Preliminary Vadose Zone Classification Methodology (Molototsi and Middle Letaba Quaternary Catchments)

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Introduction

A consultancy was approved by the Water Research Commission for the project titled "Preliminary Vadose Zone Classification Methodology (Molototsi and Middle Letaba Quaternary Catchments)", WRC (Water Research Commission) project number K8/876. The final countersigned contract was received by the University of Pretoria during June 2009.

The interest in the topic originated from the application of certain methods in quantifying unsaturated flow. In groundwater studies, the combined influence of the vadose zone is often considered an estimated parameter. Recharge is commonly estimated to account for the amount of water reaching the phreatic zone or, in vulnerability assessments, the vadose zone is often an index based on the thickness of the vadose zone (depth to water table) and the rate of seepage through the unsaturated zone. These latter parameters may not be adequate to fully address the unsaturated flow through the Earth's crust and more detailed and certain parameters may be required.

The vadose zone is considered vital for two main reasons. Firstly, this represents the zone through which recharging water moves. The rate of seepage through the vadose zone and the presence or absence of zones of varying seepage rates will inherently influence the amount of water reaching the phreatic zone. Additionally, water cannot be only assumed to migrate vertically under the influence of gravity, and localised areas of lateral movement through interflow, perching of water and sorption processes need to be considered. Secondly, the vadose zone is host to numerous potential sources of contamination. In many areas, this represents the zone where septic tanks, pit latrines, cemeteries, underground storage tanks and waste disposal sites are located. Agricultural fertilisers, pesticides and contaminants from mine tailings enter the subsurface through the vadose zone with infiltrating water to potentially contaminate the groundwater. In urban areas, additional sealing of the crust and leaking subsurface pipelines can change the local hydrology as areas for recharge and discharge can be affected directly.

The project aimed to classify the vadose zone quantitatively, i.e. to assign numerical parameters to the unsaturated zone which may aid in addressing more important matters such as recharge (zones and rates), percolation and infiltration (with regard to surface and shallow subsurface contamination sources) and, finally, the susceptibility of the aquifer to infiltrating water and contaminants. The objectives of the research were to:

- Assess some of the empirical approaches to determine hydraulic conductivity based on soil grading analyses
- Evaluate alternative parameters and methods to determine the hydraulic conductivity based on soil grading analyses
- Conduct field test to determine seepage rates and compare the results with empirical methods
- Zone the study area into areas of similar hydrological behaviour, notably with respect to groundwater depth and infiltration rate
- Determine aspects requiring refinement for future research projects.

As this consultancy project is only a preliminary classification, recommendations will be made with respect to further research required.

Methodology

The study entailed field percolation (SABS 0252-2:1993) and double ring infiltrometer tests (Jenn *et al.*, 2007c after Gartung and Neff, 1999). A combined total of 19 tests were conducted over the study area.

Additionally, empirical hydraulic conductivities were determined from soil grading analyses. Porosity was estimated according to Istomina (1957) and the applied approaches include Hazen (1930), Amer and Awad (1974), Kozeny (in Vermaak and Van Schalkwyk, 2000), USBR, Zamarin, Slichter (in Vukovic and Soro, 1992) and Alyamani and Sen (1993). Most of these methods assume the effective grain size diameter to be equal to d_{10} (or d_{20} for USBR) and the Alyamani and Sen approach incorporates the I_0-intercept. The uniformity coefficient C_U is also mostly included in the calculations.

Three approaches were merged, *viz*. the Land System Approach, the DRASTIC approach to vulnerability mapping, and the Model-Setting-Scenario approach to conceptualise the subsurface.

The Land System Approach is based on the assumption that similar land facets will have similar and repetitive soil profiles with similar soil properties. A land facet, which is the basic unit of the land system classification, is defined as part of the landscape, usually with a super-form consisting of a particular rock or surficial deposit and with soil and water regime that is either uniform over the whole facet or varies in a simple and consistent way. Characteristically land facets are small units and correspond to individual physiographic features such as outcrops, talus slopes, alluvial fans, etc. Related facets are grouped into larger terrain units. A recurrent pattern of genetically linked land facets is known as a land system. Land facets are typically mapped at scales between 1:10 000 and 1:50 000 and land systems at scales of 1:250 000 to 1:1 000 000 (e.g. Brink *et al*., 1970; Geological Society of London, 1982; Van Schalkwyk and Price, 1990).

In the DRASTIC approach to vulnerability mapping, Geographic Information Systems (GIS) are applied as it was developed by the United States Environmental Protection Agency (US EPA). This method incorporates the main geological and hydrological properties which influence and control groundwater movement into, through and out of an area, subsequently rendering the aquifer more or less prone to contamination. The seven weighted parameters which make up DRASTIC are Depth to groundwater, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity (e.g. Xiaohu *et al*., 2008; Aller *et al*., 1987).

The Model-Setting-Scenario approach combines settings and scenarios to create a conceptual model addressing the subsurface. The settings generally refer to areas characterised by constant environmental parameters such as bedrock, climate, land form, structural lineaments, surface drainage and so forth. The scenarios overlain on these settings represent hydrological parameters which can be determined in the field or in the laboratory, notably the depth to groundwater, hydraulic conductivity or transmissivity, permeability and porosity. The scenarios are then used to quantify the hydrological behaviour of each model rather than applying an index as per the vulnerability approaches (Dippenaar *et al*., 2009a).

The common parameters considered intrinsic site-specific are used to define the settings, namely climate (which is related to the water available for recharge), geology (which influences the aquifer and soil media) and landform (which is a function of topography and, notably, relief in terms of slope angle and length). The scenarios to be ranked are those DRASTIC parameters which can be determined in the field or laboratory. The depth to water represents the thickness of the vadose zone and the hydraulic conductivity is related to the rate of seepage through the vadose zone and therefore also the permeability.

The final models will be the DRASTIC parameter relating to the impact of the vadose zone. These models will therefore have very specific vadose zone thicknesses and hydraulic conductivities per setting of similar climate, geology and land form.

Study Area

The study area is situated within the Middle Letaba and Molototsi Quaternary Catchments, Limpopo Province, as shown in Figure i. According to Du Toit (1979), the topography of the area comprises of three units: the plateau area ranging from 850 to 1000 m above sea level, the escarpment ranging from 600 to 900 m and the Lowveld below 600 m. The escarpment is uneven and strikes in a north-south direction with an elevation decreasing from 900 m in the west to 600 m in the east. Both the Molototsi and Middle Letaba catchments comprise valleys draining from the southwest towards the northeast. Typically, the upper parts of the catchments are steep (slopes between 30º and cliffs), gradually decreasing towards the lower parts and the flatter flood plains (Brandl, 2006).

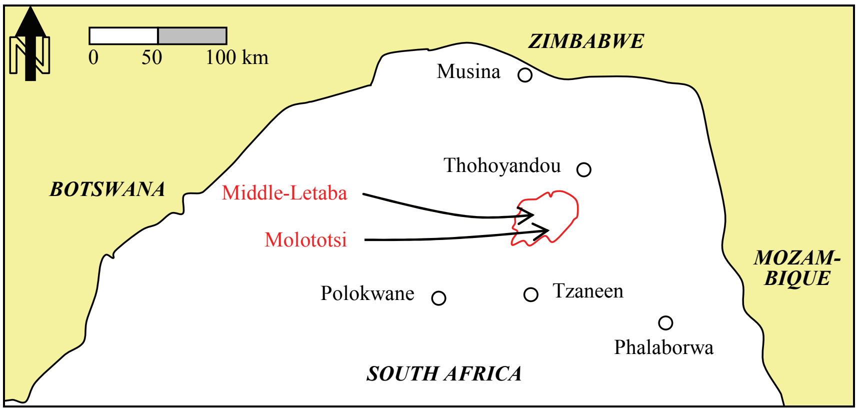

Figure i. Locality of the study area.

The climate of the area varies from arid in the west to semi-arid and temperate in the central zones and semi-arid in the east. The study area is a summer rainfall region with precipitation events which are usually in the form of intense convective thunderstorms.

The regional geology (Figure 11) of the study area comprises essentially Goudplaats-Hout River Gneiss, Duivelskloof Leucogranite and localised occurrences of amphibolite, mafic granulite and metapelite of the Bandelierkop Complex and amphibolite and magnetite quartzite of the Rhenosterkoppies Greenstone Belt. Various structural features cross-cut the area, including approximately northeast-southwest striking faults and intrusive diabase dykes.

Application and Results

In terms of the lateral or spatial zone classification, the implications are possibly significantly more limited than initially anticipated. The importance of the lateral vadose zone classes is essentially limited to one concept: initial infiltration into the root zone. What happens after this, concerns vertical vadose zone classes. It is therefore important to characterise the potential of water to bypass runoff and evaporation to – in the end – infiltrate beyond the root zone and become available for percolation. This is not necessarily solely dependent on the geology, rainfall and landform, and should, therefore, be focussed around the following parameters:

- Rainfall intensities per event over a meteorological cycle of varying climate

- *In-situ* topsoil (in tens of centimetres) textural and structural porosity rather than grading
- Vegetation and slope to reduce runoff rates, subsequently improving infiltration.

The vertical vadose zone classification became significantly more important as the project progressed. Under the assumption that water is infiltrated into the infiltration zone, the favourable parameters from a spatial classification can easily now become less favourable conditions. Vegetation, for instance, can improve infiltration, but potentially decreases percolation due to transpiration. A fine-grained soil can allow infiltration due to extensive cracking or biotic processes, but can become almost impermeable at depth. The vertical classification should therefore distinctly address the variations in these parameters per horizon between the land surface and the phreatic surface.

Conclusions and Discussion

The first objective entailed an assessment of the empirical approaches employed to estimate hydraulic conductivity from soil grading analyses. Two very distinct clusters of ranges (depending on the method) were identified, namely a low-K scenario ranging between approximately 10^{-15-}-10^{-7} m/s and a high-K scenario ranging between approximately 10^{-9}-10^{-2} m/s. Despite the great variation between the various empirical methods, all approaches seem to adequately distinguish between coarser-grained (more permeable) materials and finer-grained (less permeable) materials. However, no definite hydraulic conductivity can be assigned due to the high variation in the results.

The second objective entailed estimation of alternative parameters. The first of these comprised the estimation of the *effective grain size diameter*. This was plotted against the average hydraulic conductivities determined from the empirical approaches. Two distinct correlation situations exist: (a) for the same range of effective grain sizes, two possible fits can be seen where $K > 10^{-5}$ m/s and where $K < 10^{-5}$ m/s, or (b) high variation in K can exist within clusters separated by $d_e \approx 0.02$ mm. For excessively fine-grained materials, typically $d_e > 0.011$ mm correlating to approximately $d_{30} < d_e < d_{45}$. For coarse-grained materials, typically $d_e < 0.046$ mm, correlating to approximately $d_5 < d_e < d_{20}$. This clearly indicates the motivation for $d_e = d_{10}$ for most of the methods applicable to coarse-grained materials.

Two alternative and new parameters were also applied to the dataset. The *effective liquid limit* relates to the actual moisture content required in the bulk of the material in order to lose its plastic behaviour. This correlates fairly with the empirical hydraulic conductivities. A distinct drop in estimate hydraulic conductivity is observed around $LL_{eff} = 20$, suggesting that (under the assumption that the K values are correct) a distinct change in hydrological properties occurs around this value, resulting in a sudden drop in K of four orders of magnitude. The correlation also improves significantly around this value. A *coarseness index* was also calculated to increase the influence of pore-creating (gravel) and pore-clogging (clay) grains with respect to the more intermediate particle sizes (sand and silt). A good correlation exists between the CI^+ and K, although more definition of the parameter is required. At present, the CI^+ can either (a) serve as a correction factor for the non-uniformity of the soils and aid in achieving a scenario of $C_U = 1$, or (b) have a direct relationship to the porosity or even permeability.

Thirdly, the field and empirical results were compared. A very poor correlation was determined where the field K was typically in the range 10^{-4}-10^{-5} for empirical K between 10^{-6} and 10^{-11}. This is probably due to (a) the high variation in the empirical methods and the uncertainty of the accuracy of these methods, or (b) the field tests not necessarily reaching saturated steady-state conditions and subsequently not relating to the actual seepage rates.

The fourth objective – the zoning of the area into similar vadose zone properties pertaining to hydraulic conductivity and vadose zone thickness – was not completed during this study due to the vast amount of factors requiring refinement. Firstly, the methods applied to determine *K* in the field, laboratory and empirically need to be assessed in more detail, and secondly a vertical vadose zone classification is also required due to the changing properties with depth.

Finally, the aspects requiring refinement needed identification. These, at this preliminary stage, include better determination of porosity and hydraulic conductivity, as well as a better understanding of the influence and variation in geology with depth and spatially.

A preliminary vadose zone classification methodology is shown schematically in Figure ii.

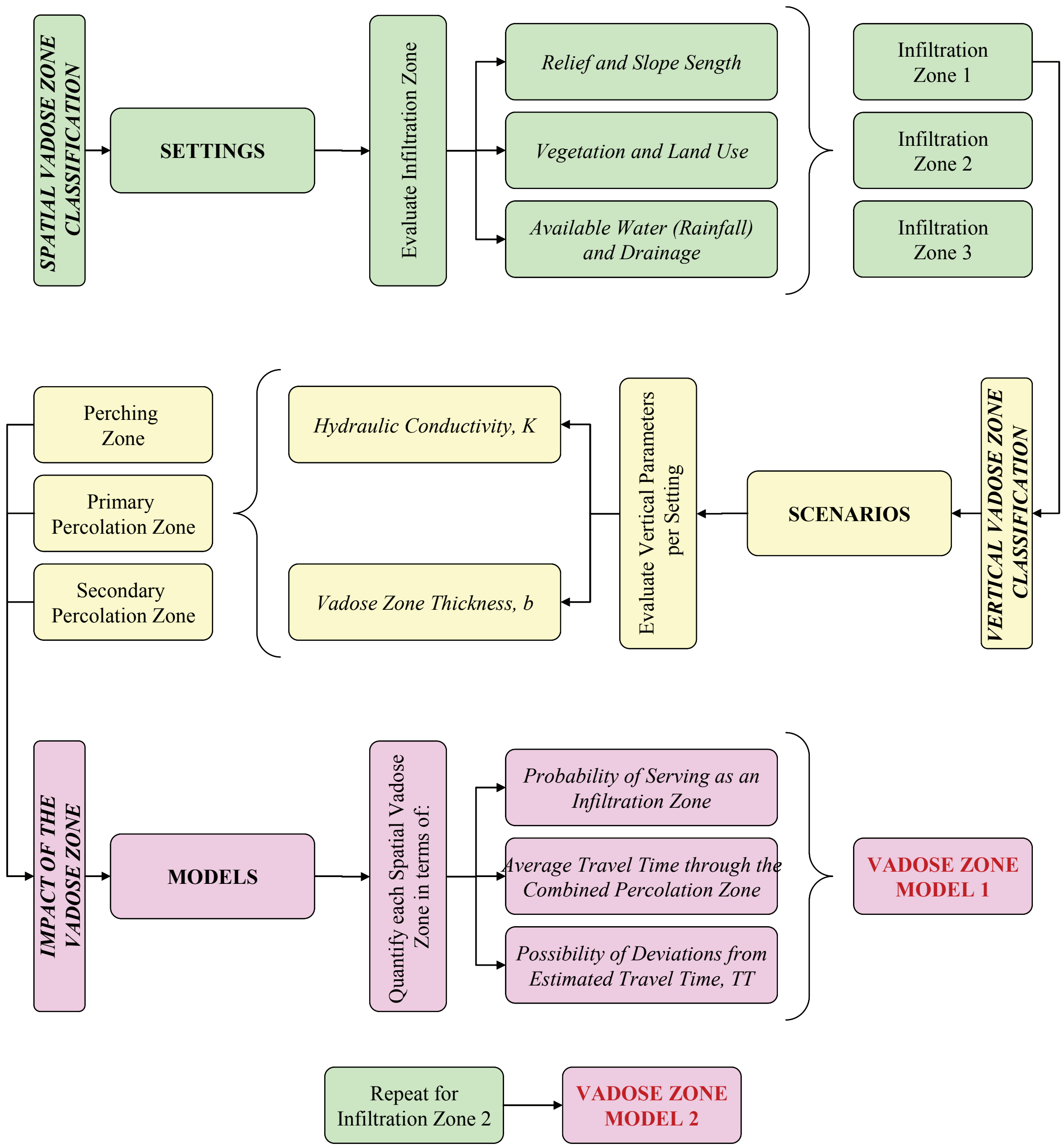

Figure ii. **Preliminary vadose zone classification methodology.**

The approach entails three phases per setting as follows:

- The ***Spatial Vadose Zone Classification*** pertains to the identification of the settings based on the possibility of infiltration of surface water into the plant root zone or infiltration zone. This initial spatial or lateral classification is a function of the slope angle and length or relief, the land cover, the geomorphological controls of surface hydrology, and the rainfall intensity. Based on this, the study area is subdivided into a number of settings or infiltration zones.

- The ***Vertical Vadose Zone Classification*** expands on the vertical variation or horizons underlying each infiltration zone. A deeper profile is required at this stage to evaluate the presence or absence of perching zones as well as primary and secondary percolation zones. For each of these horizons, the thickness should be estimated and a percolation rate should be determined, preferably via field and empirical methods. The weighted average of these horizons can be based on the thicknesses of the relevant horizons to quantify the scenario.

- The ***Impact of the Vadose Zone*** supplies a conceptual yet quantitative model of each of these zones by overlying the potential of infiltration with the vertical heterogeneity of the vadose zone horizons. The model therefore addresses the possibility of infiltration, followed by a travel time, *TT*, calculated as *b/K* for the complete thickness of the vadose zone in a specific setting. Any potential deviations (e.g. sporadic occurrences of pedocrete, springs, more pronounced biotic activity, anthropogenic impacts, etc.) should be clearly stipulated per zone and, if possible, included to provide a worst-case scenario (fastest travel time).

The Way Forward

Work is ongoing to address a number of issues. These can be classified as (1) empirical assumptions and methods, (2) field methods and applications, (3) lateral or spatial classification and (4) vertical or horizon-based classification.

