Vadose Zone Hydrology: CONCEPTS AND TECHNIQUES

MA Dippenaar, JL van Rooy, N Breedt, A Huisamen,
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WATER RESEARCH COMMISSION

TT 584/13

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Report to the
Water Research Commission

by

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WRC Report No. TT 584/13

February 2014

Obtainable from

Water Research Commission
Private Bag X03
GEZINA, 0031

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The publication of this report emanates from a project entitled *Vadose Zone Hydrology: Spatial and Temporal Influences, Assessment Techniques and Aquifer Susceptibility* (WRC Project No. K5/2052).

ISBN 978-1-4312-0507-3

Acknowledgements

Gratitude is expressed to the Water Research Commission (WRC) for funding and management of this project on vadose zone hydrology. The following members of the steering committee are thanked for their significant guidance during the project and their peer-review of the final product being this document:

- Dr S Adams — Water Research Commission: Chairperson
- Prof S Lorentz — University of KwaZulu-Natal
- Dr N Jovanovic — CSIR
- Dr J Nel — University of Western Cape / GCS
- Mr K Majola — Department of Water Affairs

Additional gratitude is expressed to the following:

- City of Tshwane, for access to cemeteries and parks in the municipality
- Department of Public Works, for access to the Randjesfontein site
- The undisclosed mine and its personnel for authorising access to the tailings storage facility
- UIS Analytical Services, Waterlab, Soillab and the University of Pretoria's Analytical Facility, for reduced rates for laboratory analyses
- Management of the University of Pretoria's Experimental Farm, where many field methods were validated prior to field work of the individual case studies
- University of Pretoria, for contribution of facilities, time and postgraduate students.

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LIST OF SYMBOLS

Symbol	Description	Units
b	Saturated thickness	[L]
C_U	Uniformity coefficient	[-/-]
d	Particle diameter represented by percentage passing denoted as subscript (d_{60}, d_{30}, d_{10})	[L] typically mm
d_e	Effective grain size diameter	[L] typically mm
d_i	Representative grain size between $d_{i(min)}$ and $d_{i(max)}$	[L] typically mm
E	Kinetic energy	[ML/T]
e	Void ratio	[-/-]
f_i	Fraction comprising grain size d_i	[-/-]
g	Gravitational acceleration	[L/T^2]
h_c	Capillary rise	[L]
i	Hydraulic Gradient, dh / dl	[-/-]
M	Mass	[M]
m	Mass (in Bernoulli's equation)	[M]
n	Number of samples in population	[-/-]
P	Pressure (or force per unit area)	[P] [M/LT^2]
r	Pore radius	[L]
S	Storativity	[-/-]
S_S	Specific storage	[1/L]
S_W	Degree of saturation	[-/-]
S_r	Residual saturation	[-/-]
S_R	Specific retention	[-/-]
S_Y	Specific yield	[-/-]
V	Volume	[L^3]
w	Gravimetric moisture/ water content (by mass; see θ)	[-/-]
W	Work required to lift a mass	[ML^2/T^2]
z	Elevation of fluid's center of gravity above a datum	[L]

Greek Symbol	Description	Units
α	Compressibility of the mineral skeleton	[LT^2/M]
β	Compressibility of water	[LT^2/M]
γ	Unit weight	
η	Porosity	[-/-]
η_e	Effective porosity	[-/-]
θ	Volumetric moisture/ water content (by volume, see w)	[-/-]
λ	Contact angle between meniscus and tube wall	[°]
μ	Dynamic viscosity	[M/LT]
ρ	Density	[M/L^3]
σ	Surface tension	
Ψ	Soil water potential	[P] [L]
ψ	Pressure head (when negative); suction head (-ψ)	[L]

L – Length; M – Mass; P – Pressure; T – Time

Subscript	**Description**	**Relating to**
A	Air phase	M V P ρ
atm	Atmospheric	P
b	Bulk, total	M V ρ Ψ
c	Capillary	h P
e	Effective	η d
g	Gravitational	Ψ
m	Matric	Ψ
o	Osmotic	Ψ
R	Retention	S
S	Solid phase	M V ρ
S	Specific	S
T	Total, bulk	M V ρ Ψ
V	Void space	V
W	Water phase	M V P ρ γ μ σ
Y	Yield	S

1. INTRODUCTION

1.1. Project Rationale

The project on *Vadose Zone Hydrology: Spatial and Temporal Influences, Assessment Techniques and Aquifer Susceptibility* (K5/2052), follows from previous work outlining the importance of classifying the vadose zone for improved understanding (Dippenaar *et al*. 2010). Given the wide range of disciplines involved in vadose zone hydrology, detailed investigation of the vadose zone is generally subject to:

- 'Mono-disciplinary' investigation for specific purposes such as either plant water availability and nutrients, potential groundwater recharge, groundwater vulnerability, seepage concerns for infrastructure development, etcetera, without adequate ability to transfer the knowledge to other applications
- Empirical or modelling assumptions based on measurable surface water and/ or groundwater input data that compromise the integrity of any subsequent modelling.

An approach involving numerous disciplines has numerous problems. Symbols and subscripts denoting parameters are not universal and are simplified here to include concepts from civil engineering, hydrogeology, chemistry, physics, soil sciences and other disciplines. Where possible, the symbols used hereafter represent those encountered in majority of the texts (e.g. η or n for porosity instead of Φ; d for particle size diameter instead of $2r$, D or Φ) and those particularly pertaining the hydrogeology in favour of other disciplines (e.g. θ for moisture content instead of w or m; or preference over soil mechanics where the symbols are often interchanged, as in k for permeability and K for hydraulic conductivity or q for specific discharge versus Q for flux). The symbols from the governing equations have been changed accordingly. All units – unless specifically noted otherwise – have also been converted to SI units rather than commonly used units. Permeability, for instance, is noted in square meters and not square centimetre, darcy or any other equivalent.

