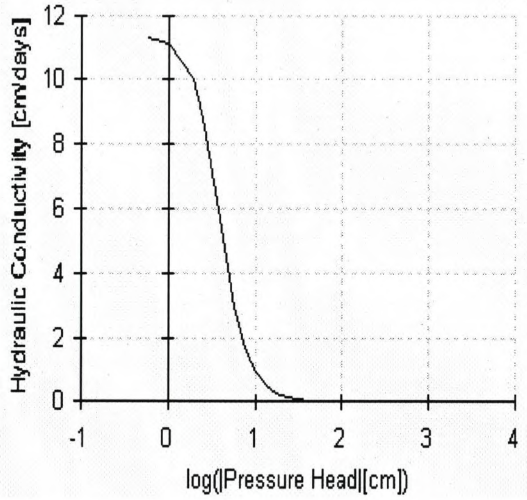

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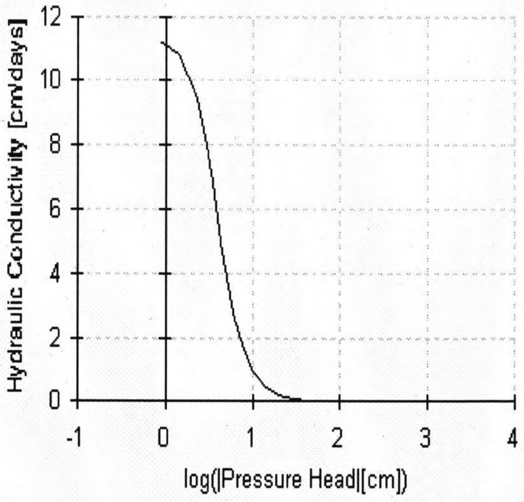

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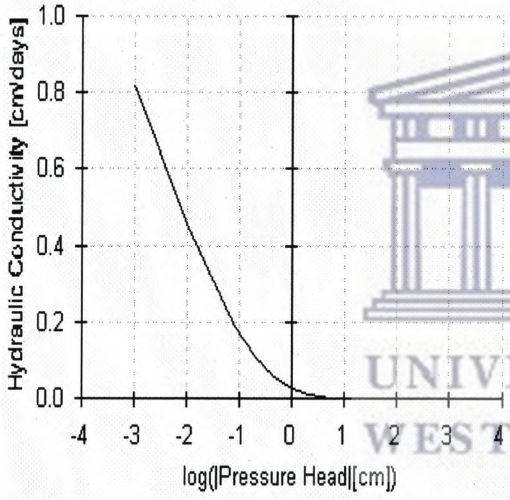

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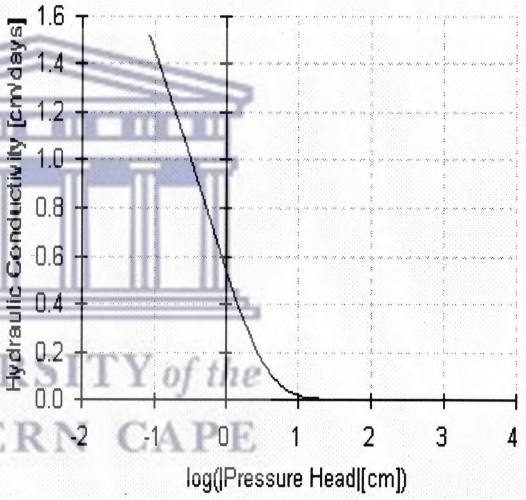

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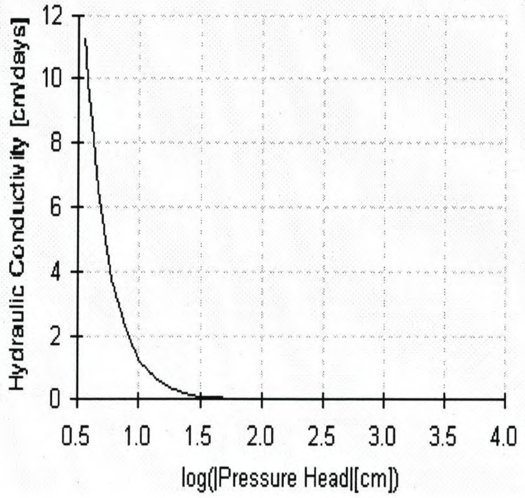