(1) In terms of the empirical methods, the main issues are:

- The assumptions pertaining to empirical grading-based estimation methods need to be refined or, if possible, dismissed. The primary assumptions are the porosity, effective grain size diameter and uniform grading, all of which directly influence the hydraulic conductivity but which cannot always be determined.

- Determination of porosity via Istomina yields porosities ranging between 0.25 and 0.26 for both exceptionally fine-grained and coarse-grained materials. This very narrow range of porosities for highly variable materials is not considered valid.

- The assumption of uniform or near-uniform materials is invalid as the majority of natural *in-situ* -soils contain a wide range of particle sizes in highly varying ratios. A uniformity coefficient below four is very scarce in nature and the applicability of the methods is therefore compromised.

- The effective grain size diameter is mostly estimated loosely around the d_{10} value without much scientific reasoning and is applied mostly in sandy materials. Calculation of the effective grain size diameter as a "most frequently occurring" grain size yields significantly different sizes for clayey and gravelly materials. The question here is, however, which particle size indefinitely determines the seepage behaviour of a material (with the notable emphasis on flow-promoting and flow-prohibiting grain sizes).

- *In-situ* structures (i.e. joints, burrows, roots) and pedological processes (i.e. eluviation and illuviation, pedogenesis) inherently either improve or mar seepage. These aspects are not included in disturbed sample analyses and subsequently are not included in the empirical results.

(2) In terms of the field methods, the main issues are:

- Most field methods assume profile saturation or pre-soaked conditions. This is rarely achieved due to lateral dispersion of water, capillary action and gravity. In clayey soils, the water will disperse three-dimensionally over greater distances and in sandy soils the majority of the water may seep vertically without ever reaching saturation. Different approaches may, therefore, be required.

- Vertical heterogeneity (vertical classification) is not addressed during field tests and the properties of one horizon is extrapolated throughout the complete vadose zone thickness.

(3) In terms of the lateral classification, the following needs to be addressed:

- Identifying zones of infiltration from surface should be considered a function of the surface soil texture and structure as this forms the primary pathway of moisture into the subsurface. From here and once past the root zone only can water become available for percolation and possibly recharge. In these lateral or spatial classes, the topsoil should therefore be considered rather than geology, climate and landform alone. This outlines the need for a combined lateral and vertical classification.

(4) In terms of the vertical classification, the following issues need to be addressed:

- The parameters to classify the vadose zone vertically should be both a flow rate (or hydraulic conductivity) and a vadose zone thickness (or depth to water level). Fast percolation to a deep water level and slow percolation to a shallow water level may require the same travel time.

- Percolation is not considered to be a continuing process. Rather, one should consider that moisture can be retained in the unsaturated zone due to capillary processes overriding gravity. A percolation event or a purging or flushing event can be triggered in any time frame, after which concentrated contaminants are mobilised rapidly rather than being slowly diluted over time. The same event can mobilise clays and ions to alter the soil properties at different depths, subsequently directly affecting seepage.

Ongoing work should focus on concepts rather than applications to clarify the fundamental scientific concepts. This can best be done by evaluating the following concepts:

- Lateral or spatial vadose zone classes and infiltration
- Vertical vadose zone classes (or vadose zone or horizons) and percolation
- Porosity estimates and textural versus structural porosity
- Travel times rather than flow rates (i.e. incorporating the water level or vadose zone thickness)
- Purging events and the triggering mechanisms
- Pedological and pedogenic processes associated with travel times and purging events that will influence porosity and percolation.

Application of the methodology is ongoing but, due to the number of important questions raised, the methodology needs to be refined. Additional study areas are presently being pursued on the granite and mafic igneous rocks of the western limb of the Bushveld Igneous Complex between Rustenburg and Northam.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABREVIATIONS

Symbol	Description
A	Cross-sectional area perpendicular to flow
C	Clay fraction
C, c	Constant values from literature
CI^+	Coarseness Index
C_U	Uniformity coefficient
d	Grain size represented by percentage denoted as subscript, e.g. d_{10}
d_e	Effective grain size diameter
d_i	Sieve or grain sizes pertaining to fraction f_i
e	Void ratio
f_i	Fraction of particles
g	Gravitational acceleration
G	Gravel fraction
G_S	Specific gravity
i	Hydraulic gradient dh/dl
k	Intrinsic permeability, absolute permeability, permeability
K	Hydraulic conductivity, coefficient of permeability
LL	Liquid Limit
LL_{eff}	Effective Liquid Limit
m	Moisture content
M	Mass
M	Silt fraction
n	Porosity
Q	Seepage, flux
q	Darcy velocity, specific discharge
S	Sand fraction
S_r	Degree of saturation
T	Temperature
V	Volume
v	(Linear) flow velocity
γ	Unit weight
μ	Absolute fluid viscosity
ρ	Mass density
$\varphi(n)$	Porosity function
Φ	Particle size/ sieve size/ grain size or diameter

Subscripts	
$_{A\ W\ S\ T}$	Air, water, solid, total fraction of sample
$_{S\ U}$	Saturated, unsaturated
$_{(max)\ (min)}$	Maximum and minimum values

INTRODUCTION

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1.1. Project Motivation

The project is based on historical research interests of the involved parties and follows on previous research within the Department of Geology. The interest in the topic originated from the application of certain methods in quantifying the unsaturated flow.

In groundwater studies, the combined influence of the vadose zone is often considered an estimated parameter. Recharge is commonly estimated to account for the amount of water reaching the phreatic zone or, in vulnerability assessments, the vadose zone is often an index based on the thickness of the vadose zone (depth to water table) and the rate of seepage through the unsaturated zone. These latter parameters may not be adequate to fully address the unsaturated flow through the Earth's crust and more detailed and certain parameters may be required.

The vadose zone is considered vital for two main reasons. Firstly, this represents the zone through which recharging water moves. The rate of seepage through the vadose zone and the presence or absence of zones of varying seepage rates will inherently influence the amount of water reaching the phreatic zone. Additionally, water cannot be only assumed to migrate vertically under the influence of gravity, and localised areas of lateral movement through interflow, perching of water and sorption processes need to be considered. Water infiltrates from land surface to percolate through the vadose zone; clearly this water is also often an important influence of foundations and subsurface sources of contamination.

Secondly, the vadose zone is host to numerous potential sources of contamination. In many areas, this represents the zone where septic tanks, pit latrines, cemeteries and waste disposal sites are located. Agricultural fertilisers and pesticides and contaminants from mine tailings enter the subsurface through the vadose zone with infiltrating water to potentially contaminate the groundwater. In urban areas, additional sealing of the crust and leaking subsurface pipelines can change the local hydrology as areas for recharge and discharge can be changed directly.

1.2. Scope of Work

The project aims to classify the vadose zone quantitatively, i.e. to assign numerical parameters to the unsaturated zone which may aid in addressing more important matters such as recharge (zones and rates), percolation and infiltration (with regard to surface and shallow subsurface contamination sources) and, finally, the susceptibility of the aquifer to infiltrating water and contaminants.

The objectives of the research were to:

- Assess some of the empirical approaches to determine hydraulic conductivity based on soil grading analyses

- Evaluate alternative parameters and methods to determine the hydraulic conductivity based on soil grading analyses
- Conduct field test to determine seepage rates and compare the results with empirical methods
- Zone the study area into areas of similar hydrological behaviour, notably with respect to groundwater depth and infiltration rate
- Determine aspects requiring refinement for future research projects.

As this consultancy project is only a preliminary classification, recommendations will be made with respect to further research required.

1.3. Methodology

As this project entails a classification methodology, the project was approached with the following course of action:

1. Assess the present methods being applied in the field and laboratory on a literature study level to ensure complete understanding of the *status quo*

2. Apply the methods to a study area in Limpopo Province

3. Correlate the results and attempt zoning the study area into different vadose zone classes.

The final methodology is to be determined and will be discussed in more detail in later sections.

THEORETICAL BACKGROUND

1.4. The Need for Vadose Zone Research

Large portions of South Africa are dependent on groundwater as a sole source of potable water. The presence of groundwater is, however, not always the concern and the emphasis shifts towards maintenance of the infrastructure and the prevention of pollution of the groundwater resource.

The utilisation of groundwater is becoming increasingly prominent due to its lower susceptibility to contamination compared to surface water (Melloul and Collin, 1998). The movement of water in the vadose zone is the mechanism of introducing surface contaminants to the groundwater or saturated zone. In order to keep the groundwater unpolluted, it becomes important to be able to outline areas of higher or lower susceptibility to pollution (Babiker *et al.,* 2005). Voss and Tesoriero (1997) elaborate on the importance of identifying such areas that are susceptible to contamination for land use planners and environmental regulators to minimize groundwater contamination. This leads to the concept of groundwater vulnerability which considers the physical environment as a means of protection against impacts, notably relating to contaminants entering the subsurface (El Naga, 2004) or that intrinsic property of a groundwater system which depends on the sensitivity of the system to any anthropogenic or natural impacts (Vrba and Zaporozec, 1994). Expanding on these concepts of susceptibility and vulnerability includes groundwater protection strategies, water use restriction, land use alteration versus groundwater contamination, monitoring, remediation and public awareness, all aiming to protect the underlying groundwater (Metni *et al*., 2004).

DWAF (2003) elaborates on contamination reduction, noting the unsaturated or vadose zone as the "first line of natural defence" against groundwater pollution as it attenuates contaminant movement. The contaminant reduction is considered dependent on the unsaturated flow rate, the type of contaminant and the media's ability to absorb the contaminant or prohibit its further movement. Although this is applied to a sanitation context, it can be expanded to any surface or subsurface contamination source.

In rural areas, ground-based sanitation systems are usually the cheapest and easiest to install. These systems, however, release significant amounts of contaminants into the subsurface to potentially reach the groundwater table in densely populated areas. The same applies to waste disposal in poorly designed waste sites and cemeteries in rural areas where the money is not always available to adequately design these systems.

In agricultural areas, the focus shifts towards irrigation with contaminated water from for instance hatcheries, fertilizer and nutrients infiltrating the subsurface, subsurface septic tanks and underground storage tanks. This also applies to more developed areas where contamination emanating from subsurface sewerage pipelines, underground storage tanks and waste disposal sites can adversely affect the groundwater regime. Considering waste disposal, landfills are (depending on its depth) essentially located within the vadose zone and leakage from such landfills increases the possibility of groundwater contamination due to the gravity-driven movement of leachate through the landfill (El Naga, 2004).

The vadose zone represents that pathway through which all these mentioned contaminants have to travel before reaching the groundwater table. According to Stephen *et al*. (2007), the movement of water and contaminant transport between the land surface and the aquifer can be very slow processes. Sililo *et al*. (2001) confirm this by stating that the travel time, attenuation capacity and contaminant quality depend on the sub-soils overlying the groundwater, the type of recharge (point versus dilute), and the vadose zone thickness (or depth to groundwater level). This clearly accentuates the need to better understand the vadose zone as the pathway between the surface and the groundwater.

Some of the fundamental concepts and assumptions regarding water movement through soil are inaccurate and very probably not plausible. This conclusion pertains to the vadose zone and therefore influences contaminant transport and recharge. Soil attracts the initial precipitation and subsequently vertical movement of water is not necessarily related to rainfall events (Oregon State University 2010). This is supported by the general perception that a certain level of saturation has to be breached, notably in low permeability soils, before seepage can commence. Recharge is therefore not a continuous process, but a function of surpassing a certain moisture content (which will differ from soil to soil) to trigger the gravity-driven movement of water.

It should be clearly noted that this project entails a ***preliminary classification methodology*** and, therefore, excludes recharge estimation and factors governing recharge as the focus is on infiltration and percolation within and through the vadose zone. At inception of the project, the aim was solely to determine spatial variations is vadose zone properties. This has changed as it was found that the fundamental concepts of vadose zone characterisation are often wrong, misapplied or too vaguely defined, leading to often irrelevant results. A thorough review and reassessment of the existing methodologies will be required in future.

1.5. The Vadose Zone Pathway

Figure 1 shows the vertical distribution of groundwater in the crust. The ***vadose zone***, also called the unsaturated zone or the zone of aeration, stretches through the so-called soil zone and intermediate zone and incorporates the upper cusp of the ***capillary fringe*** where the medium is still below saturation. Fetter (1994) defines the vadose zone as “the zone between the land surface and the water table.” He continues to state that this includes the root and intermediate zones and the capillary fringe and represents that portion of the crust where the pore spaces contain water at pressures below atmospheric, air and other gases. A perched water table may exist within the unsaturated zone.

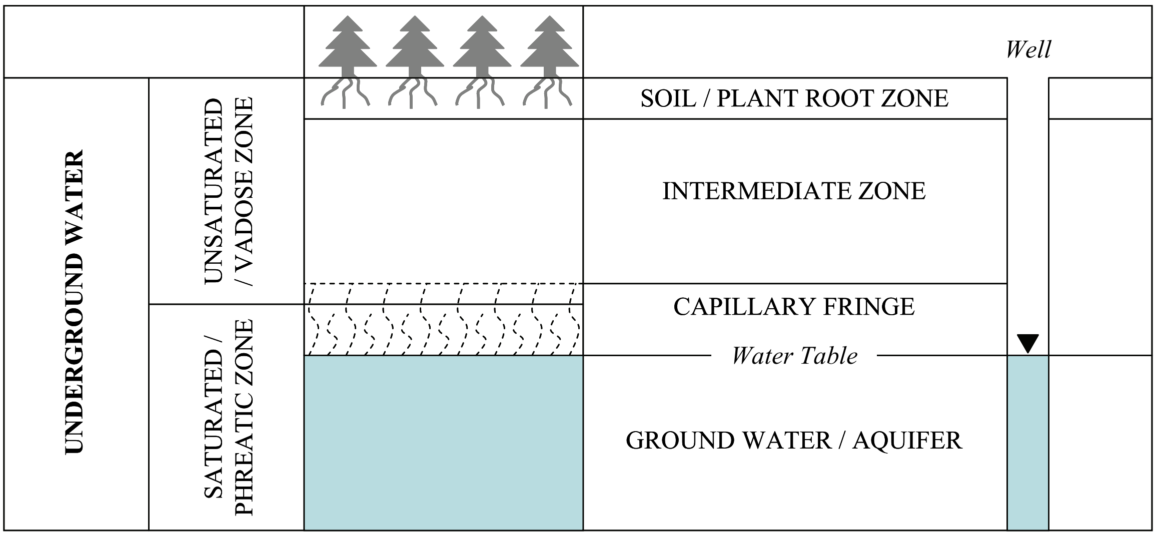

Figure 1. Vertical distribution of groundwater in the crust (not to scale).
* (From: Dippenaar *et al*., 2005, after Heath, 1995; Fetter, 1994; McCuen, 1989)

The occurrence of water in the crust can also be depicted as shown in Figure 2. In this instance, distinction is made between hygroscopic, seepage, capillary and groundwater. Skolasińska (2006) elaborates on this concept with the addition of the most common clogging microstructures which develop. Clay concentrates essentially in the vadose zone, over the water table and above impermeable barriers, mainly in the form of geopetal structures, meniscus-shape bridges, coatings (cutans), loose aggregates and massive aggregates. The first two clogging structures are associated with the vadose zone and the latter two occur where water flows around an under-developed film of adhesive water around grains. Massive aggregates and coatings are generally associated with the phreatic zone (Skolasińska, 2006; Walker, 1976).

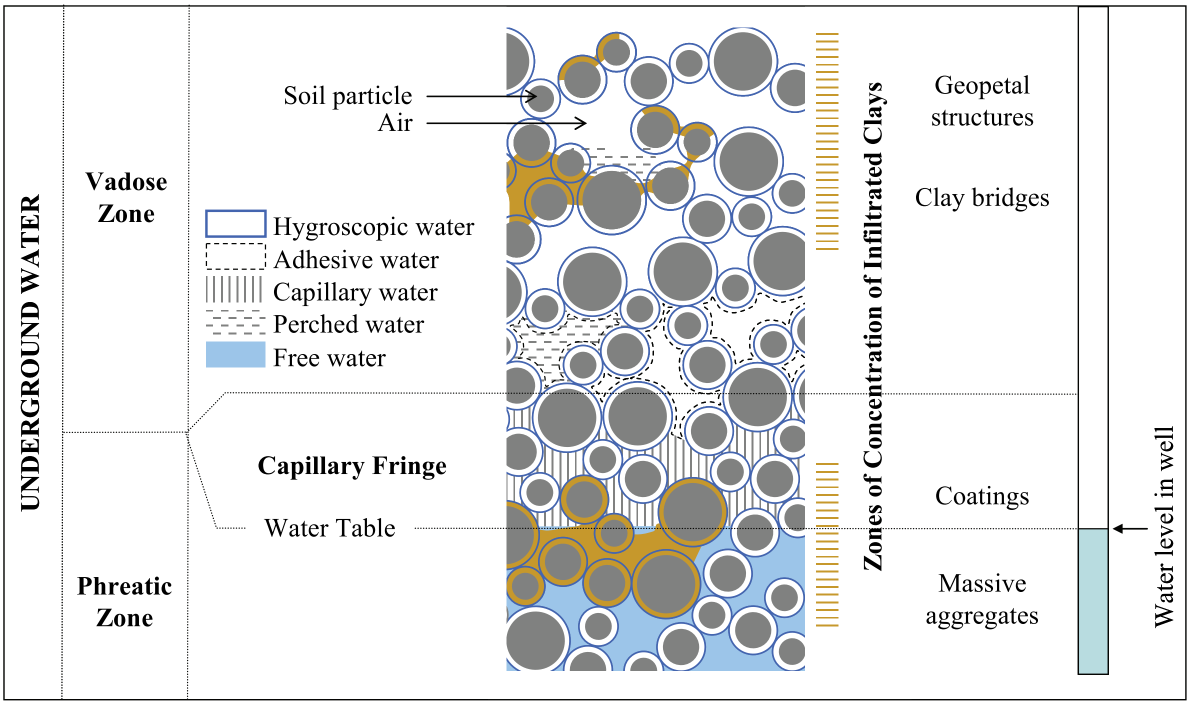

Figure 2. Vertical distribution of water in the crust and the concomitant clogging structures.
* (Adapted from: Shaw, 1994; Skolasińska, 2006; Moraes and De Ros, 1990)

The presence of perched water tables or fluctuating groundwater levels can lead to the development of pedogenic soil horizons. Due to the formation of pedocrete, the permeability is lowered and vertical percolation through this horizon becomes significantly less. The process of pedogenesis is influenced by the subsurface, down-slope drainage until such a point is reached on the slope where precipitation of transported ions commences. This is then the zone of pedogenesis, leading to the formation of laterite, ferricrete, calcrete, silcrete or other pedogenic materials based on the available ions and the climatic conditions. Depending on which process predominates, this soil horizon can be either a ***pedogenetic pedocrete*** (due to percolating water from surface and the precipitation of mobilised elements above a less permeable horizon) or a ***groundwater pedocrete*** (due to seasonal fluctuations in groundwater level or groundwater perching and the concomitant precipitation of elements dissolved in groundwater). This is shown in Figure 3.