Definitions differ per discipline. This becomes important in a multi-disciplinary field of study as confusion and misinterpretation become concerns. Hereafter, definitions apply mainly to the hydrogeological discipline where, for instance, soil refers to a mixture of solids and pore space containing essentially air or water (as opposed to a strength-based distinction from rock in engineering, or a medium subject to a long formation and inclusive or organic matter in soil sciences). Where overlapping terminology exists, all relevant and important terms have been defined. Those pertaining to hydrogeology have, however, been used throughout the text (e.g. specific discharge instead of seepage velocity; pedocrete instead of laterite).

Investigation techniques are addressed at a later stage. Techniques, methods and approaches vary between disciplines and are based on the need for investigation. It is aimed in this study to address the most important techniques, emphasising the intermediate vadose zone and subsurface processes rather than soil moisture measurements, and to incorporate these for the use of other disciplines to avoid unnecessary repetition and to find agreement between disciplines. One critical example of this is the quantification of readily available parameters such as hydraulic conductivity or permeability that, by definition, apply to saturated conditions and have to be corrected based on the moisture content or tension. Additional detailed emphasis is placed on the proper description of earth materials, deduction of the shallow flow processes and the development of the conceptual model.

Although different disciplines should continue to exist within their own respective fields of expertise, unnecessary duplication and lack of cross-disciplinary understanding should be addressed. Consolidation of diverse aspects from such different disciplines will be beneficial to a holistic understanding of the vadose zone, as well as on its importance in a vast number of applications. Clarity regarding definitions is also important, notably given the duplicate concepts of, for instance, recharge (to groundwater table or that which is potential), confinement (of aquifers or stream channels) and infiltration (including or excluding the term percolation)

Without standardisation or infringing on the very important attributes of the individual specialist disciplines, a need exists for more open dialogue between (1) various earth scientists (geologists, engineering geologists, hydrogeologists, soil scientists, pedologists, geomorphologists, hydrologists), and (2) between earth scientists and other decision makers (social scientists, engineers, town planners, economists, legal specialists, managers). Earth scientists need to translate their findings for use by a broad audience in which the results can be interpreted to a variety of applications and by a variety of specialists. As part of this, a standard multi-faceted Vadose Zone Assessment Protocol (VZAP; §9) has been deduced which outlines stages of investigation. Competency of specialists and decision-making are continuously addressed.

Although vadose zone hydrology is in itself a specialised interdisciplinary field, the applications rely on the requirements of the individual specialists involved in its study. Better dialogue between specialists is the solution rather than a single uniform discipline, and the contributions of all interested disciplines improve the quality of investigations.

Certain aspects identified in recent literature accentuate gaps in knowledge pertaining to hydrogeology and vadose zone hydrology. Some of these include, for instance, the matter of variably saturated fracture flow (Berkowitz 2002), the empirical approaches rather than field quantification, scale and heterogeneity issues (Miller and Gray 2002), and lack of cross-disciplinary understanding (Dippenaar 2012). Although it is impossible to solve issues in vadose zone hydrology given the broad scope of this project, attempts have been made to address the most important of these concerns.

1.2. How to use this Manual

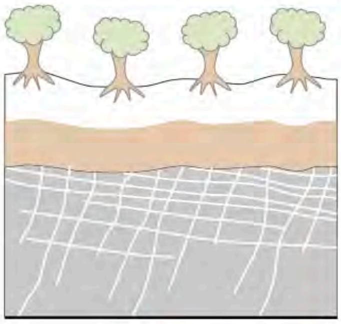
The text is subdivided into three sections, the interaction being as per Box 1.

Box 1. Using the Vadose Zone Manual.

BOX 1: USING THE VADOSE ZONE MANUAL

Part 1: Introduction to Vadose Zone Hydrology

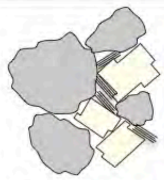
Properties of the vadose zone
Principles of unsaturated flow
Properties of the media
Classification of rock and soil



Methods to quantify
- Porosity
- Hydraulic conductivity

Including
- Empirical estimates
- Laboratory methods
- In-situ/ field approaches
- Published data
- Modelling

Validation based on case studies



Quantifying porosity

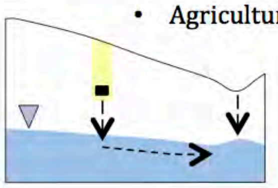
Quantifying hydraulic conductivity

Part 2: Methods and Guidelines

Applications to
- Ephemeral inland wetlands
- Platinum tailings storage facilities
- Peri-urban cemeteries
- Variable land use in urban settings
- Aquifer vulnerability
- Engineering design
- Sanitation
- Agriculture

- 5-tiered approach to vadose zone hydrological investigation
- Development of conceptual model
- Cost-benefit analysis
- Minimum requirements
- Competent persons
- Decision-making

Guidelines for Vadose Zone Assessment



Case studies with conclusions contained in Part 1 and Part 2:
- Documented high profile investigations
- Multi-disciplinary approaches
- Data in digital appendices

Part 3: Supporting Case Studies

READ MORE & CITED FROM:

The three sections comprise the following:

- Part 1 – Introduction to Vadose Zone Hydrology. This section addresses the distribution of water in the crust and important, unified basic concepts of the unsaturated zone.
- Part 2 – Methods and Guidelines. This section focuses on earth material descriptions, assessment methods (empirical, laboratory, in-situ, modelling), the relevant standard approaches to conducting these, and applications of the methods and techniques.
- Part 3 – Supporting Case Studies. The final section incorporates the case studies, including descriptions, rationales, methods applied, results, interpretation, conclusions and provisional findings. The main contributions to Parts 1 and Parts 2 have been included in the relevant theory sections and refer to the case studies as VZSA (vadose zone study area) for easy cross-referencing.