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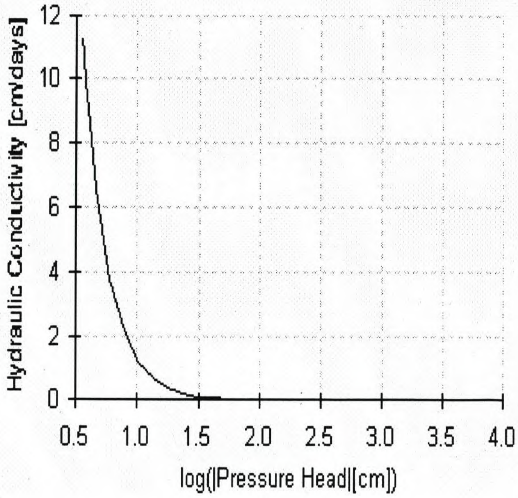

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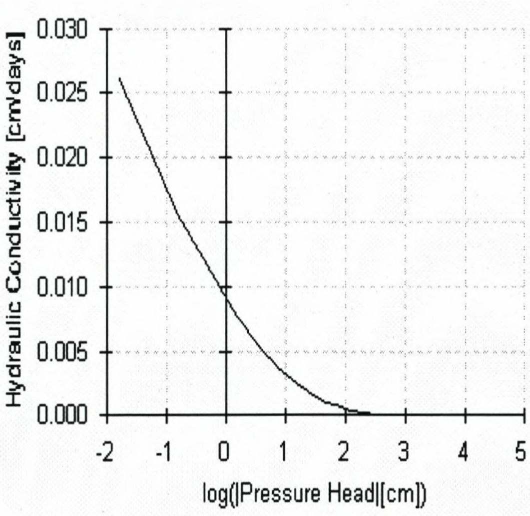

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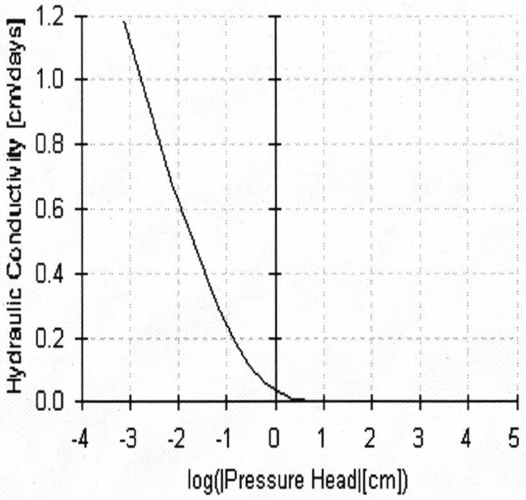

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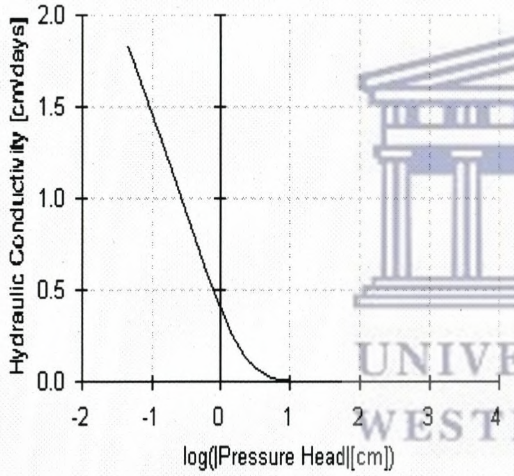

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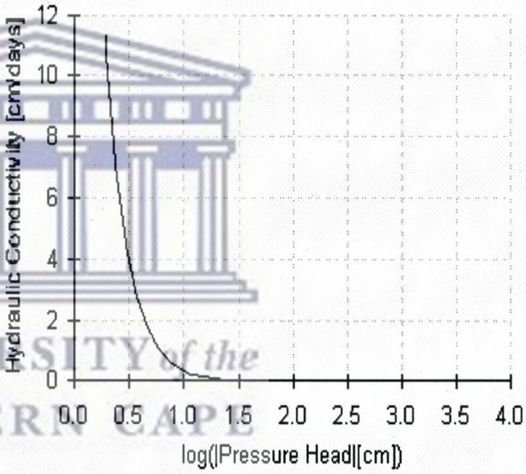