Depending on the depth to groundwater, bedrock can form a major part of the vadose zone. Bedrock underlies the transported material and often a characteristic pebble marker (or stone line), and generally grades from residual bedrock to intact bedrock at depth. The pebble marker typically forms the contact between transported and residual soils and represents that transition. Pedocrete horizons typically occur within the base of the transported soils, the pebble marker, or within the residual and completely weathered materials. Slight deviations in the proposed transitions may therefore occur.

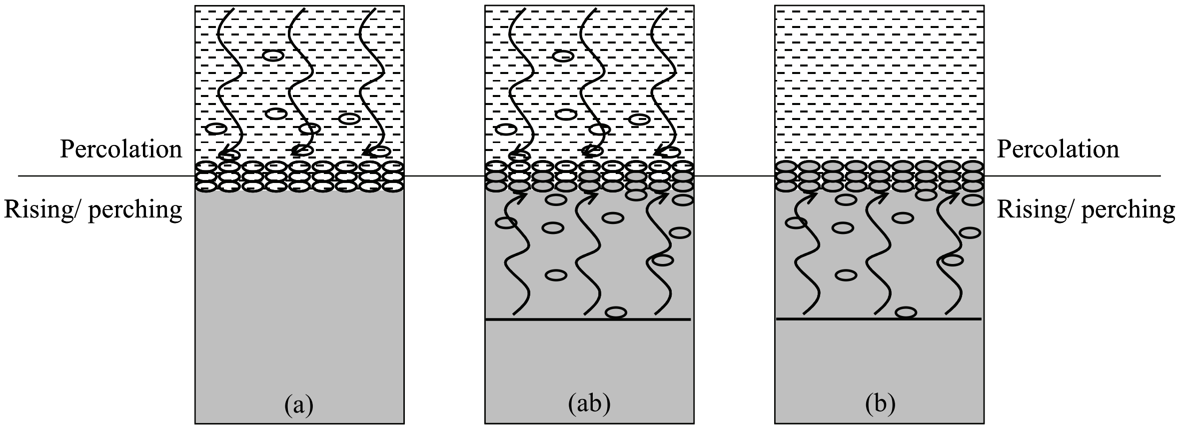

Figure 3. Pedogenetic (a), groundwater (b) and combined (ab) pedocrete formation.
* (Adapted from: McFarlane, 1976)

The factors controlling flow through rock differ from those controlling flow through unconsolidated porous materials, and a distinction therefore needs to be made. Notably, secondary porosity comes into consideration and these can often transmit higher volumes of water than primary porosity.

A ***fracture*** can be defined – in structural geological terms – as any "… discontinuity across which there has been separation…", and including faults and joints. This can be elaborated to a fracture zone, referring to a zone of such fractured rock, notably with reference to aquifer materials (Keary, 2001).

The term ***fissure*** is often applied, especially in the USA, to replace fracture. According to the American Geological Institute (1976), a fissure refers to "… an extensive crack, break or fracture in the rocks". This usually excludes mere joints or cracks which persist only for short distances.

Intact refers to unaltered and unbroken media. In terms of geology, this applies to bedrock that is fairly unweathered and unfractured with the bulk of the rock being undisturbed and unchanged. This is seldom applicable as it can be assumed that practically all rock has undergone some means of deformation or altering. Subsequently, referring to intact rock is usually reapplied to large portions of such intact rock, and clearly the term becomes subject to the scale of observation.

Based on the abovementioned terminologies, the definitions as shown in

Figure 4 will apply when addressing the physical nature of the subsurface materials.

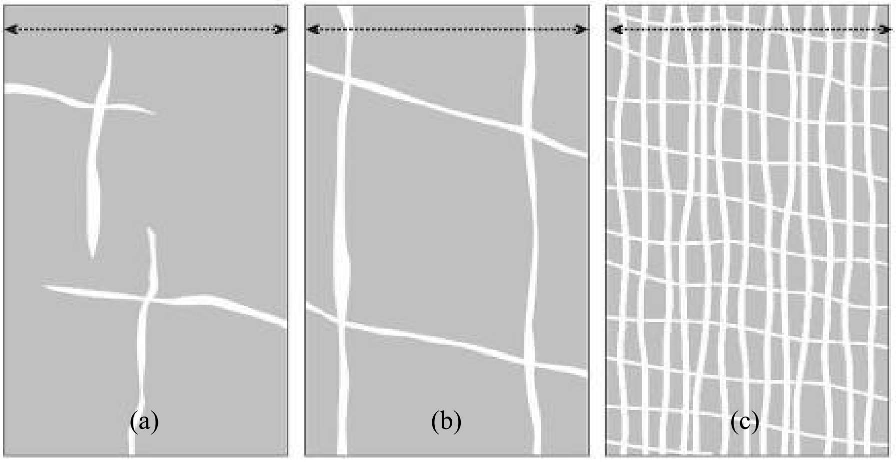

Figure 4: **Intact (a), fractured (b), and fissured rock (c); dotted arrows indicate 1's to 10's of metres.**

1.6. Transport and Flow Mechanisms

Before one can assess the actual processes driving the migration of water through the vadose zone, it is essential to first review the mechanisms of fluid transport or flow. These mechanisms mainly relate to contaminant transport, but do also apply to the mechanical movement of the fluid in which the contaminant is transported as well.

Diffusion is the movement of contaminants from a higher to a lower concentration and applies specifically to contaminant transport in stationary water (Deming, 2002). This mechanism will therefore not be considered as the intent is to assess the vertical movement of water.

Advection refers to the process whereby a contaminant or solute is transported with moving groundwater. When considering the process of advection, the linear flow velocity of the groundwater is used to address the contaminant transport process (Deming, 2002). This mode of transport can therefore be applied both as a means of bulk water flow, as well as a means of flow in the unsaturated zone. Fetter (1994) defines advection as the same rate as the average linear velocity of groundwater (when considering contaminant transport) and is defined according to Darcy's Law (0).

Dispersion refers to a process of mechanical mixing and, depending on whether the mixing is perpendicular to or along the flow path, it can be either transverse (lateral) dispersion or longitudinal dispersion (Deming, 2002). Once again, this can be applied to uncontaminated water and the influence of soil medium on the flow itself. A distinction is made between mechanical dispersion (due to changes in pore sizes and flow path lengths due to clogging of pores) and hydrodynamic dispersion (including molecular diffusion), both being functions of the average linear velocity and the dynamic dispersivity and, in the latter instance, molecular diffusion. Hydrodynamic dispersion will, however, not be relevant to the flow of water only and subsequently only mechanical dispersion will be considered. Dispersion is due to the interaction between the fluid and the porous medium through which it travels, and subsequently is influenced by the complex pore system rather than the molecular motions (Smettem, 1986; Bear, 1969).

Apart from advection (flow) and dispersion (changes in flow velocity and direction), numerous other processes propagate the flow of water in the subsurface. However, these two terms will be applied to distinguish between water that flows due to energy along interconnected pores as governed by the hydraulic head (***advection***) and changes or deviations in advection due to textural and structural changes, capillarity, adhesion and suction (***dispersion***) as shown in Figure 5.

Dispersion can be considered one of the mechanisms affecting flow in terms of changing the rate or the direction of advection. These terms can be applied to the unsaturated zone so that (a) advection is the essentially vertical gravity driven seepage (infiltration, percolation) of water and (b) dispersion is the lateral suction (capillary action, interflow) of water due to changes in matrix and structure of the materials. Additionally, water can adsorb to mineral grains.

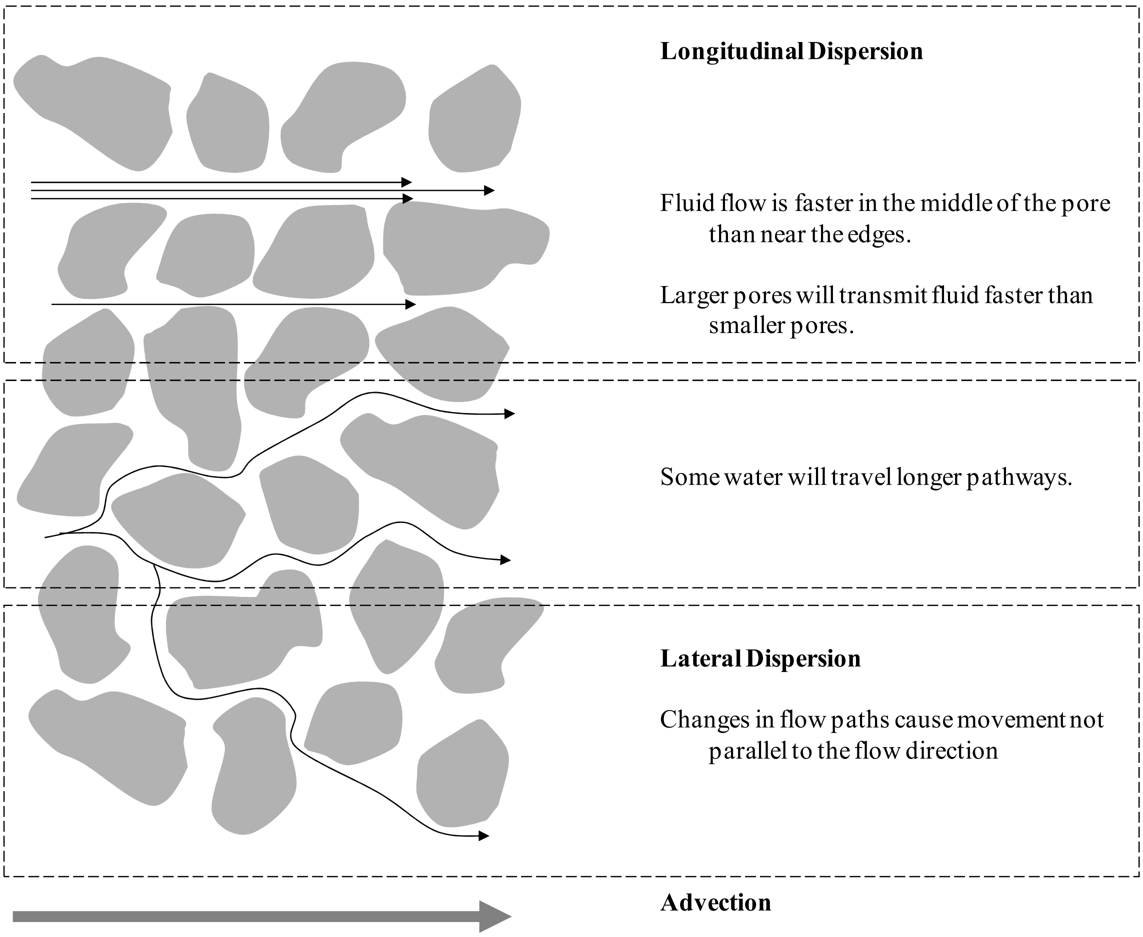

Figure 5. Schematic representation of longitudinal dispersion, lateral dispersion and advection.

* (Adapted from: Fetter, 1994)

1.7. Infiltration, Percolation and Recharge

For the sake of consistency and interdisciplinary understanding, certain terms have to be redefined. When considering the hydrological cycle, precipitation events supply water to the land surface from where three natural processes can continue: infiltration, overland flow or evaporation. Infiltration is increased by porous and permeable materials and is more pronounced during the first moments of a large precipitation event when the material is still fairly unsaturated (Fitts, 2002). Infiltration is considered the most common process of groundwater contamination and refers to the downward migration of water (originating from precipitation) under the influence of gravity through the open pores within the soil matrix. During infiltration, materials are being dissolved and/ or mobilised. Infiltration continues sub-vertically under gravity until the groundwater level is reached, from which the infiltrating water (*sic*. 'percolating' based on subsequent paragraph) will spread laterally in the direction of groundwater flow and vertically due to gravity (Boulding and Ginn, 2004).

Jenn *et al*. (2007a) define infiltration as that process responsible for letting water on ground surface pass into the vadose zone, including the volume of the water, and it is governed by gravity forces and capillary action. Allaby and Allaby (2003) define infiltration as the "downward entry of water into soil" which is confirmed by Keary (2001), stating that infiltration is the "entry of water into the soil, usually by downward flow through the surface". The American Geological Institute (1976) adds that this movement of water is through pores or small openings through the soil surface into the ground.

Once water has infiltrated into the subsurface, four processes can occur: adhesion to soil, interflow (lateral flow in the unsaturated zone), transpiration (or evaporation if shallow enough) or percolation (e.g. Fitts, 2002; Shaw, 1994). Interflow water can daylight on surface again or can start percolating further down-slope. Percolation refers to that vertical movement of water through the unsaturated zone to the water table (Shaw, 1994) or to "pass through fine interstices; to filter' as water percolates through porous rock" (American Geological Institute, 1976). In terms of pedology, percolation is considered that downward movement of water through soil material, notably in saturated or near-saturated conditions (Allaby and Allaby, 2003). Some sources consider percolation part of infiltration and do not distinguish between the two concepts.

Water eventually reaching the saturated zone is referred to as recharge (Fitts, 2002). Jenn *et al*. (2007b) define recharge as that process whereby water infiltrates through the vadose zone, eventually reaching the groundwater surface and adding water to the aquifer, occurring as the net gain from precipitation or runoff. De Vries and Simmers (2002) summarised the current understanding of recharge processes, concluding that intrinsic limitations occur with the well-established methods of recharge estimation. They further state that climate is not the only parameter of importance, but also the surface and subsurface conditions which incorporate lithology, palaeoclimate and palaeohydrological evolution.

Water, therefore, needs to (a) infiltrate from surface into the subsurface, (b) percolate through the vadose zone and (c) recharge the groundwater. For the sake of this paper, the following definitions apply:

- ***Infiltration*** refers to water entering the subsurface from the surface (due to the primary porosity or texture and secondary porosity or structure of the surficial soils which creates openings) and which is still affected by evapotranspiration; then moving sub-vertically downwards under the influences of gravity and dispersing three-dimensionally under the influence of capillary action.

- ***Interflow*** refers to water migrating laterally due to less permeable horizons (or perching on these horizons and then moving down-slope) marring the further percolation of water to either discharge as a spring or to percolate at a point further down-slope.

- ***Percolation*** refers to water migrating sub-vertically downwards within the unsaturated zone in near-saturated conditions under the influence of gravity (therefore excluding interflow) and significantly less influenced by evapotranspiration processes and excluding capillary processes.

- ***Recharge*** refers to water reaching the water table and the saturated (phreatic) zone and becoming – in effect – part of the groundwater.

Field capacity can be defined as that water content which a soil can retain after the excess free water has drained away under the influence of gravity (Allaby and Allaby, 2003). This represents a volume of water which is introduced to the subsurface but not available for percolation.

In a study by Glass *et al*. (1988) it was found that the wetting front of this infiltrating water is characterised by a fingering effect rather than a discrete line of wetting. This was experimentally measured in one-minute intervals and also shows how – during the vertical migration of these "fingers" – lateral dispersion takes place to create a less saturated "fringe" between these saturated fingers. This fingering effect is ascribed to two processes, *viz*. (a) the textural change within the soil matrix and (b) the presence of macropores in the topsoil which concentrate the flow of water non-uniformly in the subsurface layers.

1.8. Classification Systems and Nomenclature

An important aspect regarding the vadose zone is the numerous disciplinary approaches followed. Each discipline defines and describes the vadose zone based on the need for assessing this zone, and subsequently a number of approaches are available. For hydrogeological purposes, however, merging of some of these approaches may be most applicable.

As stated by Van Tol *et al*. (2009), an interactive relationship exists between soil and hydrology. During their study, they found that certain pedological materials distinctly affect hydrology in terms of recharge and/ or discharge zones, and that this is mainly noted by the colour of the soil. Another methodology is that followed in engineering geology where the soil origin predominates as a parameter intrinsically relating to the soil mineralogy and degree of consolidation. Both these parameters are directly indicative of the porosity of the soil materials.

For the civil engineer, the importance of the vadose zone is twofold, *viz*. to address seepage, and to address the material properties. Mainly this becomes a matter of assessing the moisture content, grading and density relationships of material to quantify the soil properties for designing purposes.

During a discussion session at the 2009 Biennial Groundwater Conference: Pushing the Limits (16-18 November 2009, Somerset West, South Africa), the opinion was shared that the merging of the holistic pedological naming of the soil profile together with the horizon-specific origin-based approach of engineering geology may be the best means of assessing the soil material.

Ehlen (2005) elaborates on the different perceptions on weathering and terminology (Table 1). From this, one can deduce that a certain range of interest is covered: (a) the geologist is interested in the parent material and the intrinsic chemical and mineralogical properties; (b) the soil scientist addresses the soil formation through soil classification; (c) the geomorphologist assesses the spatial context (including time) in which the landform evolved; and (d) the engineering geologist or civil engineer is concerned with the physical properties of the weathering product.

Table 1. Perspectives on weathering in different disciplines.