In this text, the following applies:

- Symbols and subscripts denoting parameters had to be simplified from civil engineering, hydrogeology, chemistry, physics, soil sciences and other disciplines. Where possible, the symbols used hereafter represent those encountered in majority of the texts and those particularly pertaining the hydrogeology in favour of other disciplines. The symbols from the governing equations have been changed accordingly and are summarised in the List of Symbols.
- Definitions apply mainly to the hydrogeological discipline where, for instance, soil refers to a mixture of solids and pore space containing essentially air or water (as opposed to a strength-based distinction from rock in engineering, or a medium subject to a long formation and inclusive or organic matter in soil sciences).
- All units – unless specifically noted otherwise – have been converted to SI units rather than commonly used units.
- Where overlapping terminology exists, all relevant and important terms have been defined. Those pertaining to hydrogeology have, however, been used throughout the text (e.g. specific discharge instead of seepage velocity; pedocrete instead of laterite).

Part 1: Introduction to Vadose Zone Hydrology

Dippenaar, M. A.

2. THE VADOSE ZONE AND VADOSE ZONE HYDROLOGY

2.1. Distribution of Water in the Crust

The vertical distribution of water in the Earth's crust is shown in Box 2. The ***vadose zone*** (also called the ***unsaturated zone*** or the ***zone of aeration***) stretches through the soil zone and intermediate zone and incorporates the complete ***capillary fringe*** where the medium is still below saturation, gradually becoming saturated towards the water table. This incorporation of the capillary fringe is occasionally questioned due to the saturated nature of the bottom part, but majority of sources agree that the vadose zone is primarily at pore pressures below atmospheric (therefore overlying the water table and including the capillary fringe where pore pressures are less than atmospheric) and only secondarily to be mainly unsaturated.

The vadose zone can also be considered as "the zone between the land surface and the water table" which includes the plant root and intermediate zones and the capillary fringe, representing that portion of the crust where the pore spaces contain water at pressures below atmospheric, air and other gases (Fetter 1994).

The ***water table*** (or ***phreatic surface***) represents the boundary between the phreatic and vadose zones as well as the surface where pressure equals atmospheric. The water table is represented by the ***water level*** in a well (indicated by an inverted triangle) to account for the deviation from the water table due to any capillary effects absent in the borehole or well itself as well as the often irregular water table in the aquifer material itself. Saturation occurs slightly above the water table due to the capillary fringe, but the rule of thumb is to measure the water level and use that value. ***Perched water tables*** are often associated with the vadose zone, depending on the vertical heterogeneity of the subsurface materials. Saturation entails the water content equal to the porosity; viz. all pore spaces are filled completely with water. This applies to the ***phreatic zone***, but also to the lower portion of the capillary fringe where water is being pulled upward due to negative pore water pressures. The saturation of the bottom part of the capillary fringe is not due to the same mechanisms as the phreatic zone and – for this reason – is considered saturated but above the water table (e.g. Fetter 1994; Fitts 2002; Keary 2001; Lapidus 1990; Todd and Mays 2005).

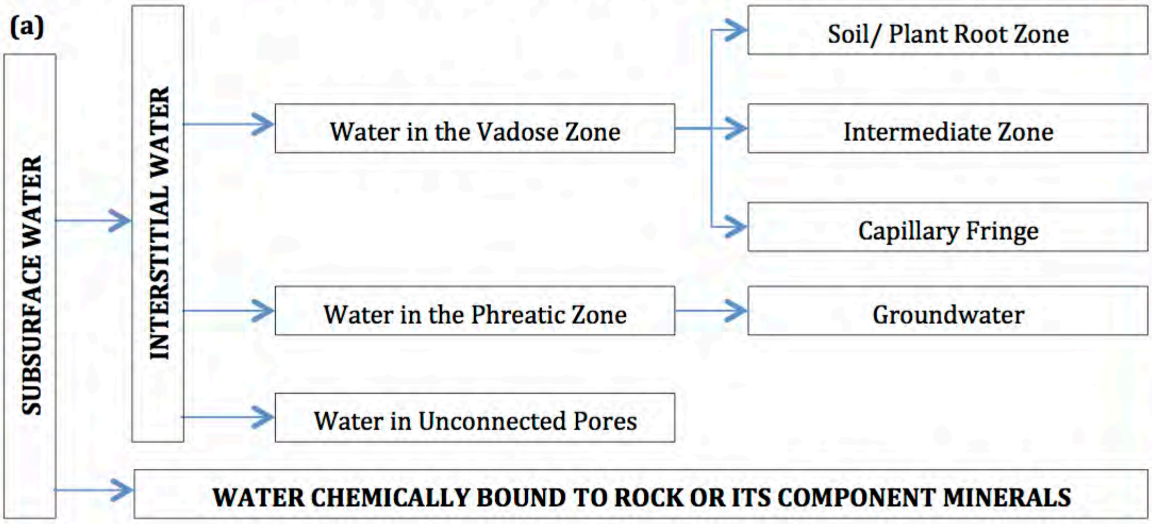
Additional to the above definition of subsurface water is also water in unconnected pores and water that is in a chemical combination with a rock or its component minerals. This unconnected pore water in combination with the vadose and phreatic water are collectively referred to as ***interstitial water*** (Driscoll 1989).

Box 2. Subsurface Water and its Distribution.

BOX 2: SUBSURFACE WATER AND ITS DISTRIBUTION

Subsurface water is divided into water chemically bound to rocks or minerals and ***interstitial water***. The latter forms part of the vadose and phreatic zones and also include dead-end pore spaces.