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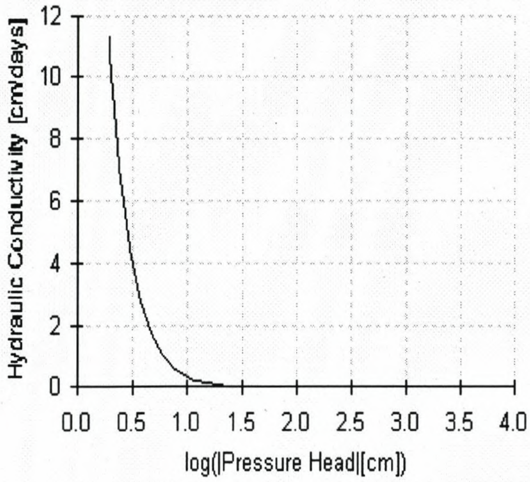

6

APPENDIX F

RETC Output data file

```
                          Ithemba site 1 topsoil
*********************************************************************

*       *
*       Analysis        of      soil    hydraulic       properties      *

*       *
*       Welcome to      RETC    *
*       *
*       Variable        N       and     M       (Mualem-theory  for     K)      *
*       Analysis        of      retention       data    only    *
*       MType=  1       Method= 3       *
*       *
*********************************************************************


INITial values  of      the     coefficients
===================================

No      Name    INITial value   Index
1       ThetaR  0.0485  0
2       ThetaS  0.3904  1
3       Alpha   0.0347  1
4       n       1.7466  1
5       m       0.4275  1
6       l       0.5     0
7       Ks      105.12  0


Observed        data
=============
Obs.No.   Pressurehead         Watercontent         Weighting coefficient
1                    1              0.3829                  1

2                   15              0.3803                  1

3                   30              0.3541                  1

4                   45              0.3492                  1
5                184.5              0.254                   1
6                320.5              0.217                   1
7                510.9              0.2073                  1

NIT     SSQ     ThetaS  Alpha   n       m
0       0.05387 0.3904  0.0347  1.7466  0.4275
1       0.00434 0.3928  0.0287  1.005   0.2075
2       0.00124 0.3805  0.0213  1.6895  0.1639
3       0.00028 0.3839  0.028   2.0693  0.1353
4       0.00019 0.3832  0.0284  2.2831  0.1271
5       0.00018 0.3834  0.0275  2.1897  0.1352
6       0.00018 0.3833  0.028   2.251   0.1307
7       0.00018 0.3834  0.0277  2.2151  0.1336
8       0.00018 0.3833  0.0278  2.2372  0.1319
9       0.00018 0.3833  0.0277  2.224   0.1329
10      0.00018 0.3833  0.0278  2.232   0.1323
11      0.00018 0.3833  0.0278  2.2272  0.1327
12      0.00018 0.3833  0.0278  2.2301  0.1325
13      0.00018 0.3833  0.0278  2.2284  0.1326
14      0.00018 0.3833  0.0278  2.2294  0.1325
15      0.00018 0.3833  0.0278  2.2288  0.1326
16      0.00018 0.3833  0.0278  2.2292  0.1326
17      0.00018 0.3833  0.0278  2.2289  0.1326
18      0.00018 0.3833  0.0278  2.2291  0.1326

Correlation     matrix
```

```
                                Ithemba site 1 topsoil
==================
Theta    Alpha    n        m
1        2        3        4
1        1
2        -0.1509  1
3        -0.5349  0.8499   1
4        0.4858   -0.9029  -0.9915 1

RSquated          for        regression      of       observed        vs      fitted
values   =        0.99487898
=================================================================


Nonlinear         least-squares    analysis:        final    results

===============================================

95%      Confidence          limits
Variable          Value      S.E.Coeff.       T-Value Lower     Upper

Thetas   0.38332 0.00724 52.95      0.3603   0.4064
Alpha    0.02777 0.01167 2.38       -0.0094  0.0649
n        2.22907 1.32171 1.69       -1.9771  6.4352
m        0.13256 0.10248 1.29       -0.1936  0.4587


Observed          abd        fitted    data
=========================
NO       P        log-P      WC-obs    WC-fit    WC-dev
1        1.00E+00            0         0.3829    0.3833    -0.0004
2        1.50E+01            1.1761    0.3803    0.3775    0.0028
3        3.00E+01            1.4771    0.3541    0.3614    -0.0073
4        4.50E+01            1.6532    0.3492    0.3428    0.0064
5        1.85E+02            2.266     0.254     0.2544    -0.0004
6        3.21E+02            2.5058    0.217     0.2238    -0.0068
7        5.11E+02            2.7083    0.2073    0.2014    0.0059


Sum      of       squares of         observed         versus    fitted   values
=============================================

Unweighted        Weighted
Retention         data       0.00018 0.00018
Cond/Diff         data       0         0
All      data     0.00018 0.00018


Soil     hydraulic           properties          (MType    =        1)
======================================

WC       P        logP       Cond      logK     Dif      logD
0.0553   -1.89E+07           7.277     9.69E-15          -14.014 9.07E-05            -4.042
0.0587   -4.79E+06           6.681     4.15E-13          -12.382 6.57E-04            -3.182
0.0622   -1.81E+06           6.258     5.98E-12          -11.224 2.68E-03            -2.572
0.0656   -8.51E+05           5.93      4.73E-11          -10.325 7.97E-03            -2.099
0.069    -4.59E+05           5.662     2.56E-10          -9.592  1.94E-02            -1.712
0.0724   -2.72E+05           5.435     1.07E-09          -8.971  4.12E-02            -1.385
0.0758   -1.73E+05           5.239     3.69E-09          -8.434  7.91E-02            -1.102
0.0792   -1.16E+05           5.066     1.10E-08          -7.959  1.41E-01            -0.852
0.0827   -8.15E+04           4.911     2.92E-08          -7.535  2.35E-01            -0.628
0.0861   -5.90E+04           4.771     7.05E-08          -7.152  3.75E-01            -0.426
0.0895   -4.40E+04           4.643     1.58E-07          -6.801  5.73E-01            -0.242
0.0929   -3.35E+04           4.525     3.32E-07          -6.479  8.47E-01            -0.072
0.0963   -2.61E+04           4.416     6.59E-07          -6.181  1.22E+00            0.085
0.0997   -2.07E+04           4.315     1.25E-06          -5.903  1.71E+00            0.232
0.1032   -1.66E+04           4.22      2.27E-06          -5.643  2.34E+00            0.369
```