Discipline	**Primary Interest in Weathering and Profiling**
Soil science	Soil-forming processes; classification; shallow profiles from open pits; one-dimensional A, B and C horizons
Geotechnical Engineering / Engineering Geology	Physical environment; site characterisation; soil/ rock mechanics; one-dimensional rock material versus rock mass
Geomorphology	Weathering processes; spatial context; weathering versus landform evolution; weathering rates; dating of events
Geology	Mineralogy and chemistry (especially clay chemistry); notably intact bedrock and not overburden; one-dimensional movement of elements

* (After: Ehlen, 2005)

Based on this, the importance of an interdisciplinary approach is once again accentuated. For the pedologist, the main importance of water is the availability thereof to be used by plants. For the engineering geologist and civil engineer, water is crucial when considering drainage, seepage and moisture affecting foundation and subsurface structures. Additionally, moisture in the soil alters mineralogy which affects the use of the materials during construction. Geology addresses the aquifer material and structure; geomorphology drives recharge and discharge, as well as runoff and infiltration; soil science taxonomy is based on the hydrological behaviour of soils; and the civil engineering or engineering geological approach assigns numerical values (referred to as seepage) to the material. Depending on the purpose of soil classification for the various disciplines, different parameters are incorporated. However, irrespective of the classification system or discipline, the behaviour of moisture within the material is always a critical aspect.

This section aims to supply an overview of some of the most important soil classification systems to collate these systems into an optimised hydrological classification. It is important to note certain existing overlaps between the existing disciplines and that all approaches have been significantly summarised.

1.8.1. Pedology / Geology / Geomorphology

For the earth scientists – collectively including all disciplines studying the earth surface or subsurface – soil is a combination of minerals, organic matter, water, air and living organisms and refers to that portion of the regolith (rock and mineral fragments resulting from weathering of rock) which can support plant growth (Lutgens and Tarbuck, 2003; Miller, 1999). The American Geological Institute (1976) adds that soil refers to that earth material which can support rooted plants resulting from the modification due to physical, chemical and biological agents. The approach is to classify the soil into horizons, *viz*. the *O-horizon (*leaf litter), *A-horizon* (topsoil), *B-horizon* (subsoil) and *C-horizon* (parent material) lying on unweathered bedrock (Miller, 1999).

In terms of classification in South Africa, a diagnostic soil horizon has to occur, either in its entirety or partially, within 1.50 m from the land surface. If a young surficial material is present overlying the soil, the classification is based on the younger material only if its thickness exceeds 500 mm. Soil classification is then based on soil form and soil family. Soil forms refer to the type and sequence of diagnostic horizons (O, A, (G), E, B, C, R) and materials. Soil families refer to the conceptual approximations based on selected soil properties only (Soil Classification: a Taxonomical System for South Africa, 1991).

Well-drained to somewhat poorly drained soils often occur together in a typical topo-sequence (*viz*. changing concurrently with change in slope feature). This sequence of soil profiles can usually be superimposed on other similar topographical features, provided that the parent materials (i.e. bedrock) remain the same. The only parameters therefore influencing the soil type are drainage (given that the climate does not vary significantly over the study area) and changes in relief. This gives rise to the concept of a *catena* where the different soils can be distinguished based on the colours of the surficial horizons (Brady & Weil, 1999).

1.8.2. Engineering Geology / Geotechnical Engineering

For the engineer (and, to some extent, the engineering geologist), the definition of soil changes significantly, including all regolith (American Geological Institute 1976) and any loose, soft and deformable material (Allaby and Allaby, 2003). The engineering geologist in South Africa classifies soils based on the guide to soil profiling by Jennings *et al*. (1973) and contained in Brink and Bruin (2002). This system is presently being incorporated into a new South African National Standard (SANS 2009) pertaining to engineering geological investigations. The empirical correlation of these parameters with hydraulic conductivity was researched in detail by Van Schalkwyk and Vermaak (2002). The system is based on six parameters abbreviated as MCCSSO (Jennings *et al*., 1973):

- ***M***oisture; dry, slightly moist, moist, very moist and wet (where moist is the approximate equivalent of field capacity)
- ***C***olour; indicative of soil chemistry as well as aerobic versus anaerobic conditions with secondary discolouration features also indicated.
- ***C***onsistency; very loose, loose, medium dense, dense, very dense for cohesionless soils; very soft, soft, firm, stiff, very stiff for cohesive soils (typically > 10% clay content)
- ***S***oil structure; intact for soils without prominent structure; other structures include joints, voided, open, pinholed, shattered, slickensided, etc.
- ***S***oil type; grain size distribution (grading-related) in terms of clay, silt, sand and gravel content
- ***O***rigin; transported (e.g. colluvium, alluvium, aeolian), pebble marker, pedogenic, residual (*in-situ* weathered from parent rock), bedrock.

Craig (1999) states that soil classification should be based on the soil material as well as the *in-situ* soil mass. The soil material is described based on the particle size distribution or grading and the plasticity. On the other hand, the soil mass is described based on the *in-situ* soil structure, firmness or strength and details of discontinuities or weathering. The soil is eventually classified based on the soil material only without incorporation of the soil mass properties.

Additional to this, the Geotechnical Engineer also considers phase relationships in soils. Most soils are three-phase systems, comprising solid soil particles, pore air and pore water (Craig, 1999). Numerous parameters are defined based on the weight, mass or volume relationships between these three phases, the most important being the moisture content *m* (Equation 1), specific gravity G_S (Equation 2), degree of saturation S_r (Equation 3), void ratio *e* (Equation 4), porosity *n* (Equation 5), the relationship between *e* and *n* (Equation 6), and a variety of density and unit weight parameters, (ρ and γ). *M* and *V* denote mass and volume respectively with the subscripts $_A$, $_W$, $_S$ and $_T$ referring to air, water, solids and total.

$$m = \frac{M_W}{M_S}$$ **Equation 1**

$$G_S = \frac{M_S}{V_S \rho_W} = \frac{\rho_S}{\rho_W}$$ **Equation 2**

$$S_r = \frac{V_W}{V_V} = \frac{mG_S}{e}$$ **Equation 3**

$$e = \frac{V_V}{V_S}$$ **Equation 4**

$$n = \frac{V_V}{V_T}$$ **Equation 5**

$$e = \frac{n}{1-n} \Leftrightarrow n = \frac{e}{1+e}$$ **Equation 6**

1.9. Seepage (Darcy's Law), Conductivity and Permeability

For most Civil Engineers, the terms seepage applies to moisture moving through a porous material. Engineers also tend to interchange the symbols used, often utilising *k* for hydraulic conductivity (or coefficient of permeability) and *K* for (intrinsic) permeability. For the sake of consistency, the hydrogeologically accepted notations will be used where *K* represents hydraulic conductivity and *k* the intrinsic permeability.

The ***coefficient of permeability***, ***constant of proportionality*** or (***hydraulic) conductivity***, *K*, measures the resistance of the soil to the flow of water and has the units of velocity [L/T] (Das, 2008). Hydraulic conductivity is applied when the fluid is known to be water and therefore represents a property of the medium and the ease with which the medium can transmit water (Fitts, 2002). The ***(intrinsic or absolute) permeability***, *k*, can be defined as the soil property allowing seepage of fluids through interconnected void spaces and has the units of area [L^2] (Das, 2008).

Darcy's Law and the interrelationship between these two parameters and seepage (Q as per Darcy's Law [L^3/T]) is shown in Equation 7 and Equation 8 respectively where ρ = mass density of the fluid [M/L^3], g = gravitational acceleration [L/T^2], μ = absolute fluid viscosity [M/LT], i = hydraulic gradient [L/L] and A = cross-sectional area perpendicular to flow [L^2]. The hydraulic gradient is calculated as the change in hydraulic head, dh, over the change in distance, dl, between the two points of observation.

$$Q = KiA = K\frac{dh}{dl}A$$ **Equation 7**

$$K = \frac{k\rho g}{\mu}$$
$$9.77 \cdot 10^6\, k(m^2) \approx 1.00K(m.s^{-1}) \text{ for water (acc. Deming 2002)}$$ **Equation 8**

Note that the Q is applied to seepage or a flux as per hydrogeological standards and not according to the soil mechanical q. The darcy velocity or specific discharge, q, and linear flow velocity, v, are calculated as shown in Equation 9 and Equation 10 respectively where n_e represents the effective porosity (See 0).

$$q = \frac{Q}{A} = Ki$$ **Equation 9**

$$\bar{v} = \frac{q}{n_e}$$ **Equation 10**

1.10. Porosity and Effective Grain Size

As shown in Equation 6, the porosity is related to the void ratio. Determining the porosity is based on the volume of voids and the total volume of the sample (Equation 5) – therefore parameters which require an undisturbed soil sample. Porosity is, however, often calculated based on soil grading properties which exclude the *in-situ* structure and density of the soil.

A study by Lipiec *et al.* (2006) evaluated the soil porosity and water infiltration influenced by tillage methods. An assessment of single-porosity and dual-porosity modelling by Haws *et al.* (2005) accentuated the problems pertaining to initial parameter estimation and the influence on the final results, as well as the geomorphological heterogeneities. Flint and Selker (2003) elaborate on the importance of distinguishing between porosity, n, and effective porosity, n_e, the latter referring to the pores available for transmission of a fluid.

Dudoignon *et al.* (2007) distinguish between three types of porosities, specifically for clay-rich marsh soils, as follows:

- Macroporosity referring to the volume of vertical prism joints
- Mesoporosity due to shrinkage and the resulting crack network (100-2 000 μm)
- Microporosity relating to the clay-matrix and the particle arrangement.

A similar approach of classification is recommended by Kutílek (2004), *viz*:

- Macropores or non-capillary pores where the openings are sufficiently large that capillary menisci no longer form.
- Micropores or capillary pores where forces on the water – air interface and pore configuration are considered; subdivided into matrix pores within soil aggregates and structural pores between the aggregates
- Submicroscopic pores precluding water molecule clusters and continuous flow paths

Similar work assessing the influences of different scales of porosity also conclude – to some extent and with minor deviations – the distinction between some form of submicroporosity (no flow paths due to clogging), microporosity (due to clay matrix and particle arrangement), mesoporosity (small-scale structures in the soil) and macroporosity (due to jointing). These can be broadly subdivided into porosity influenced either by textural or matrix controls (primary porosity) or structural controls (secondary porosity) on different scales (e.g. Dexter and Richard, 2009). This corresponds to the engineering consideration of both the soil material (creating primary porosity) and soil mass (creating secondary porosity). A summary of the porosity terminology is shown in Figure 6.

	Primary / Textural Porosity **Soil Material**	**Secondary / Structural Porosity** **Soil Mass**
Macroporosity	Significant geological structures, e.g. Columnar jointing, piping	Significant geological structures, e.g. Fractures, joints, fissures
Mesoporosity	Pedological structures, e.g. Shrinkage cracks, termite nests, root voids	Geological structures, e.g Bedding, foliation
Microporosity	Soil aggregates and capillarity, e.g. Soil grading and effective pore size diameter	Structural pores between aggregates, e.g. Near-closed structures, laminations
Submicroporosity	Effective clogging texture, e.g. Clay content, adsorption and diffusion of water	Effective clogging structure, e.g. Joint infilling, precipitates

Figure 6. Scales and types of porosity pertaining to seepage in the vadose zone.

Norton and Knapp (1997) defined the total porosity as shown in Equation 11 with n_T the total porosity, n_F the effective flow porosity, n_D the diffusion porosity and n_R the residual porosity where no transport takes place as the pores are not interconnected. Tullborg and Larson adjusted this concept of total porosity to include n_N the unconnected porosity and n_C the connected porosity as shown in Equation 12.

$$n_T = n_F + n_D + n_R$$

Equation 11

$$n_T = n_N + n_C$$

Equation 12

The question remains whether the effective flow porosity and the connected porosity can be considered equal and also equal to the effective porosity n_e as per Equation 13.

$$n_e = n_F = n_C$$
$$n_T = n_e + n_D + n_R = n_e + n_N$$

Equation 13

Porosity can be estimated according to Istomina (1957) as shown in Equation 14. This estimate is based on the uniformity coefficient (C_U) which is the ratio between the upper limit particle sizes accounting for the finest 60% (d_{60}) and 10% (d_{10}) of the sample respectively. Determination of the d_{10} fraction is, however, not always possible as many grading analyses do not determine smaller diameters than 0.002 mm.

$$n = 0.255 \cdot \left(1 + 0.83^{C_U}\right) \text{where } C_U = \frac{d_{60}}{d_{10}}$$

Equation 14

Another assumption in determination of the hydraulic conductivity is the effective grain size diameter, d_e, defined as the diameter of a spherical grain in a uniform porous medium (therefore, $C_U = 1$) with a hydraulic conductivity equal to that of the corresponding natural material (Vukovic and Soro, 1992). It therefore implies that the diameter of the pore through which water flows is related to the effective grain size and, subsequently, that a direct relationship should exist between the effective grain size and the porosity.

Most often, assumptions are simply being made that $d_e = d_{10}$, $d_e = d_{17}$ or $d_e = d_{20}$ or $d_e = d_{50}$ (when considering the average particle size). The d_e calculation is usually based on the arithmetic mean of different proportions of different grain diameters occurring in a sample. On a more practical level, the effective grain size cannot only be related to the frequency of different grain sizes or the mean grain size. In order to determine the effective grain size, the pore-creating grains (gravel, coarse sand) have to be somehow compared with the clogging grains (fine silt, clay). Most sources recommend calculating the effective grain size diameter as shown in Equation 15 or Equation 16 where f_i is the fraction of particles (in decimals, e.g. percentage divided by 100) between the sieve sizes $d_{i(min)}$ and $d_{i(max)}$.

$$\frac{1}{d_e} = \sum_{i=1}^{n} \left(\frac{\sqrt{d_{i(\max)} \cdot d_{i(\min)}}}{f_i} \right)$$

Equation 15

$$\frac{1}{d_e} = \sum_{i=1}^{n} \left(\frac{\left(d_{i(\max)} + d_{i(\min)}\right)}{2 f_i} \right)$$

Equation 16

Flint and Selker (2003) and Vukovic and Soro (1992) summarise the most common porosity functions used to predict permeability. These porosity functions, φ, relate the influence of porosity on permeability, k, as shown in Table 2.. Note that saturation-dependent functions have been excluded and that different references use the reciprocals of the equations supplied below.

Table 2. Porosity functions used in the prediction of permeability.

Porosity Function	Cited from
$n^{-3.287}$	Slichter, 1898
$n^{-1.0}$	Kruger, 1918
$(1 - n)^2 / n$	Zunker, 1920
$(1 - n)^2 / n^3$	Blake, 1922; Kozeny, 1927; Carman, 1937
$[(1 - n)^{-3} / (n - 0.13)]^2$	Terzaghi, 1925
$[1 + 10\,(n - 0.26)]$	Hazen, 1930
$69.43 - n$	Hulbert and Feben, 1933
$n^{-6.0}$	Hatch, 1934; Mavis and Wilsey, 1936
$n^{-4.0}$	Fehling, 1936
$n^{-4.1}$	Rose, 1945
$[(1 - n) / n^{1.5}]\,[(1 - n)^2 + 0.018]$	Rapier, 1949
n^2	Marshall, 1958
$n^{4/3}$	Millington and Quirk, 1961
$n^{-5.5}$	Rumpf and Gupte, 1971
N	Dullien, 1975

The majority of these methods apply to very specific material only, typically with the following conditions:

- The materials are generally fine-grain to coarse-grain sands requiring for the definite determination of a d_{10} value, implying that less than 10% material finer than 0.002 mm (clay fraction) should be present for standard grading analyses.
- The effective grain size diameter is assumed to be d_{10}-d_{20} which, once again, assumes that the finest 10-20% of the material is responsible for the hydraulic properties of the material.
- The uniformity coefficient is typically $C_U < 4$ implying well-graded or poorly sorted materials; the higher the C_U, the more improbable a correlation with an ideal $C_U = 1$ material becomes.
- Many methods were developed based on very small datasets (typically less than 30 samples each) and have not been thoroughly reviewed for decades.

The validity of porosity estimations is therefore uncertain and more refinement is needed.

1.11. Hydraulic Conductivity

For the purpose of comparing results, common parameters have to be determined through the various methods. The infiltration capacity and percolation rate (for field tests) and vertical hydraulic conductivity (for empirical methods) – all with the units length per time (or volume per cross-sectional area per time) – are therefore being used. The rate of water movement is subsequently converted to a one-dimensional, vertical direction, correcting for the area of influence, small-scale heterogeneities and estimates of Darcy parameters.

1.11.1. Hydraulic conductivity based on soil grading

The hydraulic conductivity can be estimated based on the grading, porosity and effective grain size diameter of the soil sample. These parameters form a critical part in defining the engineering properties of the material as well as the hydrological behaviour. A thorough study of these methods was conducted by Vermaak and Van Schalkwyk (2000).

In order to address the hydraulic conductivity based on empirical results, it is important to first assess the accuracy of the parameters before evaluating the methods. These parameters are shown in Equation 17, comprising a constant (C also incorporating gravitation acceleration g and a correction for the flow velocity v), the porosity function $\varphi(n)$ and the effective particle size or grain size diameter d_e. The constant is usually based on experimental results and subsequently vary between the methods.

$$K = \frac{g}{v} \cdot C \cdot \varphi(n) \cdot d_e^2$$ **Equation 17**

Ten methods were selected and applied to the dataset. Three of these methods were excluded from the interpretation due to inconsistent results. The selection of these methods was based on the similar input parameters, the readiness of obtaining all the required parameters in one fairly cheap laboratory test, and the exclusion of tabulated experimental constants in the mathematical approach.

Where temperature factors or effective grain sizes were not specified, these were taken as 15°C and d_{10} respectively to allow for better comparison between the methods. Porosity was estimated according to Istomina (1957). Note that the d_{10} value is not always available and subsequently estimates had to be made for excessively fine-grained soils.