(a)

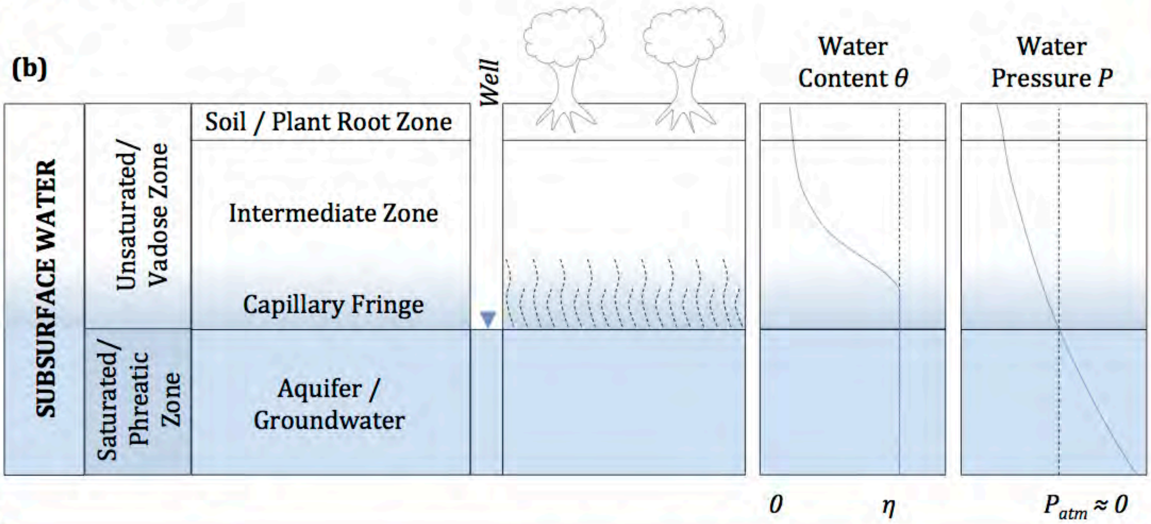


The ***vadose zone*** (also unsaturated zone or zone of aeration) stretches from the land surface through the soil zone and intermediate zone and incorporates the complete ***capillary fringe*** (where the medium may be saturated, but is always at negative pore water pressures).

The ***water table*** (or phreatic surface) is the boundary between the phreatic and vadose zones as well as the surface where pressure equals atmospheric. The ***water table*** is represented by the ***water level*** in a well (indicated by the inverted triangle) as capillary forces will result in deviations.

The ***phreatic zone*** is characterised by positive pore water pressures and complete saturation of pores with water.

(b)



READ MORE & CITED FROM:

Driscoll 1989; Fetter 1994; Fitts 2002; Todd and Mays 2005; Younger 2005

2.2. The Movement of Water in the Subsurface

The hydrological cycle (or water cycle) is an intricate interaction between water from the atmosphere, Earth surface and subsurface. The movement of water in the subsurface is shown in Box 3. Conventional hydrogeology is mainly interested in recharge which can be defined as water eventually reaching the saturated zone (Fitts 2002) or 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 (Jenn et al. 2007a; 2007b).

The problem, however, is recharge estimation. The present day understanding of recharge processes has been summarised, concluding that intrinsic limitations occur with the well-established methods of recharge estimation and that climate is not the only parameter of importance, but also the surface and subsurface conditions which incorporate lithology, palaeoclimate and palaeohydrological evolution (De Vries and Simmers 2002).

Before water can recharge the aquifer, it first needs to infiltrate from surface into the subsurface and then percolate through the vadose zone to the water table. Infiltration is often 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 such as ions and clays are being dissolved and/ or mobilised for possible precipitation or deposition further down in the profile. Infiltration continues sub-vertically under gravity until the groundwater level is reached, from which the infiltrating water (sic. 'percolating' based on the subsequent paragraph) will spread laterally in the direction of groundwater flow and vertically due to gravity (Boulding and Ginn 2004). Infiltration can also be defined as that process responsible for letting water on ground surface pass into the vadose zone, including the volume of the water, and 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, adhesive water is trapped in the vadose zone and transpired water leaves the subsurface and returns to the atmosphere. 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).

Box 3. The Water Cycle and Movement of Subsurface Water.