0.1066	-1.35E+04	4.131	3.99E-06	-5.399	3.14E+00	0.497
0.11	-1.12E+04	4.047	6.77E-06	-5.169	4.15E+00	0.618
0.1134	-9.28E+03	3.968	1.12E-05	-4.952	5.41E+00	0.733
0.1168	-7.80E+03	3.892	1.80E-05	-4.745	6.95E+00	0.842
0.1202	-6.62E+03	3.821	2.83E-05	-4.549	8.82E+00	0.945
0.1237	-5.65E+03	3.752	4.35E-05	-4.362	1.11E+01	1.044
0.1271	-4.86E+03	3.687	6.57E-05	-4.183	1.38E+01	1.138
0.1305	-4.21E+03	3.624	9.74E-05	-4.011	1.69E+01	1.229
0.1339	-3.67E+03	3.564	1.42E-04	-3.847	2.07E+01	1.315
0.1373	-3.21E+03	3.507	2.05E-04	-3.689	2.50E+01	1.398
0.1407	-2.83E+03	3.451	2.90E-04	-3.537	3.01E+01	1.478
0.1442	-2.50E+03	3.398	4.07E-04	-3.391	3.60E+01	1.556
0.1476	-2.22E+03	3.346	5.63E-04	-3.25	4.27E+01	1.63
0.151	-1.98E+03	3.296	7.71E-04	-3.113	5.04E+01	1.702
0.1544	-1.77E+03	3.248	1.04E-03	-2.981	5.91E+01	1.772
0.1578	-1.59E+03	3.201	1.40E-03	-2.853	6.90E+01	1.839
0.1612	-1.43E+03	3.156	1.87E-03	-2.729	8.02E+01	1.904
0.1647	-1.30E+03	3.112	2.46E-03	-2.609	9.28E+01	1.968
0.1681	-1.17E+03	3.07	3.22E-03	-2.493	1.07E+02	2.029
0.1715	-1.07E+03	3.028	4.18E-03	-2.379	1.23E+02	2.089
0.1749	-9.73E+02	2.988	5.39E-03	-2.269	1.40E+02	2.147
0.1783	-8.89E+02	2.949	6.90E-03	-2.161	1.60E+02	2.204
0.1817	-8.14E+02	2.911	8.77E-03	-2.057	1.82E+02	2.259
0.1852	-7.47E+02	2.873	1.11E-02	-1.955	2.05E+02	2.313
0.1886	-6.87E+02	2.837	1.40E-02	-1.856	2.32E+02	2.365
0.192	-6.33E+02	2.801	1.74E-02	-1.758	2.61E+02	2.416
0.1954	-5.85E+02	2.767	2.17E-02	-1.664	2.93E+02	2.466
0.1988	-5.41E+02	2.733	2.69E-02	-1.571	3.28E+02	2.515
0.2022	-5.01E+02	2.7	3.31E-02	-1.481	3.66E+02	2.563
0.2057	-4.65E+02	2.667	4.06E-02	-1.392	4.07E+02	2.61
0.2091	-4.32E+02	2.636	4.95E-02	-1.305	4.53E+02	2.656
0.2125	-4.02E+02	2.605	6.02E-02	-1.221	5.02E+02	2.701
0.2159	-3.75E+02	2.574	7.29E-02	-1.137	5.56E+02	2.745
0.2193	-3.50E+02	2.544	8.79E-02	-1.056	6.14E+02	2.788
0.2227	-3.27E+02	2.515	1.06E-01	-0.976	6.77E+02	2.83
0.2262	-3.06E+02	2.486	1.27E-01	-0.898	7.45E+02	2.872
0.2296	-2.87E+02	2.458	1.51E-01	-0.821	8.18E+02	2.913
0.233	-2.69E+02	2.43	1.80E-01	-0.746	8.98E+02	2.953
0.2364	-2.53E+02	2.403	2.13E-01	-0.671	9.83E+02	2.993
0.2398	-2.38E+02	2.376	2.52E-01	-0.599	1.08E+03	3.032
0.2432	-2.24E+02	2.35	2.97E-01	-0.527	1.18E+03	3.07
0.2467	-2.11E+02	2.324	3.49E-01	-0.457	1.28E+03	3.108
0.2501	-1.99E+02	2.298	4.10E-01	-0.388	1.40E+03	3.145
0.2535	-1.87E+02	2.273	4.79E-01	-0.319	1.52E+03	3.182
0.2569	-1.77E+02	2.248	5.59E-01	-0.252	1.65E+03	3.218
0.2603	-1.67E+02	2.223	6.51E-01	-0.186	1.80E+03	3.254
0.2637	-1.58E+02	2.199	7.56E-01	-0.121	1.95E+03	3.29
0.2672	-1.50E+02	2.175	8.76E-01	-0.057	2.11E+03	3.325
0.2706	-1.42E+02	2.151	1.01E+00	0.006	2.29E+03	3.36
0.274	-1.34E+02	2.127	1.17E+00	0.068	2.48E+03	3.394
0.2774	-1.27E+02	2.104	1.35E+00	0.129	2.68E+03	3.429
0.2808	-1.21E+02	2.081	1.55E+00	0.19	2.90E+03	3.463
0.2842	-1.14E+02	2.058	1.78E+00	0.25	3.14E+03	3.497
0.2877	-1.08E+02	2.035	2.04E+00	0.309	3.39E+03	3.531
0.2911	-1.03E+02	2.012	2.33E+00	0.368	3.67E+03	3.564
0.2945	-9.76E+01	1.99	2.66E+00	0.425	3.96E+03	3.598
0.2979	-9.27E+01	1.967	3.04E+00	0.483	4.29E+03	3.632
0.3013	-8.80E+01	1.944	3.46E+00	0.539	4.63E+03	3.666
0.3047	-8.35E+01	1.922	3.94E+00	0.595	5.01E+03	3.7
0.3082	-7.93E+01	1.899	4.48E+00	0.651	5.42E+03	3.734
0.3116	-7.52E+01	1.876	5.08E+00	0.706	5.87E+03	3.769
0.315	-7.14E+01	1.854	5.76E+00	0.761	6.36E+03	3.803
0.3184	-6.77E+01	1.831	6.53E+00	0.815	6.90E+03	3.839
0.3218	-6.42E+01	1.807	7.39E+00	0.869	7.49E+03	3.875
0.3252	-6.08E+01	1.784	8.36E+00	0.922	8.15E+03	3.911
0.3287	-5.75E+01	1.76	9.46E+00	0.976	8.89E+03	3.949
0.3321	-5.43E+01	1.735	1.07E+01	1.029	9.71E+03	3.987
0.3355	-5.13E+01	1.71	1.21E+01	1.082	1.06E+04	4.027