Where the clay content (denoted by C as a percentage) of the soil ranges between 5 and 60 % and the sand content (S) between 5 and 70 %, the regression model of Rawls, Ahuja and Brankensiek (1992) based on the Brutsaert (1967) equation can be applied (Equation 18) to determine the saturated hydraulic conductivity. This method, however, supplied values orders of magnitude lower than all of the other methods, and was therefore not included in the analysis.

$$\begin{aligned} K_S = & \left(2.7778 \times 10^{-6}\right) \exp(19.523n - 8{,}968 - 0.028C + 0.0002S^2 - 0.009C^2 - \\ & 8.395n^2 + 0.078Sn - 0.003S^2n^2 - 0.019C^2n^2 + 0.00002S^2C + \\ & 0.027C^2n + 0.001S^2n - 0.000004C^2S) \end{aligned}$$ **Equation 18**

For clean, coarse-grained materials, the Hazen (1930) method can be applied. This expression is a function of the temperature (T) and a constant parameter c defined by the Lange formula in terms of the porosity (Equation 19). The temperature was assumed to be 15°C to be comparable with the other methods which follows later.

$$K_S = c \cdot T_1 \cdot {d_{10}}^2$$
$$T_1 = 0.70 + 0.03 \cdot T$$
$$c = 4.6\times10^{-3} + 4.6\times10^{-2} \cdot (n - 0.26)$$

Equation 19

Amer and Awad (1974) based their equation (Equation 20) on 36 samples as a function of C_U, d_{10} and porosity n. For these samples the following applied: $0.137 < d_{10} < 0.548$ and $1 < C_U < 21$.

$$K_S = 9.3\times10^{-3} \cdot {C_U}^{0.6} \cdot {d_{10}}^{2.32} \cdot \left(\frac{n^3}{(1+n)^2}\right)$$

Equation 20

Shababi, Das and Tarquin (1984) followed a similar approach to Amer and Awad as shown in Equation 21. This method was, however, excluded from the analysis as it yielded values orders of magnitude higher than the other methods.

$$K_S = 1.2 \cdot {C_U}^{0.735} \cdot {d_{10}}^{0.89} \cdot \left(\frac{n^3}{(1+n)^2}\right)$$

Equation 21

Another method dependent on the d_{10} value and the porosity was developed by Slichter (Equation 22) and is described by Vukovic and Soro (1992). The porosity function ($n^{3.287}$) has an error of approximately 5%.

$$K_S \approx 0.1012 \cdot n^{3.287} \cdot {d_{10}}^2$$

Equation 22

Beyer (discussed in Vukovic and Soro, 1992) determines saturated hydraulic conductivity as shown in Equation 23. This method was eventually excluded from the interpretation due to inconsistent and highly variable results.

$$K_S = 4.5\times10^{-3} \cdot \log\left(\frac{500}{C_U}\right) \cdot {d_{10}}^2$$

Equation 23

A number of approaches was developed by Kozeny (Vermaak and Van Schalkwyk, 2000), including methods comprising temperature correction factors, porosities and effective grain size diameters determined by the weight distribution of different particle size ranges. A simplification of Kozeny's findings assume a groundwater temperature of 15°C and an effective grain size diameter equal to d_{10} (Equation 24).

$$K_S = 0.0625 \cdot \left(\frac{n^3}{(1-n)^2} \right) \cdot {d_{10}}^2$$

Equation 24

Vukovic and Soro (1992) also discuss the USBR method applied widely in the USA. This method ignores porosity and uses only the d_{20} value (Equation 25).

$$K_S = 0.0036 \cdot {d_{20}}^{2.30}$$

Equation 25

The Zamarin Formula (Vukovic and Soro, 1992) is shown in Equation 26 utilises a constant for temperature correction (0.926 for 15°C) and suggests determination of the effective grain size via weighting of the particle size analysis.

$$K_S = 8.07 \cdot \frac{n^3}{(1-n)^2} \cdot (1.275 - 1.5n)^2 \cdot (0.926) \cdot d_{10}^2$$

Equation 26

Finally, the Alyamani and Sen (1993) method incorporates the x-intercept of the line passing through d_{50} and d_{10} and does not require a predetermined porosity function (Equation 27). The determined K-value is in the units m/d.

$$K_S = 1300\left[I_0 + 0.025(d_{50} - d_{10})\right]^2$$

Equation 27

1.11.2. Field methods to determine hydraulic conductivity

The ***percolation test*** as per the South African National Standard SABS 0252-2:1993 was applied for the field determination of a percolation rate which is related to the saturated hydraulic conductivity. This method entails the excavation of a vertical test hole with 150 mm diameter and 400 mm depth. All sides of the excavation are to be scarified.

The test hole has to be pre-soaked and the water level is then allowed to drop to 180 mm and time measurements are taken for the drop to 130 mm. The hole is refilled to a water level of 180 mm and the measurements are repeated until the percolation rates do not vary by more than 10% between consecutive readings. The percolation rate (mm/h) is determined by dividing the last drop in water level (mm) by the time taken for this drop (h). For the sake of this paper, the percolation rates were converted to m/s for comparison with the results of the empirical methods.

Another method is discussed by Jenn *et al*. (2007c after Gartung and Neff, 1999). ***Double-ring infiltrometers*** are used to measure the flow under saturated conditions and are very suitable for fine-grained soils with low plasticity (K between $1 \cdot 10^{-8}$ and $5 \cdot 10^{-5}$ m.s^{-1}). These tests are carried out in the unsaturated zone and comprise an outer ring (1 000 mm diameter) used to saturate the soil profile and an inner ring (300 mm diameter) to measure the amount of water required to maintain a specific level. The steady-state flow rate measured in the inner ring is used to determine the saturated vertical hydraulic conductivity according to Darcy's Law. A similar laboratory-based method was applied by Aimrun *et al*. (2004) where a standpipe and a brass ring are used in the calculation of the saturated hydraulic conductivity.

According to Reynolds and Elrick (1986), the hydraulic conductivity determined via this method is 50-75% less than the actual value due to different processes preventing complete saturation of the soil.

The vertical unsaturated hydraulic conductivities determined via the two field methods to some extent mimic laboratory rising or falling head permeability tests. The influence of the *in-situ* moisture content is being evaluated but is excluded from these preliminary results and all hydraulic conductivities are calculated for saturated or near-saturated conditions. As the soil is pre-soaked, it can be assumed that the main direction of water movement should be vertical under the influence of gravity through the unsaturated zone.

METHODOLOGY

At the inception of the project, only the lateral or spatial classification was considered for the purpose of estimating zones of infiltration to – in the end – quantitatively evaluate the influence of surface-derived water on the groundwater regime. However, it was decided that the vertical profile also needs better understanding and that the surface soil characterisation is not adequate due to distinct changes in vertical permeability and/ or conductivity. A vertical vadose zone classification (description of the vadose horizons) has therefore been included in the study.

1.12. Lateral or Spatial Vadose Zone Classification

Considering that this project requires a preliminary vadose zone classification methodology, it becomes important to outline the required parameters. For this purpose, three approaches were merged, *viz*. the Land System Approach, the DRASTIC approach to vulnerability mapping, and the Model – Setting – Scenario approach to conceptualise the subsurface.

The Land System Approach is based on the assumption that similar land facets will have similar and repetitive soil profiles with similar soil properties. A land facet, which is the basic unit of the land system classification, is defined as part of the landscape, usually with a super-form consisting of a particular rock or surficial deposit and with soil and water regime that is either uniform over the whole facet or varies in a simple and consistent way. Characteristically land facets are small units and correspond to individual physiographic features such as outcrops, talus slopes, alluvial fans, etc. Related facets are grouped into larger terrain units. A recurrent pattern of genetically linked land facets is known as a land system. Land facets are typically mapped at scales between 1:10 000 and 1:50 000 and land systems at scales of 1:250 000 to 1:1 000 000 (e.g. Brink *et al*., 1970; Geological Society of London, 1982; Van Schalkwyk and Price, 1990).

In the DRASTIC approach to vulnerability mapping, Geographic Information Systems (GIS) are applied as it was developed by the United States Environmental Protection Agency (US EPA). This method incorporates the main geological and hydrological properties which influence and control groundwater movement into, through and out of an area, subsequently rendering the aquifer more or less prone to contamination. The seven weighted parameters which make up DRASTIC are Depth to groundwater, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone and hydraulic Conductivity (e.g. Xiaohu *et al*., 2008; Aller *et al*., 1987).

The Model – Setting – Scenario approach combines settings and scenarios to create a conceptual model addressing the subsurface. The settings generally refer to areas characterised by constant environmental parameters such as bedrock, climate, land form, structural lineaments, surface drainage and so forth. The scenarios overlain on these settings represent hydrological parameters which can be determined in the field or in the laboratory, notably the depth to groundwater, hydraulic conductivity or transmissivity, permeability and porosity. The scenarios are then used to quantify the hydrological behaviour of each model rather than applying an index as per the vulnerability approaches (Dippenaar *et al*., 2009a).

The interrelationship between these approaches is shown in Figure 7. The common parameters considered intrinsic site-specific are used to define the settings, namely climate (which is related to the water available for recharge), geology (which influences the aquifer and soil media) and landform (which is a function of topography and, notably, relief in terms of slope angle and length).

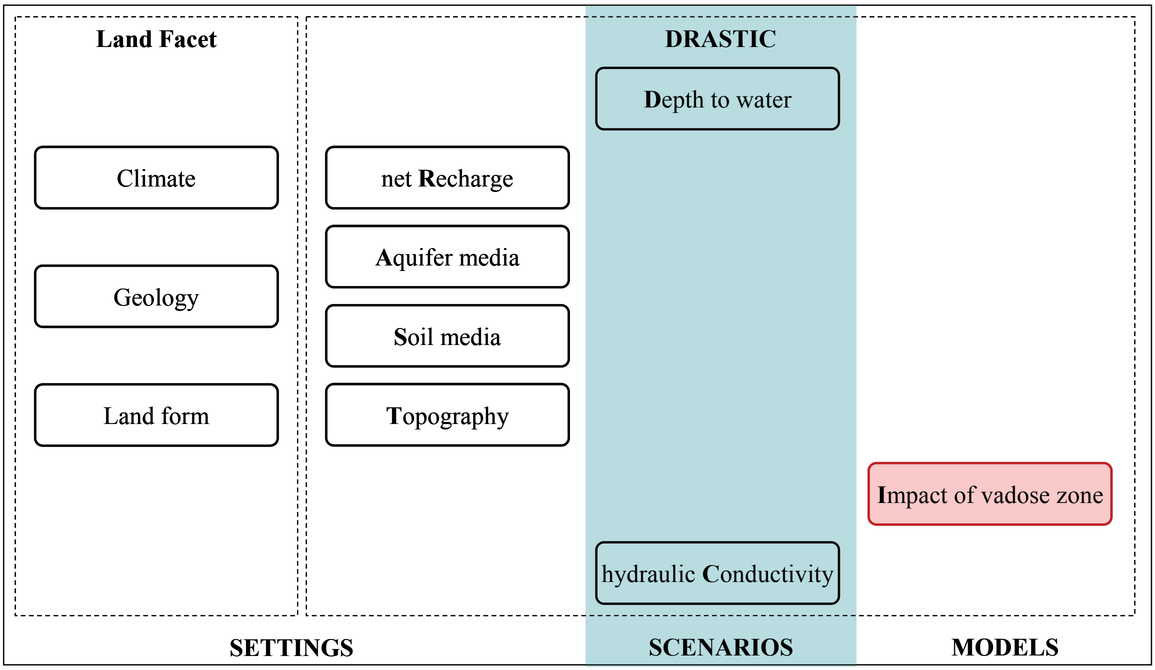

Figure 7. Definition of the settings and scenarios based on the Land System Approach and DRASTIC vulnerability parameters.

The scenarios to be ranked are those DRASTIC parameters which can be determined in the field or laboratory. The depth to water represents the thickness of the vadose zone and the hydraulic conductivity is related to the rate of seepage through the vadose zone and therefore also the permeability.

The final models will be the DRASTIC parameter relating to the impact of the vadose zone. These models will therefore have very specific vadose zone thicknesses and hydraulic conductivities per setting of similar climate, geology and land form.

1.13. Vertical Vadose Zone Classification or Vadose Zone Horizons

For the purpose of the vertical vadose zone classification, a number of concepts have been considered. In a profile from surface to the aquifer, the distinguishing zones or vadose horizons can be summarised as shown in Table 3.

These same horizons are shown schematically in Figure 8. Note that horizons (a)-(d) represent the vadose zone, (e) represents the cusp or transition at the capillary fringe and (f) is the phreatic, saturated or groundwater zone. The infiltration and phreatic zones will always form the beginning point of entry into the subsurface and the final entry into the aquifer itself, but the four intermediate zones may be present, absent, accentuated or obscured depending on the site.

Table 3. Vertical vadose zone classes or horizons.

Horizon / Vertical Zone	Correlation	Motivation
(a) Infiltration Zone	Soil Zone	The generally lesser consolidated, more voided transported surficial soils; plant root zone
(b) Perching Zone		The engineering geological and pedological horizon forming due to eluviation and illuviation
(c) Primary Percolation Zone		The residual and completely weathered bedrock and transported soils in which water passes through primary porosity
(d) Secondary Percolation Zone	Intermediate Zone	The lesser weathered bedrock in which water migrates through secondary fractures
(e) Capillary Zone		Zone of rise from the groundwater due to capillary suction in the soil pores
(f) Phreatic Zone	Phreatic Zone	The hydrogeological zone where all voids are water-filled and flow is predominantly lateral

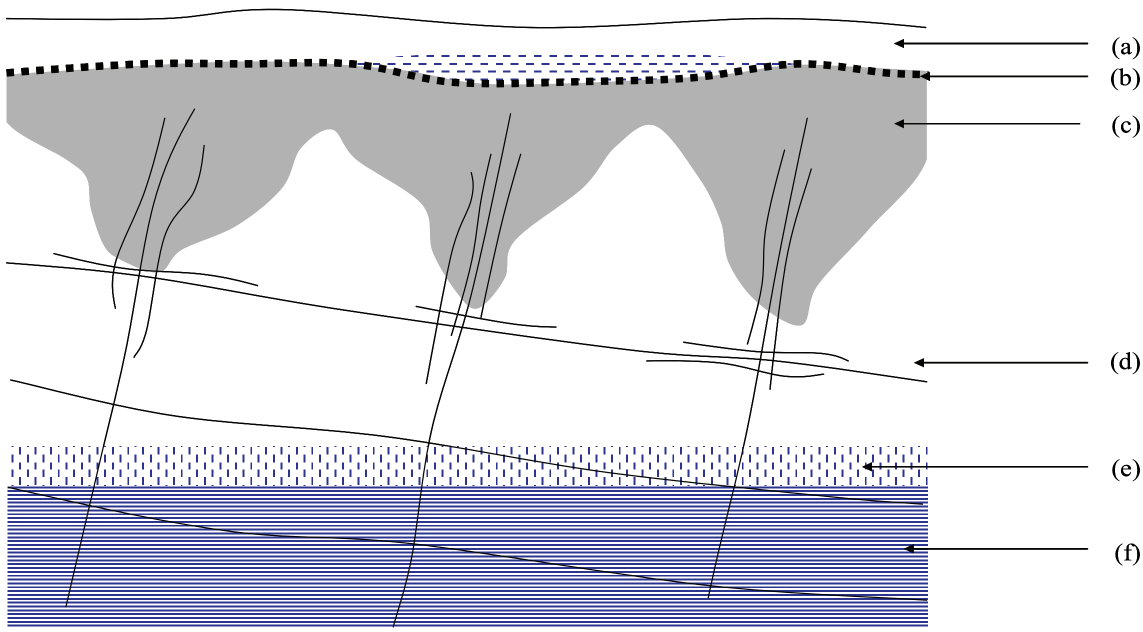

Figure 8. Vertical zoning and classification of vadose zone (a-d) overlying the capillary (e) and phreatic (f) zones.

The (a) horizon depicts the transported soil materials or shallow bedrock which either allows or prohibits water from surface to influence the soil profile. This horizon is generally characterised by abundant biotic activity including plant roots and termite nests. From here, infiltrating water can either spread laterally on a more impermeable horizon, (b), from where transpiration, interflow or surface discharge can result. Alternatively, water can percolate beyond this horizon into the residual and weathered bedrock (saprolite). This horizon (c) is typically characterised by bedrock behaving as soils and water will generally percolate due to primary porosity. Lesser weathered bedrock at depth becomes more intact with discreet secondary structures which control further percolation (horizon (d). These four zones therefore have to be evaluated as distinct hydrological units as each can promote, retard or prohibit further percolation, and together determine the impact of the vadose zone. For each of these vertical zones, a hydraulic conductivity or infiltration/ percolation rate has to be determined and combined for final assessment of the travel times and aquifer susceptibility.

APPLICATION

The study area comprising the Molototsi and Middle Letaba quaternary catchments are used to evaluate the preliminary vadose zone classification methodology. The site locality is shown in Figure 9.

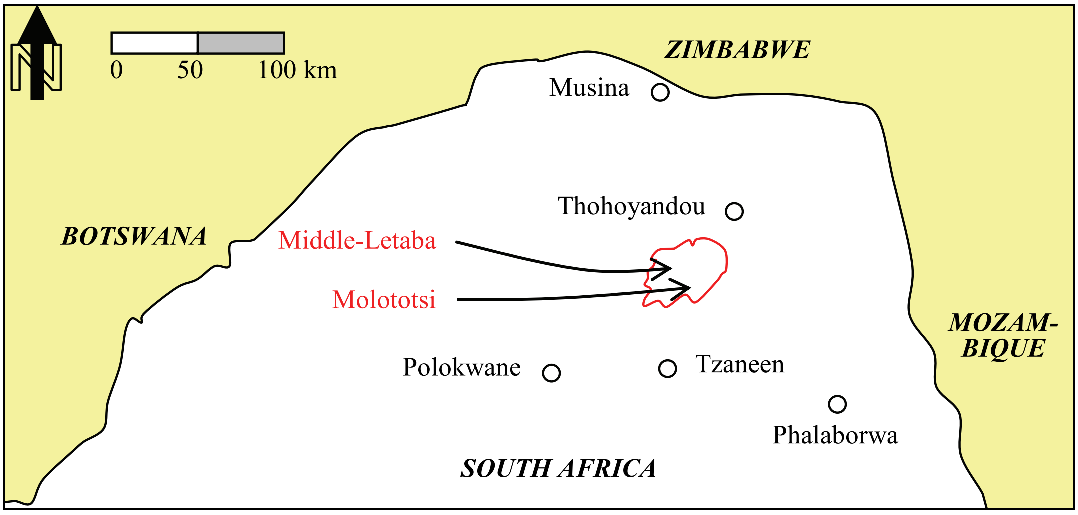

Figure 9. Locality of the Molototsi and Middle Letaba quaternary catchments.