BOX 3: THE WATER CYCLE AND MOVEMENT OF SUBSURFACE WATER

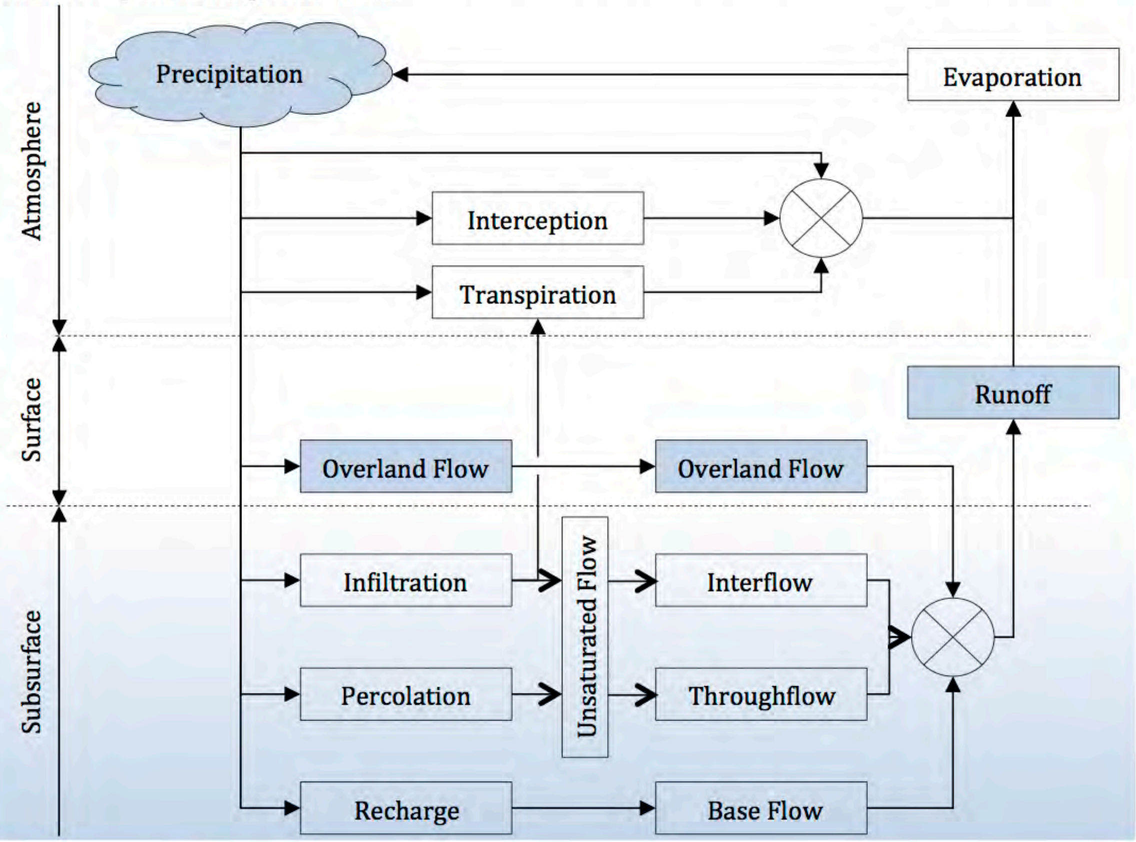
INFILTRATION refers to water entering the subsurface from the surface (due to the primary porosity or texture and secondary porosity or structure of the surficial soils which creates openings) and which is still affected by evapotranspiration; then moving sub-vertically downwards under the influences 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.

THROUGHFLOW is often distinguished from interflow as that portion which discharges to surfaces at the foot of a slope, whereas interflow discharges directly into surface water bodies.

PERCOLATION (similar to **potential recharge**) 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.



READ MORE & CITED FROM: Dippenaar et al. 2010, Fetter 1994, Todd and Mays 2005, Younger 2007

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). Rose (2006) replaces the term percolation with translocation, which is the subsequent movement of water down through the soil profile following infiltration into the soil surface. The term translocation is, however, elsewhere applied as the displacement of fines through moving water, and will henceforth be used in this manner. Some sources consider percolation part of infiltration and do not distinguish between the two concepts, whereas others refer to (potential) recharge with reference to percolation, i.e. where infiltrating water exceeds the depth of influence of evapotranspiration.

The so-called ***zero flux plane*** (ZFP) – although not always present and applicable – is often used in recharge estimation and relate to this concept. The ZFP is a hypothetical surface separating upward water movement through evapotranspiration from downward movement through drainage. Although not clearly defined within context of the classification of the vadose zone, evapotranspiration is mainly limited to the soil or plant root zone. Nonetheless, the possibilities of interflow and throughflow should be considered.

2.3. Vadose Zone Hydrology per Discipline

Different disciplines have diverse perspectives regarding the subsurface, mainly due to the differing interests in the subsurface. These include their approaches to soil or rock classification and their understanding of the subsurface and surface processes such as weathering and landscape development. Hydrological behaviour of the subsurface is possibly the one parameter common in all where different disciplines consider hydrology as an influence on the soil or rock material (Table 2-1). For this reason, input from multiple disciplines may clarify the issues around water movement through the subsurface.

Table 2-1. Perspectives on weathering and the soil zone in various disciplines (after Ehlen 2005).

Discipline	Primary Interest in Weathering
Soil science / Pedology	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

The study of subsurface hydrology generally falls within the earth scientific disciplines of soil science, geology and hydrology with notable input from other applied sciences such as botany, geography, meteorology and geomorphology. These latter disciplines involve the application of knowledge gained from earth science and water science to fields of importance such as plant water availability, biodiversity, water cycle interactions and geomorphological processes.

For the earth scientist, however, the study is of the earth materials and includes its composition and formation. The intricate interaction of soil, rock, water and organic material is constant throughout and form the fundamental basis of the study of subsurface hydrology.

Finally, the geotechnical (civil) engineer is interested in the interaction between subsurface moisture and infrastructure. This further increase the importance of including all disciplines interested in subsurface waters, regardless of the reason.

The vadose zone falls within a framework overlapping between and combining the specialisation of many different disciplines. Having primarily developed at the hand of soil science related to the plant root zone through which plant available water and nutrients cycle, the study of vadose zone hydrology has grown considerably. Vadose zone hydrology includes the specialist input of notably soil scientists, surface water hydrologists, hydrogeologists and engineering geologists, but such collaborative efforts are still mostly limited to the implications of soil water on biodiversity or the protection offered to the aquifer by the overlying unsaturated media, and hence closely linked with studies in geotechnical engineering and ecology.

Disciplinary interaction governs the extent to which each specialist field expands its own principles as follows (reference.com/ dictionary.com 2013):

- ***Multidisciplinarity*** – joining disciplines without integration (e.g. panel of specialists of all relative individual fields such as soil scientist, ecologist and hydrogeologist)
- ***Crossdisciplinarity*** – crossing boundaries to study one discipline in terms of another (e.g. relating concepts of, for instance, ecology to soil science in the proper understanding of wetland habitats)
- ***Interdisciplinarity*** – connecting and integrating disciplines (e.g. pedohydrology, engineering geology, geobotany)
- ***Transdisciplinarity*** – dissolving boundaries between disciplines (e.g. single expert of all relative individual fields, but with feedback between disciplines).