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                                    Ithemba site 1 topsoil
0.3389   -4.83E+01          1.684    1.37E+01          1.135    1.17E+04          4.068
0.3423   -4.54E+01          1.657    1.54E+01          1.189    1.29E+04          4.11
0.3457   -4.26E+01          1.63     1.75E+01          1.242    1.43E+04          4.155
0.3492   -3.98E+01          1.6      1.98E+01          1.296    1.59E+04          4.203
0.3526   -3.71E+01          1.569    2.24E+01          1.35     1.79E+04          4.253
0.356    -3.44E+01          1.536    2.54E+01          1.405    2.03E+04          4.307
0.3594   -3.16E+01          1.5      2.89E+01          1.461    2.33E+04          4.366
0.3628   -2.89E+01          1.46     3.30E+01          1.518    2.70E+04          4.432
0.3662   -2.60E+01          1.415    3.78E+01          1.577    3.21E+04          4.506
0.3697   -2.30E+01          1.362    4.36E+01          1.639    3.92E+04          4.593
0.3731   -1.98E+01          1.297    5.06E+01          1.705    5.01E+04          4.7
0.3765   -1.62E+01          1.209    5.98E+01          1.777    6.93E+04          4.841
0.3799   -1.16E+01          1.065    7.27E+01          1.861    1.16E+05          5.064
0.3816   -8.44E+00          0.926    8.23E+01          1.916    1.86E+05          5.27
0.3825   -6.15E+00          0.789    8.93E+01          1.951    2.92E+05          5.465
0.383    -4.07E+00          0.609    9.54E+01          1.98     5.12E+05          5.709
0.3833   -1.44E+00          0.16     1.02E+02          2.01     1.94E+06          6.288
0.3833   -5.14E-01          -0.289   1.04E+02          2.018    7.04E+06          6.848
0.3833   0.00E+00           1.05E+02          2.022