The Molototsi and Middle Letaba quaternary catchments both form part of the Luvuvhu/ Letaba Water Management Area (WMA2) which, in turn, is subdivided into the Limpopo, Olifants and Shingwedzi Primary Catchments. Both the Molototsi and Middle Letaba Quaternary Catchments form part of the Letaba River Secondary Catchment in the Olifants River Primary Catchment. The quaternary catchments are shown in Table 4.

Table 4. Quaternary catchments within WMA2.

	Primary Catchment	Secondary Catchment	Quaternary Catchment	Description
A	Limpopo	A9 (Luvuvhu River)	A91A,B,C,D	Luvuvhu at Levubu
			A91E,F,G	Paswane Dam Site
			A91H,J	Lububhu at Mutale
			A91K	Luvuvhu at Limpopo
			A92A,B,C,D	Mutale at Luvuvhu
B	Olifants	B81 (Letaba River)	B81A,B	Tzaneen Dam
			B81C,D,E,F	Groot Letaba at Molototsi
			B81G,H	Molototsi
			B81J	Groot Letaba at Klein Letaba
	Shingwedzi	B90	B83A,B,C,D,E	Letaba at Olifants
			B90A,B,C,D,E	Mphongolo
			B90F,G,H	Shingwedzi

* (From: WSM, 2003)

In order to achieve both a spatial and vertical vadose zone classification, the investigation has to be conducted in a twofold approach.

1.14. Lateral or Spatial Vadose Zone Classification

The first part comprises the overlaying of geology, topography and rainfall information. All data were obtained from the relevant geological and topocadastral sheets and the South African Weather Bureau.

1.14.1. Topography

The site topography is shown in Figure 10 (red indicating the elevated areas and blue the drainage features). According to Du Toit (1979), the topography of the area comprises of three units: the plateau area ranging from 850 to 1000 m above sea level, the escarpment ranging from 600 to 900 m and the Lowveld below 600 m. The plateau is characterised by flat plains which are not necessarily present in the study area. The escarpment is uneven and strikes in a north-south direction with an elevation decreasing from 900 m in the west to 600 m in the east. Both the Molototsi and Middle Letaba catchments comprise valleys draining from the southwest towards the northeast. Typically, the upper parts of the catchments are steep (slopes between 30º and cliffs), gradually decreasing towards the lower parts and the flatter flood plains (Brandl, 2006).

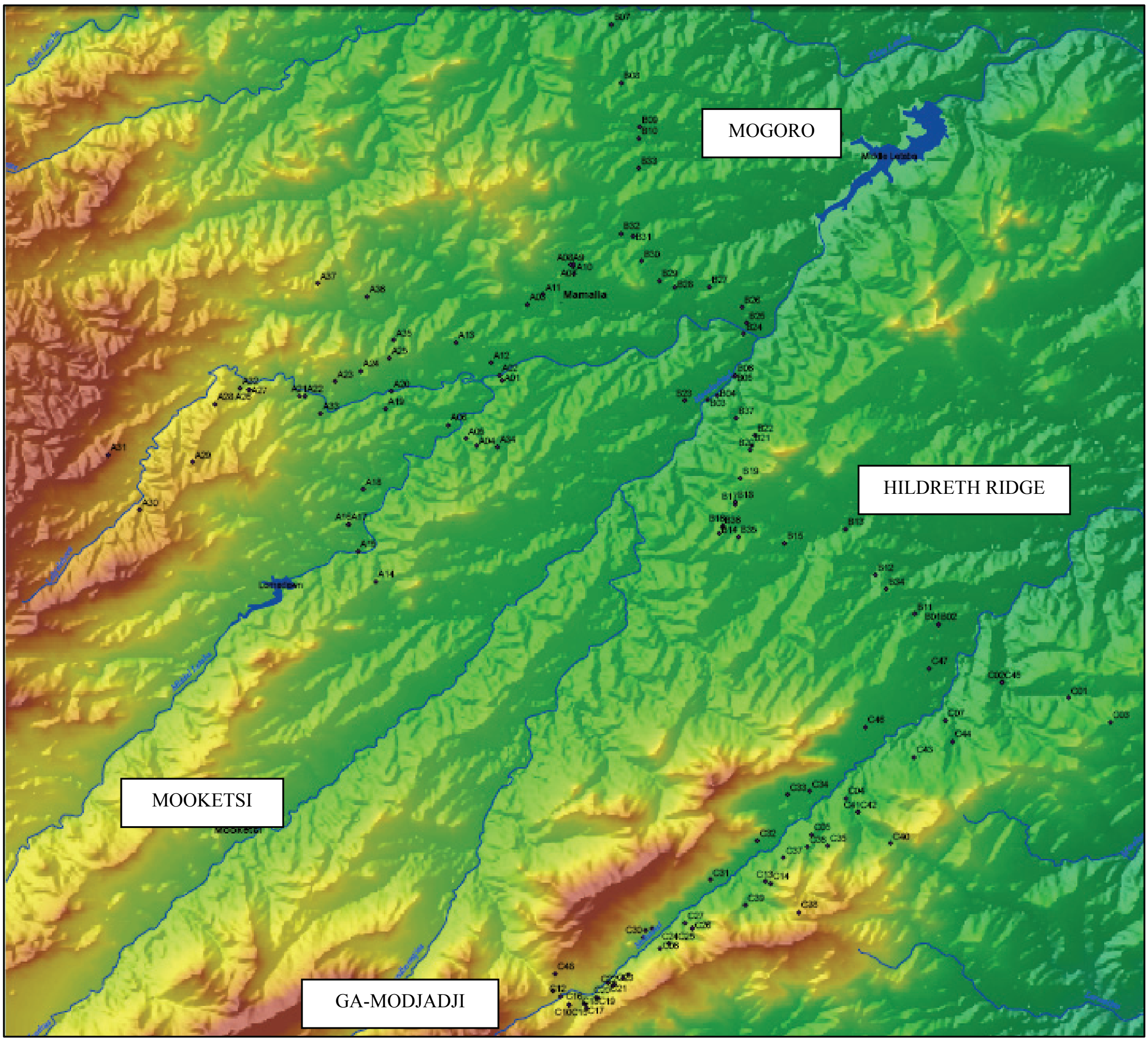

Figure 10. **Topography of the study area (sampling positions indicated).**

The topography of the Limpopo Basin consists of undulating terrain between ranges of hills and mountains. Throughout the basin, the northward flowing tributaries of the Limpopo River have incised deep gorges through the hills and mountain ranges that are visible as erosion remnants (SARDC and IMERCSA, 2003). This undulating nature is confirmed by the 1:50 000 topographic map 2330AD Hildreth Ridge and by MDB (2006).

1.14.2. Climate

The climate of the Limpopo basin varies from arid in the west to semi-arid and temperate in the central zones and semi-arid in the east. The study area is a summer rainfall region with precipitation events which are usually in the form of intense convective thunderstorms. The nearest average climatic data are shown in Table 5. (SARDC and IMERCSA, 2003).

Table 5. Proximate climate data.

Town/ Station	Average Annual Rainfall	Average Temperature (Jun)	Average Temperature (Jan)
Tzaneen	881 mm	21.9°C	29.1°C
Louis Trichardt	495 mm	20.2°C	27.1°C
Malamulele	691 mm	23.2°C	30.5°C
Ga-Kgapane	503 mm	22.2°C	29.6°C
Giyani	421 mm	23.9°C	31.0°C

The upper steeper areas of the valley have far more lush vegetation which may be due to orographic rainfall caused by the steep gradient in this region and up-valley winds. The lower parts of the valley make up an alluvial fan with multiple converging stream and river channels. The basin lies to the East of Tzaneen and comprises of residual soils covered in most areas by colluvium from further up the valley. Due to the wet climate, alluvial soils will also be present in areas close to water paths (Brandl, 2006).

1.14.3. Geology

The regional geology (Figure 11) of the study area comprises essentially Goudplaats – Hout River Gneiss, Duivelskloof Leucogranite and localised occurrences of amphibolite, mafic granulite and metapelite of the Bandelierkop Complex and amphibolite and magnetite quartzite of the Rhenosterkoppies Greenstone Belt. Various structural features cross-cut the area, including approximately northeast – southwest striking faults and intrusive diabase dykes. The geology is described in detail in The Geology of South Africa and is characterised by the following stratigraphic units (Anhaeusser, 2006; Brandl, 2006; Brandl *et al*., 2006; Kramers *et al*., 2006; Robb *et al*., 2006):

- The Goudplaats – Hout River Gneiss is of Paleoarchaen age (ca 3.6-3.2 Ga) and is highly variable, ranging between well-layered to homogeneous, leucocratic to melanocratic, and fine-grained to pegmatoidal. The dominant phase of the Goudplaats-Hout River suite in the study area is light- to dark-grey gneisses, with some minor leucocratic gneisses, hornblende amphibolite and hornblende-biotite tonalitic gneisses.

- The Duivelskloof Leucogranite (ca. 3.28 Ga) is found towards the southern portions of the study area, comprising a large batholitic intrusion stretching south from the Giyani Greenstone Belt. The bedrock is generally off-white and medium-grained texture with pockets of more pegmatoidal, finer-grained, darker coloured and foliated granite.

- The younger Bandelierkop Complex forms part of the Southern Marginal Zone (SMZ) of the Limpopo Belt, representing granulite facies high-grade supracrustal gneisses of metapelitic composition. These gneisses are tectonically intermingled with the Goudplaats – Hout River Gneiss during the intrusion. The HRSZ (comprising reverse and strike-slip displacements) forms the boundary between the SMZ (of which the Bandelierkop Complex form part) and the Kaapvaal Craton (of which the Gouplaats – Hout River Gneiss forms part) and is characterised by an abrupt drop in metamorphic grade towards the south.

- The Rhenosterkoppies Greenstone Belt (ca. 3.1-2.95 Ga) comprises amphibolite and magnetitic quartzite with scattered outcrops in the study area. The amphibolite is a fine to coarse-grained mafic igneous rock characterised by foliation and lineation. The iron formation is believed to be formed through chemical precipitation and consists of interlayered chert, magnetite, haematite and grunerite

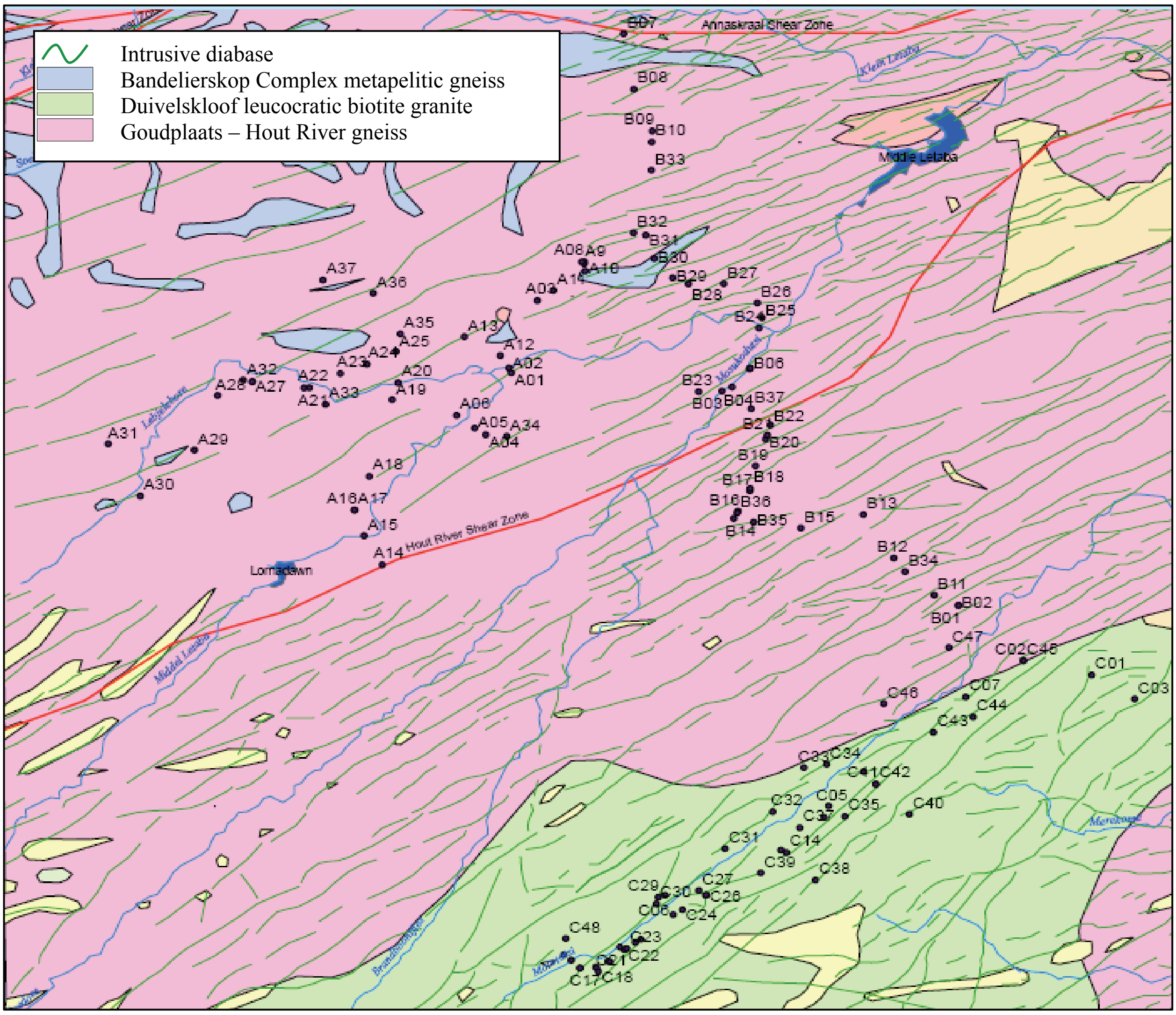

Figure 11. **Regional geology of the study area (sampling positions indicated).**

1.14.4. Findings

At inception of this project, the definition of settings was very luring and promising as a primary means of assessing the vadose zone properties. This is still true to some point in that this does in fact control the material properties of the vadose zone. Geological materials define the parent material and geomorphology to some extent determines the depths to or thicknesses of the different materials. However, this makes it clear that these are vertical variations rather than spatial, requiring for a vertical vadose zone classification.

In terms of the lateral or spatial zone classification, the implications are possibly significantly more limited than initially anticipated. The importance of the lateral vadose zone classes is essentially limited to one concept: initial infiltration into the root zone. What happens after this concerns vertical vadose zone classes. It is therefore the purpose to characterise that potential of water to bypass runoff and evaporation to – in the end – infiltrate beyond the root zone and become available for percolation.

Is geology relevant to this phase? Not really, as transported materials may have different properties and biological influences adjust the texture and structure. Geology becomes more important with reference to the vertical zones.

Is rainfall relevant? To some extent, yes, as too little rain evaporates and too much rain are forced to runoff due to the energy, causing for a certain window or range of rainfall to be able to infiltrate. Is the rainfall intensity relevant? Yes, and once again within a certain range to allow infiltration beyond evaporation and runoff.

Is land form relevant? Potentially, but the emphasis should maybe shift more to the presence of vegetation to decrease runoff, the slope length and minor deviations in slope to create "ponding zones" for infiltration, and the gaining versus losing nature of drainage features.

The lateral or spatial vadose zone classification should, therefore, be focussed around the following parameters:

- Rainfall intensities per event over a meteorological cycle of varying climate
- *In-situ* topsoil (in tens of centimetres) textural and structural porosity rather than grading
- Vegetation and slope to reduce runoff rates, subsequently improving infiltration.

1.15. Vertical Vadose Zone Classification or Vadose Zone Horizons

The second part – the vertical vadose zone classification or the subdivision of the vertical profile into horizons – is based largely on the thorough description of a number of open excavations and the laboratory analyses of representative materials for grading analyses.

1.15.1. Discussion of Empirical Results

The results of nineteen grading analyses are shown in Figure 12. The separate results and profile descriptions are attached in the appendices. The 10% cumulative percentage is indicated as a dotted red line: note the amount of samples not exhibiting a calculated d_{10} value; i.e. the clay fraction exceeds 10% of the sample mass, and therefore the d_{10} value cannot be determined graphically. This absence of an evident d_{10} value therefore accentuates the wrong application of several empirical methods developed for well sorted or poorly graded sands, thereby excluding even slightly cohesive materials from the methodology.

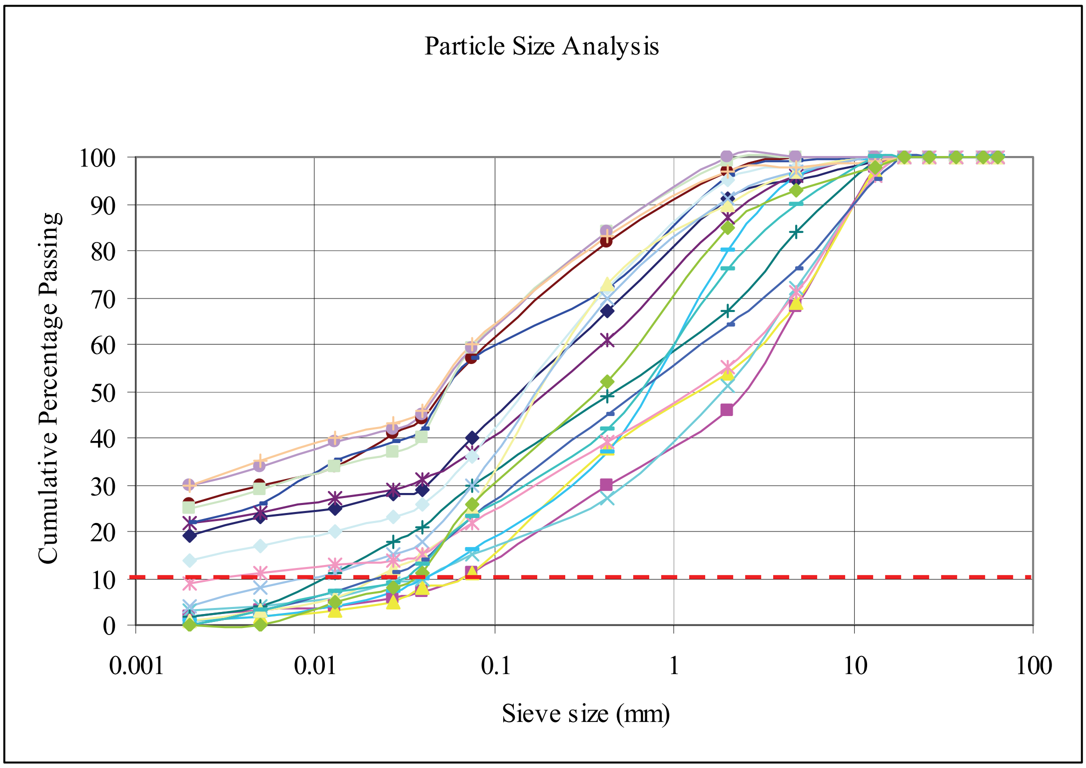

Figure 12. **Grading analyses on 19 samples from the Molototsi and Middle Letaba areas.**

Through determination of the effective grain size diameter, d_e, as per Equation 16, the results can be summarized as follows:

- Excessively fine-grained soils typically correlate to a $d_e > 0.011$ mm, correlating to approximately $d_{30} < d_e < d_{45}$.
- Excessively coarse-grained soils typically correlate to a $d_e < 0.046$ mm, correlating to approximately $d_5 < d_e < d_{20}$.
- All soils noted above are well graded based on a range $12 < C_U < 650$ in the instances where a d_{10} value could be determined.