Hypothetical interactions between three earth scientific disciplines related to vadose zone hydrology are shown in Figure 2-1. This also shows the logical progress in the development of vadose zone hydrology through the following:

- The combined multidisciplinary efforts of disciplines formed the logical starting point in characterising the vadose zone.
- The interest of integrated crossdisciplinary understanding and knowledge resulted in improved understanding.
- The development of a "new" field of study in vadose zone hydrology is likely the present situation, although no single specialist exists.
- Transdisciplinarity, however, claims single expertise of all related disciplinary input, and presents imminent dangers such as the loss of detail by overloading with unordered and often unrelated data given the vast study theory, and the compromise of detailed conceptual understanding to rapid holistic thinking. Nonetheless, if properly executed, transdisciplinarity has the feedback mechanism

between disciplines as a positive attribute and all separate disciplines therefore influence each other's decisions.

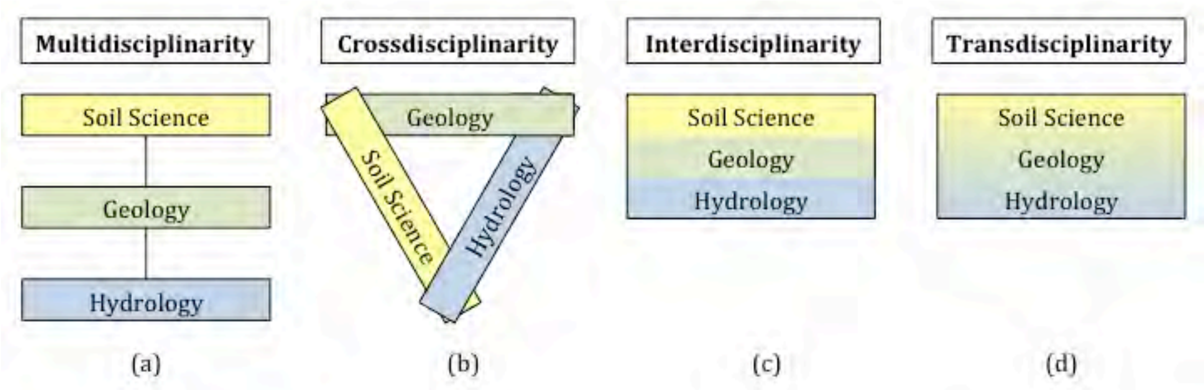


Figure 2-1. **Interaction between earth scientific disciplines.**

It is for this reason that this text has been prepared. Without intention to infringe upon the specialist disciplines or to claim expertise on fields pertaining to notably the soil zone and the applications to plant growth, this text has been prepared with the purpose of clarifying concepts for a wide audience, but with the focus on geomechanics, Quaternary processes and hydrogeology, and with application to land use change and urban densification.

The following section briefly summarises some disciplines into broad, generic overviews of the role of vadose zone hydrology in various earth scientific and environmental disciplines. Those specialist fields interested solely in the mechanical properties and surface processes have been excluded for simplification purposes. Certain disciplines have also been grouped together where the one's application of the field of vadose zone hydrology is directly linked to the approaches followed by the other.

2.3.1. Environmental science and ecology

Environmental science is an exceptionally broad field of study with a wide range of specialisations where the environmental scientist is typically involved in the impact assessment of a proposed development and serves the function of collating specialist reports and deducing specific constraints. Numerous examples exist, most of which are covered by other specialists in applications for land use change, but some specific high profile applications should be noted.

Wetlands, notably in arid countries such as South Africa, are critical in controlling the hydrological cycle and in ensuring biodiversity. Excluding the obvious wetlands in contact with surface water (fluvial, lacustrine, coastal), special types of ephemeral inland wetlands as addressed in §8.1 are harder to identify based on the four indicators of terrain, soil form, soil wetness and vegetation as stipulated by DWA (2005) and elaborated by for instance Day et al. (2010), Ewart-Smith et al. (2006), SANBI (2009) and Tiner (1999). These wetlands typically occur from perched water tables in the vadose zone and are broadly categorised as seeps and springs (Ewart-Smith et al. 2006) or seasonally waterlogged slopes termed paluslopes (Semeniuk and Semeniuk 1995).

Other notable applications involve contamination assessments and ecological assessments where the complete hydrological cycle and biodiversity complement the earth scientific approach. The latter involves the ecologist, botanist and/ or zoologist and the soil zone and riparian interaction become habitat dependent on the movement of water and nutrients through the vadose zone.

2.3.2. Hydrogeology and geohydrology

For the groundwater scientist, the vadose zone essentially play three vital roles, viz. (1) protecting the phreatic zone from surface contamination and which can be evaluated at preliminary screening level through for instance aquifer vulnerability assessments; (2) determining the likelihood, rate, mode and position of aquifer recharge; and (3) governing processing such as shallow interflow, throughflow, moisture retention and the subsequent formation of some types of springs and wetlands.

Aquifer vulnerability in general is addressed by Foster et al. (2002) and Foster et al. (2013), related to Africa by Robins et al. (2007), and its application to urban areas in South Africa by Sililo et al. (2001). Aquifer recharge is also discussed in elaborate detail by, for instance, Beekman and Xu (2003) and De Vries and Simmers (2002).

The hydrogeologist is involved in the licensing of water for the change of land use to any potentially contaminated future use (s21(g) of the National Water Act (NWA 1998), including cemeteries (s21 of the Environmental Conservation Act, ECA 1989), ground-based sanitation systems, filling stations, mining or water treatment plants. Important input parameters of the recharge and aquifer vulnerability are typically required for such contamination assessments, as well as for water supply investigations.

Regarding water supply, the vadose zone governs recharge and provides some degree of protection to water in the aquifer. However, specific developing contributions in the water supply and quantity fields as noted by Gleeson and Cardiff (2013) very specifically include human-induced changes such as land cover and the impacts of changing flows on ecological systems.