End       of        problem
==============

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APPENDIX G

MACRO 5.0 Output data file

Date	Water content (tot.) m3/m3 topsoil	Water content (tot.) m3/m3 150cm	Solute leaching (mg/m2)
			0.000661975
2.00401E+11	0.3955844	0.3999245	0.001707994
2.00401E+11	0.3922662	0.3993136	0.002680629
2.00401E+11	0.3902486	0.3983119	0.003630416
2.00401E+11	0.4107753	0.3976824	0.004557862
2.00401E+11	0.4071359	0.402227	0.005461706
2.00401E+11	0.4000795	0.4038012	0.00634233
2.00401E+11	0.3963803	0.4029652	0.007200128
2.00401E+11	0.3938178	0.4017136	0.008035644
2.00401E+11	0.3918381	0.4004451	0.008849482
2.00401E+11	0.3902152	0.3992456	0.009642273
2.00401E+11	0.3888344	0.3981299	0.01041464
2.00401E+11	0.3876291	0.3970942	0.01116721
2.00401E+11	0.3865569	0.3961305	0.01190058
2.00401E+11	0.3855893	0.3952302	0.01261534
2.00401E+11	0.3847061	0.3943855	0.01331205
2.00401E+11	0.3838923	0.3935899	0.01399127
2.00401E+11	0.3831368	0.3928376	0.01465351
2.00401E+11	0.382431	0.3921238	0.0152993
2.00401E+11	0.3817678	0.3914446	0.01592911
2.00401E+11	0.3811419	0.3907964	0.01654343
2.00401E+11	0.3805487	0.3901762	0.0171427
2.00401E+11	0.3799845	0.3895815	0.01772737
2.00401E+11	0.3794463	0.3890101	0.01829786
2.00401E+11	0.3789313	0.38846	0.01885459
2.00401E+11	0.3784375	0.3879295	0.0193979
2.00401E+11	0.3913478	0.3874586	0.01992834
2.00401E+11	0.386482	0.387927	0.0204461
2.00401E+11	0.383095	0.3885252	0.0209516
2.00401E+11	0.3814841	0.3884862	0.0214452
2.00401E+11	0.3803549	0.3881427	0.02192721
2.00402E+11	0.3794598	0.387685	0.02239797
2.00402E+11	0.3787029	0.3871888	0.02285779
2.00402E+11	0.3801605	0.3866897	0.02330696
2.00402E+11	0.3788739	0.3863097	0.02374578
2.00402E+11	0.3778086	0.3859715	0.02417454
2.00402E+11	0.3771091	0.3855671	0.02459349
2.00402E+11	0.3765172	0.38513	0.02500292
2.00402E+11	0.3759865	0.3846856	0.02540307
2.00402E+11	0.3754979	0.3842453	0.02579419
2.00402E+11	0.3750411	0.3838136	0.02617655
2.00402E+11	0.3746098	0.3833924	0.02655044
2.00402E+11	0.3741995	0.3829821	0.02691611
2.00402E+11	0.3738073	0.3825826	0.02727382
2.00402E+11	0.3734308	0.3821937	0.02762381
2.00402E+11	0.3730681	0.3818148	0.02796632
2.00402E+11	0.3727179	0.3814456	0.02830158
2.00402E+11	0.3723789	0.3810854	0.0286298
2.00402E+11	0.3720502	0.3807339	0.02895119
2.00402E+11	0.3717309	0.3803906	0.02926595
2.00402E+11	0.3714203	0.3800552	0.02957428
2.00402E+11	0.3711177	0.3797271	0.02987635
2.00402E+11	0.3708227	0.3794061	0.03017235
2.00402E+11	0.3705347	0.3790917	0.03046244
2.00402E+11	0.3702533	0.3787838	0.0307468