The grading analyses of the 19 samples were used to calculate the hydraulic conductivities by means of eight methods as shown in Figure 13. Note the two very distinct clusters of ranges (depending on the method): low-K ranging between approximately 10^{-15}-10^{-7} m/s and high-K ranging between approximately 10^{-9}-10^{-2} m/s.

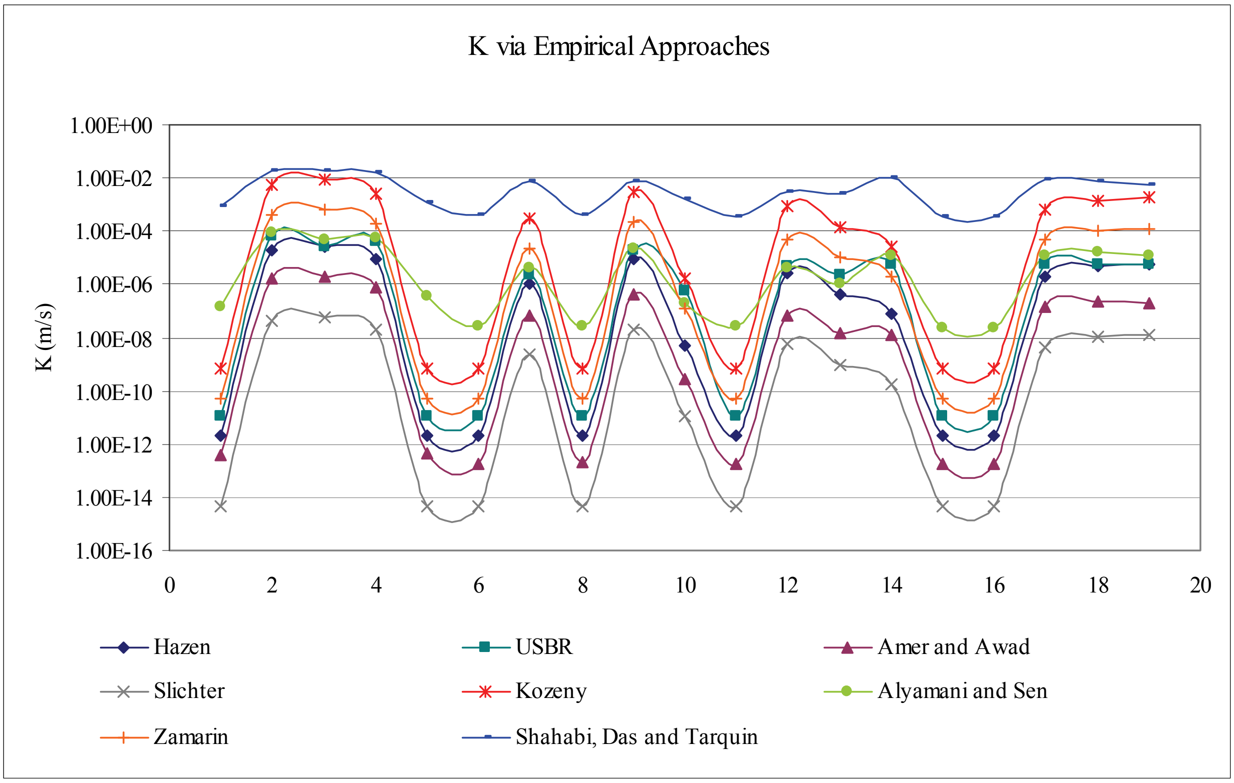

Figure 13. Empirical K-values via eight methods on 19 samples from the Molototsi and Middle Letaba areas.

Two alternative approaches were employed for comparison of the results, namely the effective liquid limit and the coarseness index. These approaches were developed during the study with the aim of incorporating the liquid limit, referring to that moisture content where the soils starts behaving as a liquid (Equation 28), and also to supply more weight to the pore-forming grains or gravel and pore-clogging grains or clays (Equation 29). *LL* refers to the percentage liquid limit, $\Phi_{0.425}$ represents the percentage material finer than 0.425 mm, and *G*, *S*, *M* and *C* denote the percentages gravel, sand, silt and clay respectively. Note that the average hydraulic conductivity was calculated as the average between the methods indicated on Figure 13 but excluding Shababi, Das and Tarquin.

$$LL_{eff} = LL \cdot \left(\frac{\phi_{0.425}}{100} \right)$$ **Equation 28**

$$CI^{+} = \log \left(\frac{G^2 + S}{M + C^2} \right)$$ **Equation 29**

A fair correlation exists between the effective liquid limit and the average empirical hydraulic conductivity (Figure 14). A distinct drop in estimate hydraulic conductivity is observed around $LL_{eff} = 20$, suggesting that (under the assumption that the *K* values are correct) a distinct change in hydrological properties occurs around this value, resulting in a sudden drop in *K* of four orders of magnitude.

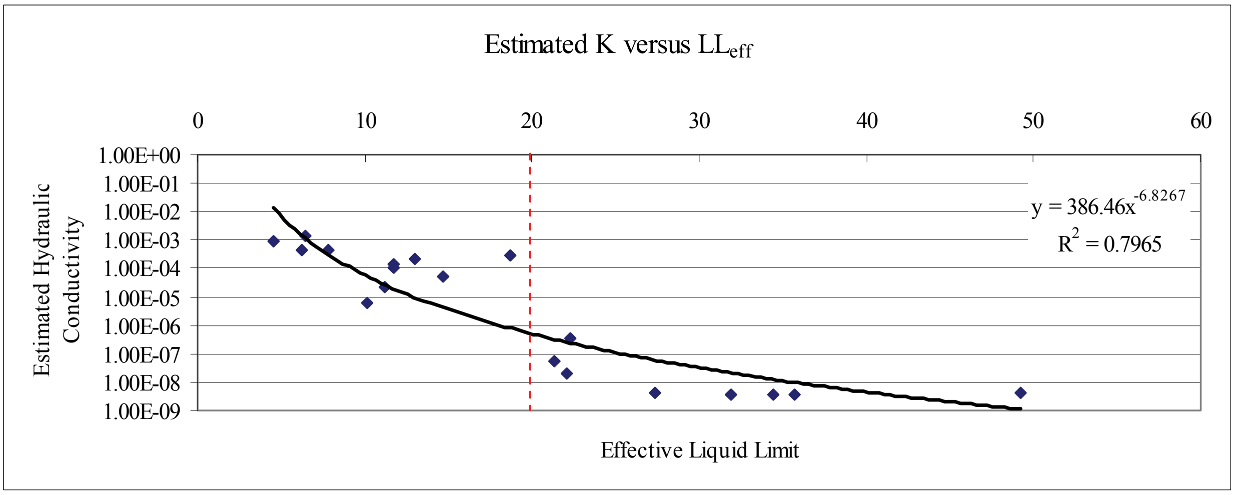

Figure 14. **Effective Liquid Limit (LL_{eff}) versus average empirical K (m/s).**

An good correlation also exists between the coarseness index and the average empirical hydraulic conductivity (Figure 15). This applies to the whole range of excessively fine-grained ($CI^+ \rightarrow -4$ for essentially only clay) to coarse-grained materials ($CI^+ \rightarrow 4$ for essentially only gravel) and the intermediate mixtures ($CI^+ \rightarrow 0$ for well graded materials) and might – to some extent – serve as a correction factor for the non-uniformity of the soils.

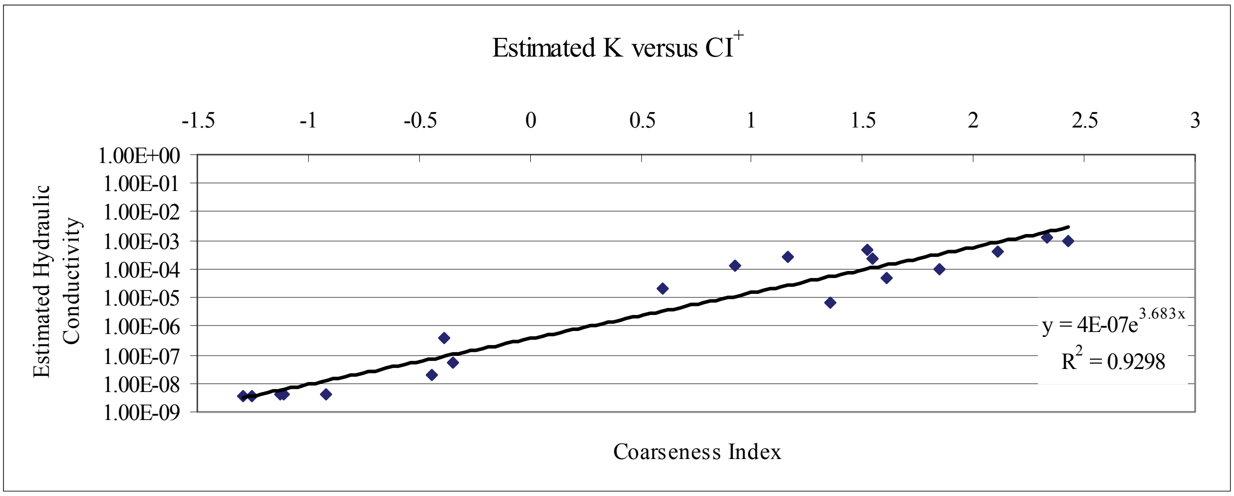

Figure 15. **Coarseness Index (CI^+) versus average empirical K (m/s).**

The effective grains sizes were calculated according to Equation 15. Figure 17 shows the correlation between the effective grain size and the average empirical hydraulic conductivity. Note the two distinct correlations for the same range of calculated effective grain sizes where $K > 10^{-5}$ m/s and where $K < 10^{-5}$ m/s. An alternative grouping based on $d_e \approx 0.02$ mm is indicated by the dotted lines.

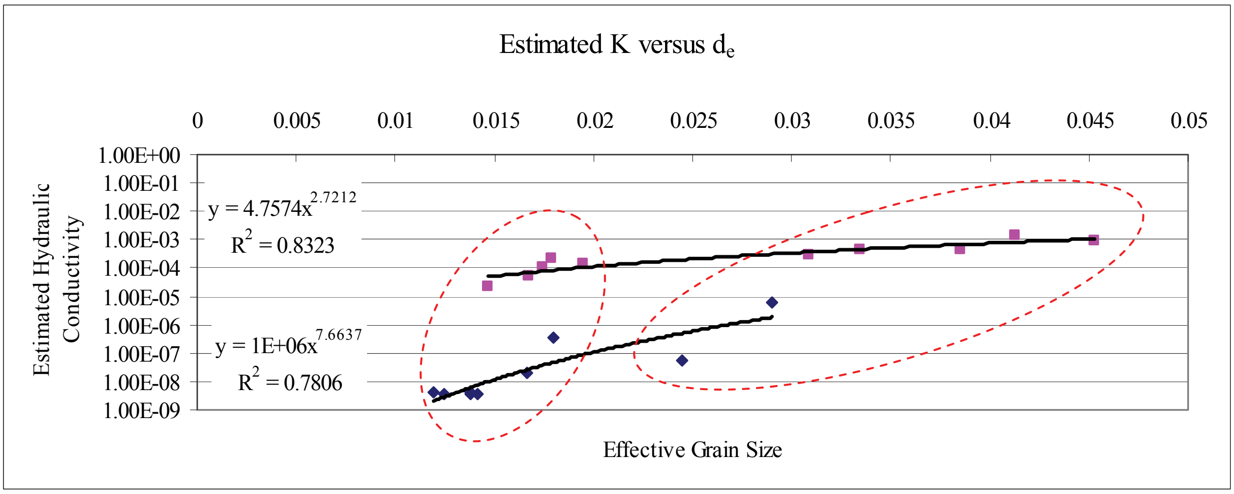

Figure 16. **Effective Grain Size (d_e) versus average empirical K (m/s).**

1.15.2. Discussion of Field Results

16 field tests were conducted on surface (Table 6). A correlation between the field tests and the corresponding average empirical values are supplied. Poor correlation exists with the laboratory analyses, potentially due to the inherent disturbed nature of the surface soils (due to biotic and anthropogenic impacts), leading to the higher conductivity values obtained via the field methods. This voided nature is expected to decrease with depth as the influence of plant roots, termites and surface disruption becomes less. Furthermore, these results are classically extrapolated to the percolation zones where they should, in fact, be considered indicative of potential infiltration only.

Table 6: Results of field percolation and double-ring infiltration tests.

Station	***Test***	***K (m/s)***	***Material at End of Hole***	***Laboratory Correlation (m/s)***
AP12	Percolation	$1.82 \cdot 10^{-05}$	Stiff clay	$2.42 \cdot 10^{-08}$
AP14	Percolation	$1.61 \cdot 10^{-04}$	Granite-gneiss	$1.79 \cdot 10^{-06}$
AP15	Percolation	$1.12 \cdot 10^{-04}$	Granite-gneiss	$3.50 \cdot 10^{-11}$
AP19	Percolation	$1.15 \cdot 10^{-04}$	Granite-gneiss	$2.18 \cdot 10^{-06}$
AP20	Percolation	$1.10 \cdot 10^{-04}$	Granite-gneiss	$1.14 \cdot 10^{-06}$
AP33	Percolation	$2.75 \cdot 10^{-04}$	Granite-gneiss	$1.14 \cdot 10^{-06}$
Stop1	Double-ring	$4.58 \cdot 10^{-05}$	Micaceous granite-gneiss	$6.42 \cdot 10^{-10}$
Stop4	Percolation	$7.94 \cdot 10^{-04}$	Granite-gneiss	$8.14 \cdot 10^{-07}$
Stop7	Double-ring	$1.00 \cdot 10^{-04}$	Granite-gneiss	$1.14 \cdot 10^{-06}$
C1	Percolation	$5.25 \cdot 10^{-05}$	Not identified	Not identified
C2	Percolation	$1.94 \cdot 10^{-04}$	Not identified	Not identified
C3	Percolation	$1.05 \cdot 10^{-04}$	Not identified	Not identified
BP01	Percolation	$4.39 \cdot 10^{-04}$	Stiff clay	Not identified
BP02	Percolation	$4.39 \cdot 10^{-04}$	Granite-gneiss	Not identified
BP03	Percolation	$8.33 \cdot 10^{-04}$	Granite-gneiss	Not identified
BP04	Percolation	$5.88 \cdot 10^{-04}$	Granite-gneiss	Not identified
BP05	Percolation	$1.40 \cdot 10^{-03}$	Granite-gneiss	Not identified

Figure 17 shows the lateral dispersion of infiltrating water during an infiltration test conducted in Modjadji, Limpopo Province. Note the offset (from perpendicular) of seepage in the vertical face with respect to the test hole, potentially due to heterogeneities channelling flow in this direction.

Test site (400mm deep); dotted line indicating shortest pathway to exposed face

Seepage in exposed face

Figure 17. Lateral dispersion of infiltrating water in Modjadji, Limpopo Province (2009).

It is evident that – even under hypothetically saturated conditions – infiltration is not solely vertical, but has a definite lateral component, potentially due to capillary action and the structure of the soil. This also represents the soil around the test reaching and exceeding field capacity after which free water is available to drain under the influence of gravity, namely, percolation. This accentuates the influence of (a) structural heterogeneities within the soil, (b) lateral dispersion prior to vertical seepage and (c) the questions around saturated conditions for field tests.

Four profiles from the study area were compared with the hypothetical vertical vadose zone classes (Figure 18). Profiles (a) and (c) occur in the slightly drier Middle Letaba catchment where topography is also more even. Profiles (b) and (d) occur in the Molototsi catchment where slopes are somewhat steeper, the conditions are slightly more temperate and the leucogranite occurs in close proximity.