2.3.3. Engineering geology and geotechnical engineering

The influence of moisture becomes increasingly important in engineering geological and geotechnical investigations. Water – being practically incompressible in its liquid state – keeps soil structure intact and only with reduction in moisture content, often associated with simultaneous loading of the soil, can the soil undergo vertical shortening. Further volume change can be expected in cohesive or non-granular clayey soils in the form of heave and shrinkage of active clay minerals such as montmorillonite. Given also the weathered rock, soil, pedogenic and unconsolidated materials, Clauss et al. (1969) emphasis the benefit of pedology and Quaternary geology for the engineering geologist.

The draft South African National Standard (SANS 2009b) suggests the inclusion of seepage in the delineation of sites for development in terms of being most favourable (permanent or perched water table more than 1.5 m below ground surface), intermediate (less than 1.5 m) or least favourable (swamps and marshes). Additionally, inclusion of regional geohydrological data and local data in the instance of dolomite land has to be included. It is also required to comment on the prominent water courses, preferred drainage routes and should properly interpret groundwater seepage conditions.

Water is important in construction in that surface water causes erosion and flooding, and groundwater controls effective stress and frictional strength. Changes in groundwater conditions induced by engineering (e.g. dewatering, tunnelling or groundwater lowering) mobilise water and can possibly also cause internal erosion, increasing effective stress and self-weight compaction of earth materials. Rising water levels may furthermore weaken the ground supporting structure due to, for instance, dissolution of cementing materials (Hencher 2007). Atterberg limits – relating moisture content to soil consistency – are important engineering parameters with notable respect to cohesive soils and influence decisions regarding use of on-site materials, stabilisation and anticipated geological problems.

Water is noted as one of the factors with the highest incidence that affects the geotechnical behaviour of materials and result in (González De Vallejo and Ferrer 2011):

- Dissolution resulting in loss of material in soluble rocks and karstification, causing cavities, subsidence and/ or collapse
- Erosion or piping resulting in loss of material, sheetwash, internal erosion and gully erosion, causing subsidence, collapse, settlement, piping and/ or silting
- Chemical reactions resulting in changes in chemical composition, attacking cement, aggregates, metals and rocks
- Weathering resulting in changes in the chemical and physical properties of the materials, causing decrease in strength and increasing deformability and permeability.

2.3.4. Soil science, pedology and hydrology

For the soil scientist and pedologist, the vadose zone is important notably in the soil or plant root zone and involve application to plant water availability, irrigation efficiency, nutrients and more recently to the fields of contaminated land investigation from, for instance, tailings storage facilities and cemeteries. The development of the understanding of unsaturated flow and movement of solutes in the vadose zone is discussed by Fetter (1999, §4.1) and can primarily be attributed to the soil scientist with significant development in the field of contaminant transport through this zone.

The soil scientist is also involved in the classification of wetlands with soil form and soil wetness being two important indicators as discussed in previously. The close relationship between soil water and soil science is probably most notable in the developing science of hydropedology. Hydropedology is defined as "… integration of pedology with hydrology to enhance the holistic study of soil-water interactions and landscape-soil-hydrology relationships across space and time, aiming to understand pedologic [sic.] controls on hydrologic [sic.] processes and properties, and hydrologic [sic.] impacts on soil formation variability, and functions" (Lin et al. 2008 in Le Roux et al. 2010)." Hydropedology is also well documented by Bouma (2006) in international context.

Assessment of soil resources is documented for the application of irrigation water management by Stevens and Laker (2012) and key hydrological processes are addressed with the purpose of upscaling for use in models by Lorentz et al. (2008) and include hillslope processes, preferential flow and near-surface soil water.

2.4. Considerations in Vadose Zone Hydrology

As will be addressed later in detail, the vadose zone has very specific considerations during investigation. Early cognisance of the additional influences on hydraulic parameters in the vadose zone and the impacts thereof are important and will contribute to using this text and improving investigation quality. Although not complete, some of these are shown in Figure 2-2 and include:

1. Surface
   - 1.1. Climate – precipitation, evaporation
   - 1.2. Plant water availability and transpiration
   - 1.3. Surface water – groundwater interaction
   - 1.4. Sensitive ecosystems
   - 1.5. Land use and land cover
2. Shallow subsurface
   - 2.1. Infiltration
   - 2.2. Perched water tables
   - 2.3. Interflow, throughflow
   - 2.4. Translocation and pedogenesis
3. Deep subsurface
   - 3.1. Percolation to eventual recharge
   - 3.2. Soil vadose zone
   - 3.3. Fractured rock vadose zone
   - 3.4. Variable saturation.