2.00402E+11	0.3699782	0.378482	0.03102558
2.00402E+11	0.369709	0.3781861	0.03129894
2.00402E+11	0.3694453	0.3778957	0.03156701
2.00402E+11	0.3691869	0.3776107	0.03182923
2.00402E+11	0.4015411	0.3914824	0.03208785
2.00403E+11	0.4471527	0.4711971	0.03234092
2.00403E+11	0.4347016	0.4595553	0.03258923
2.00403E+11	0.4261981	0.4455307	0.0328329
2.00403E+11	0.427224	0.4375938	0.03307209
2.00403E+11	0.4193419	0.4337453	0.03330686
2.00403E+11	0.4144923	0.4294226	0.03353735
2.00403E+11	0.4110093	0.4255981	0.03376364
2.00403E+11	0.410959	0.4224289	0.03398587
2.00403E+11	0.4074432	0.4201801	0.0342041
2.00403E+11	0.4047088	0.41789	0.03441843
2.00403E+11	0.4025772	0.4156855	0.03462896
2.00403E+11	0.4007424	0.4136781	0.03483577
2.00403E+11	0.3991119	0.4118543	0.03503894
2.00403E+11	0.397638	0.410188	0.03523856
2.00403E+11	0.3962903	0.4086557	0.03543469
2.00403E+11	0.3950476	0.4072382	0.03562742
2.00403E+11	0.393894	0.4059198	0.03581682
2.00403E+11	0.3928172	0.4046878	0.03600295
2.00403E+11	0.3918074	0.4035318	0.03618589
2.00403E+11	0.3908569	0.4024431	0.03636569
2.00403E+11	0.3899588	0.4014144	0.03654242
2.00403E+11	0.3891079	0.4004397	0.03671614
2.00403E+11	0.3882993	0.3995136	0.0368869
2.00403E+11	0.387529	0.3986315	0.03705477
2.00403E+11	0.3867938	0.3977897	0.03721979
2.00403E+11	0.3860904	0.3969846	0.03738202
2.00403E+11	0.3854163	0.3962132	0.03754151
2.00403E+11	0.3847693	0.395473	0.0376983
2.00403E+11	0.3841471	0.3947614	0.03785245
2.00403E+11	0.3835481	0.3940765	0.03800349
2.00403E+11	0.419505	0.4077575	0.03815297
2.00404E+11	0.4345537	0.4643034	0.03829945
2.00404E+11	0.4257892	0.445746	0.03844343
2.00404E+11	0.4271043	0.4376109	0.03858498
2.00404E+11	0.4386922	0.4379862	0.03872416
2.00404E+11	0.4370475	0.446974	0.03886097
2.00404E+11	0.4255344	0.4404067	0.03899546
2.00404E+11	0.4188884	0.4340495	0.03912762
2.00404E+11	0.4292681	0.4302033	0.03925757
2.00404E+11	0.4342458	0.4329028	0.03938529
2.00404E+11	0.4361426	0.4348269	0.03951082
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2.00412E+11	0.4080473	0.3921276	0.04524221
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Date	Signature Student no.	Time	Staff