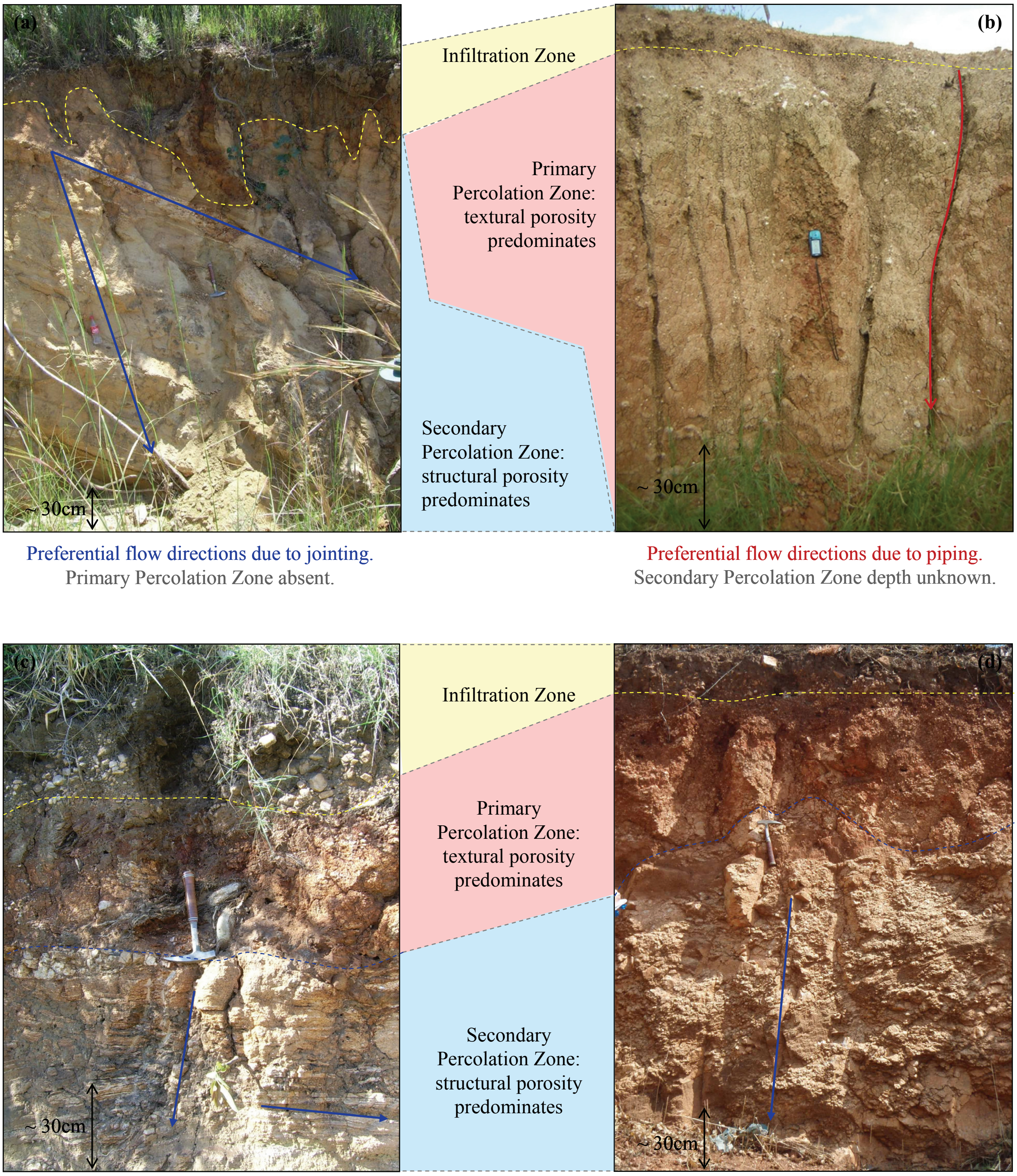

Figure 18. Vertical vadose zone classes on similar bedrock (arrows indicate anticipated flow directions).

Note how – even though underlain by similar bedrock – the profiles differ significantly with respect to the vadose zone horizons as follows:

- (a) Two clear joint directions are assumed to control flow; the primary percolation zone is absent.
- (b) One clear direction (potentially due to piping) which can channel percolation; the secondary percolation zone depth is unknown.
- (c) All three upper zones are present.
- (d) All three upper zones are present.

1.15.3. Findings

The vertical vadose zone classification became significantly more important as the project progressed. Under the assumption that water is infiltrated into the infiltration zone, the favourable parameters from a spatial classification can easily now become less favourable conditions. Vegetation, for instance, can improve infiltration, but potentially decreases percolation due to transpiration. A fine-grained soil can allow infiltration due to extensive cracking or biotic processes, but can become almost impermeable at depth. The vertical classification should therefore distinctly address the variations in these parameters per horizon.

CONCLUSIONS

The project entailed five main objectives, *viz*. (i) assessing empirical approaches to determine hydraulic conductivity from soil grading analyses, (ii) evaluation alternative parameters and methods, (iii) comparing field test results with the empirical approaches, (iv) zoning the study area into areas with similar vadose zone properties, and (v) determine aspects for further refinement of the project.

The first objective entailed an assessment of the empirical approaches employed to estimate hydraulic conductivity from soil grading analyses. Two very distinct clusters of ranges (depending on the method) were identified, namely a low-K scenario ranging between approximately 10^{-15}-10^{-7} m/s and a high-K scenario ranging between approximately 10^{-9}-10^{-2} m/s. Despite the great variation between the various empirical methods, all approaches seem to adequately distinguish between coarser-grained (more permeable) materials and finer-grained (less permeable) materials. However, no definite hydraulic conductivity can be assigned due to the high variation in the results.

The second objective entailed estimation of alternative parameters. The first of these comprised the estimation of the *effective grain size diameter*. This was plotted against the average hydraulic conductivities determined from the empirical approaches. Two distinct correlation situations exist: (a) for the same range of effective grain sizes, two possible fits can be seen where $K > 10^{-5}$ m/s and where $K < 10^{-5}$ m/s, or (b) high variation in K can exist within clusters separated by $d_e \approx 0.02$ mm. For excessively fine-grained materials, typically $d_e > 0.011$ mm correlating to approximately $d_{30} < d_e < d_{45}$. For coarse-grained materials, typically $d_e < 0.046$ mm, correlating to approximately $d_5 < d_e < d_{20}$. This clearly indicates the motivation for $d_e = d_{10}$ for most of the methods applicable to coarse-grained materials.

Two alternative and new parameters were also applied to the dataset. The *effective liquid limit* relates to the actual moisture content required in the bulk of the material in order to lose its plastic behaviour. This correlates fairly with the empirical hydraulic conductivities. A distinct drop in estimate hydraulic conductivity is observed around $LL_{eff} = 20$, suggesting that (under the assumption that the K values are correct) a distinct change in hydrological properties occurs around this value, resulting in a sudden drop in K of four orders of magnitude. The correlation also improves significantly around this value. Finally, a *coarseness index* was calculated to increase the influence of pore-creating (gravel) and pore-clogging (clay) grains with respect to the more intermediate particle size (sand and silt). A good correlation exists between the CI^+ and K, although more definition of the parameter is required. At present, the CI^+ can either (a) serve as a correction factor for the non-uniformity of the soils and aid in achieving a scenario of $C_U = 1$, or (b) have a direct relationship to the porosity or even permeability.

Thirdly, the field and empirical results were compared. A fairly poor correlation was determined where the field K was typically in the range 10^{-4}-10^{-5} for empirical K between 10^{-6} and 10^{-11}. This is probably due to (a) the high variation in the empirical methods and the uncertainty of the accuracy of these methods, or (b) the field tests not necessarily reaching saturated steady-state conditions and subsequently not relating to the actual seepage rates.

The fourth objective – the zoning of the area into similar vadose zone properties pertaining to hydraulic conductivity and vadose zone thickness – was not completed during this study due to the vast amount of factors requiring refinement. Firstly, the methods applied to determine K in the field, laboratory and empirically need to be assessed in more detail, and secondly a vertical vadose zone classification is also required due to the changing properties with depth.

Finally, the aspects requiring refinement needed identification. These, at this preliminary stage, include better determination of porosity and hydraulic conductivity, as well as a better understanding of the influence and variation in geology with depth and spatially.

1.16. Preliminary Vadose Zone Classification Methodology

A preliminary vadose zone classification methodology is shown schematically in Figure 19.

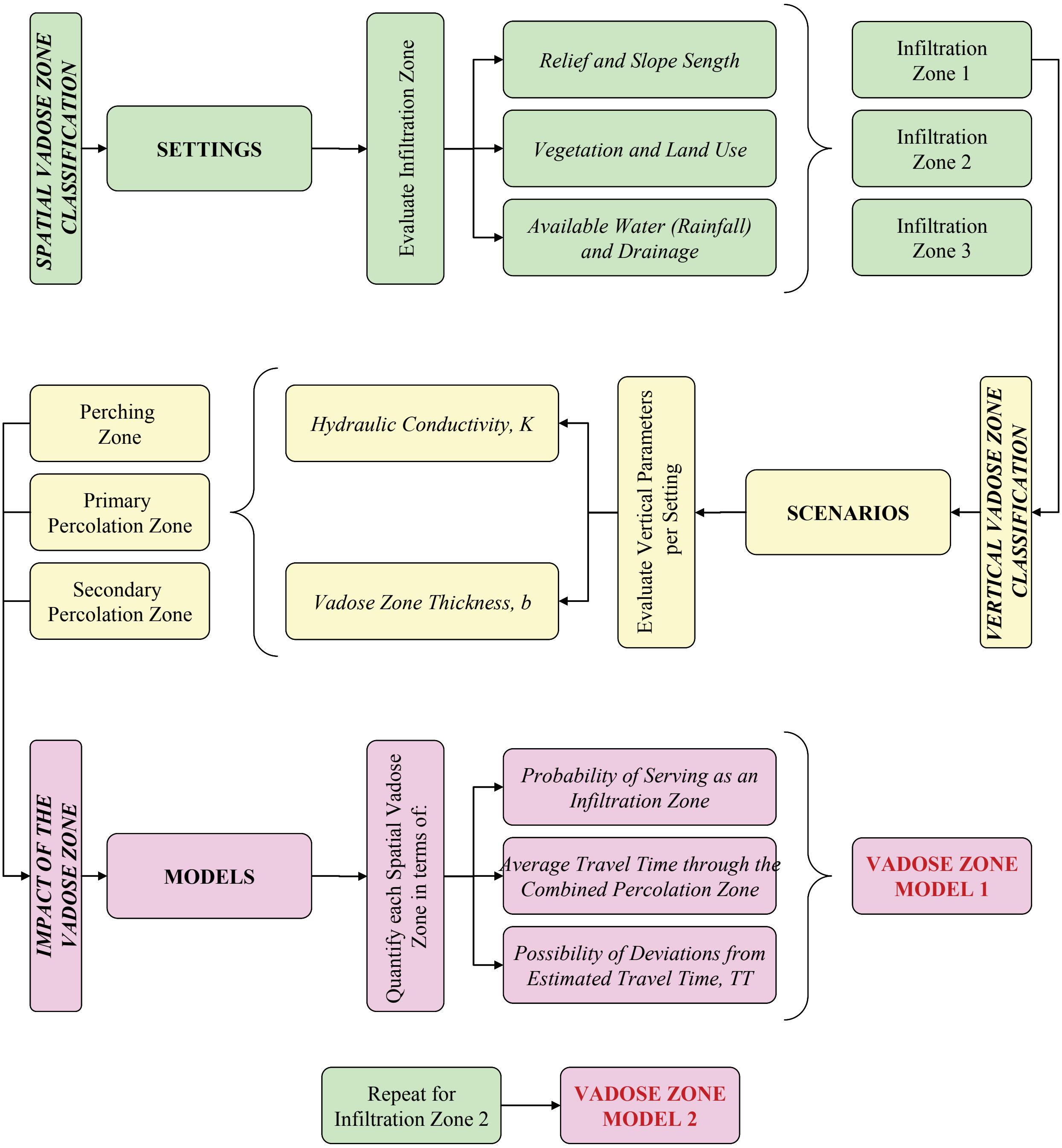

Figure 19. Flow chart depicting the preliminary methodology for vadose zone classification.

The approach entails three phases per setting as follows:

- The ***Spatial Vadose Zone Classification*** pertains to the identification of the settings based on the possibility of infiltration of surface water into the plant root zone or infiltration zone. This initial spatial or lateral classification is a function of the slope angle and length or relief, the land cover, the geomorphological controls of surface hydrology, and the rainfall intensity. Based on this, the study area is subdivided into a number of settings or infiltration zones.

- The ***Vertical Vadose Zone Classification*** expands on the vertical variation or horizons underlying each infiltration zone. A deeper profile is required at this stage to evaluate the presence or absence of perching zones as well as primary and secondary percolation zones. For each of these horizons, the thickness should be estimated and a percolation rate should be determined, preferably via field and empirical methods. The weighted average of these horizons can be based on the thicknesses of the relevant horizons to quantify the scenario.

- The ***Impact of the Vadose Zone*** supplies a conceptual yet quantitative model of each of these zones by overlying the potential of infiltration with the vertical heterogeneity of the vadose zone horizons. The model therefore addresses the possibility of infiltration, followed by a travel time, *TT*, calculated as *b/K* for the complete thickness of the vadose zone in a specific setting. Any potential deviations (e.g. sporadic occurrences of pedocrete, springs, more pronounced biotic activity, anthropogenic impacts, etc.) should be clearly stipulated per zone and, if possible, included to provide a worst-case scenario (fastest travel time).

1.17. Main Issues and Concerns

Work is ongoing to address a number of issues. These can be classified as (1) empirical assumptions and methods, (2) field methods and applications, (3) lateral or spatial classification and (4) vertical or horizon-based classification.

(1) In terms of the empirical methods, the main issues are:

- The assumptions pertaining to empirical grading-based estimation methods need to be refined or, if possible, dismissed. The primary assumptions are the porosity, effective grain size diameter and uniform grading, all of which directly influence the hydraulic conductivity but which cannot always be determined.

- Determination of porosity via Istomina yields porosities ranging between 0.25 and 0.26 for both exceptionally fine-grained and coarse-grained materials. This very narrow range of porosities for highly variable materials is not considered valid.

- The assumption of uniform or near-uniform materials is invalid as the majority of natural *in-situ* - soils contain a wide range of particle sizes in highly varying ratios. A uniformity coefficient below four is very scarce in nature and the applicability of the methods is therefore compromised.

- The effective grain size diameter is mostly estimated loosely around the d_{10} value without much scientific reasoning and is applied mostly in sandy materials. Calculation of the effective grain size diameter as a "most frequently occurring" grain size yields significantly different sizes for clayey and gravelly materials. The question here is, however, which particle size indefinitely determines the seepage behaviour of a material (with the notable emphasis on flow-promoting and flow-prohibiting grain sizes).

- *In-situ* structures (i.e. joints, burrows, roots) and pedological processes (i.e. eluviation and illuviation, pedogenesis) inherently either improve or mar seepage. These aspects are not included in disturbed sample analyses and subsequently are not included in the empirical results.

(2) In terms of the field methods, the main issues are:

- Most field methods assume profile saturation or pre-soaked conditions. This is rarely achieved due to lateral dispersion of water and capillary action. In clayey soils, the water will disperse three-dimensionally over greater distances and in sandy soils the majority of the water may seep vertically without ever reaching saturation. Different approaches may, therefore, be required.

- Vertical heterogeneity (vertical classification) is not addressed during field tests and the properties of one horizon is extrapolated throughout the complete vadose zone thickness.

(3) In terms of the lateral classification, the following needs to be addressed:

- Identifying zones of infiltration from surface should be considered a function of the surface soil texture and structure as this forms the primary pathway of moisture into the subsurface. From here and once past the root zone only can water become available for percolation and possibly recharge. In these lateral or spatial classes, the topsoil should therefore be considered rather than geology, climate and landform alone. This outlines the need for a combined lateral and vertical classification.

(4) In terms of the vertical classification, the following issues need to be addressed:

- The parameters to classify the vadose zone vertically should be both a flow rate (or hydraulic conductivity) and a vadose zone thickness (or depth to water level). Fast percolation to a deep water level and slow percolation to a shallow water level may require the same travel time.

- Percolation is not considered to be a continuing process. Rather, one should consider that moisture can be retained in the unsaturated zone due to capillary processes overriding gravity. A percolation event or a purging event can be triggered in any time frame, after which concentrated contaminants are mobilised rapidly rather than being slowly diluted over time. The same event can mobilise clays and ions to alter the soil properties at different depths, subsequently directly affecting seepage.

1.18. Applications and Implications of the Research

Intricate correspondence with a number of professional hydrogeologists, engineering geologists, civil engineers, soil scientists and geomorphologists outlined the following:

- Collapse settlement can be induced by the sudden purging events which mobilises the movement of clay minerals, which may cause leaching and an open structure inducing subsequent settlement of the overlying horizons. The sudden water movement through and wetting up of an existing dry, open-structured soil may also induce collapse under loading. The clay minerals are then trapped deeper in the profile, often concentrated to such an extent that a shallow perching zone can results. The same can apply to the process of pedogenesis where mobile elements can be deposited due to changing redox conditions resulting from this purging event.

- Mobilisation and migration of contaminants through landfills, mine dumps, cemeteries, waste disposal sites, sewage systems and numerous other surface sources of pollution become event-driven rather than rainfall-driven, meaning that these contaminants can be mobilised at higher concentrations rather than slowly over time. Waterlogged conditions can potentially also prevail for long periods (until a purging event) during which ecosystems can be affected.

- The implications on recharge as a purging event rather than a continuous process are accentuated as rainfall can no longer be the sole determinant in recharge estimations. Additionally, recharge is localised and not a surficial-uniform process and these purging events occur scattered across the later vadose zone classes.

- The safe locating of potentially contaminating infrastructure should not be based solely on application rates or percolation rates, but should include an assessment of the vertical and horizontal variations. These rates can serve as an indicator, but essentially one should define whether the location is prone to infiltration with respect to the spatial variations, as well as whether the materials themselves can allow water movement and contaminant transport once infiltrated with respect to the vertical variations.

1.19. The Way Forward

Ongoing work should focus on concepts rather than applications to clarify the fundamental scientific concepts. This can best be done by evaluating the following concepts:

- Lateral or spatial vadose zone classes and infiltration
- Vertical vadose zone classes (or vadose zone or horizons) and percolation
- Porosity estimates and textural versus structural porosity
- Travel times rather than flow rates (i.e. incorporating the water level or vadose zone thickness)
- Purging events and the triggering mechanisms
- Pedological and pedogenic processes associated with travel times and purging events that will influence porosity and percolation.

Application of the methodology is ongoing but, due to the number of important questions raised, the methodology needs to be refined. Additional study areas have been selected and authorisation granted within the Thabazimbi Municipality to review the application on sedimentary rocks and less disturbed more homogenous environments. Similar work is also presently being pursued on the granite and mafic igneous rocks of the western limb of the Bushveld Igneous Complex between Rustenburg and Northam.

The future aim with the two new study areas and the Basement study area is to assess the vertical vadose zone variation to be able to supply a map-based quantitative evaluation of the vadose zone properties.

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APPENDICES

The following are included on the companion CD:

- Laboratory grading analyses
- Soil profile descriptions
- Photographs of all sampling locations