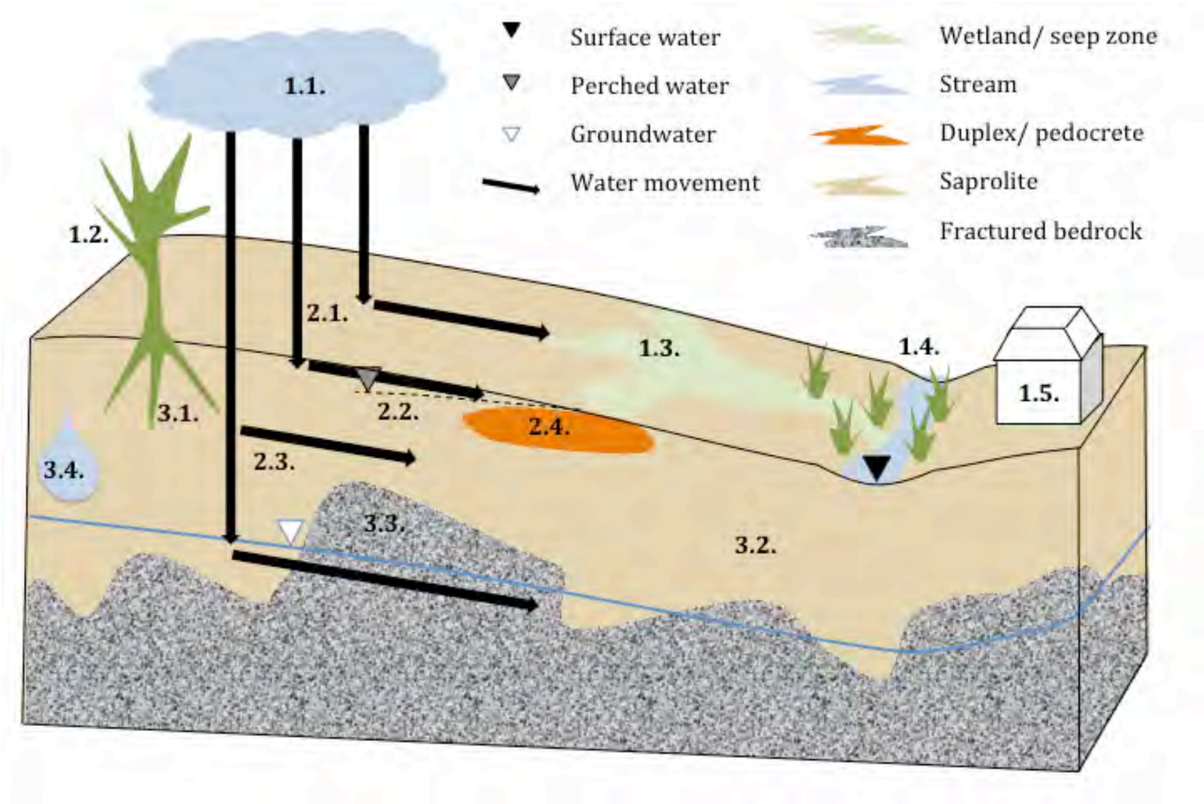


Figure 2-2. **Some considerations in vadose zone assessment.**

3. THE MEDIA

In soil sciences, soils are considered a mixture of four components, namely minerals (or the inorganic constituents), soil organic matter, soil water and soil air. In soil mechanics reference is rather made to three phases, which basically represents the soil scientific components with the exclusion of organic matter. It is difficult to address phase relationships as studied in soil mechanics under the subsequent headings of ***Water***, ***Soil*** or ***Rock*** as the intrinsic purpose of phase relationships are to assign parameters based on the abundance or absence of certain phases, i.e. solid soil particles, pore water or pore air. For this reason, the basic phase relationships will be addressed briefly prior to the relevant subsections. Note that symbols vary between disciplines and even within the field of hydrogeology. The use of symbols has been simplified to represent majority of the texts and the equations have been adjusted accordingly.

3.1. Basic Phase Relationships

Numerous parameters are defined based on the weight, mass or volume relationships between these three phases, the most important being the ***gravimetric moisture or water content*** w and the ***volumetric water content*** θ (Equation 1), ***specific gravity*** G_S (Equation 2), ***degree of saturation*** S_W (Equation 3), ***void ratio*** e (Equation 4), ***porosity*** η (Equation 5), the relationship between e and η (Equation 6), and a variety of density and unit weight parameters (e.g. ***density*** $\rho = M / V$ and ***specific weight*** $\gamma = \rho \cdot g$). M and V denote mass and volume respectively with the subscripts $_A$, $_W$, $_S$ and $_T$ referring to air, water, solids and total. Note how gravitational moisture content ratios mass of water to mass of solids, whereas volumetric moisture content relates volume of water to the total or bulk volume. The interrelationships between these parameters are shown in Figure 3-1 and further elaboration is available in great detail in most topical soil mechanics books (e.g. Craig 1999; Das 2008; Knappett and Craig 2012).

$$w = \frac{M_W}{M_S} \ \ and \ \ \theta = \frac{V_W}{V_T}$$ **Equation 1**

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

$$S_W = \frac{V_W}{V_V} = \frac{m \cdot G_S}{e}$$ **Equation 3**

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

$$\eta = \frac{V_V}{V_T} = 1 - \left[\frac{\rho_{T(saturated)}}{\rho_S}\right]$$ **Equation 5**

$$\eta = \frac{e}{1+e} \ \ and \ \ e = \frac{\eta}{1-\eta}$$ **Equation 6**

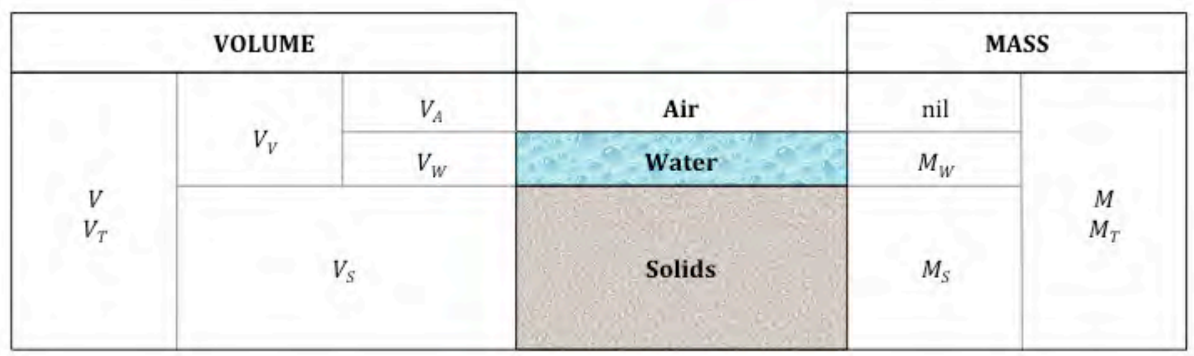


Figure 3-1. **Phase relationships in unsaturated media.**

Whereas porosity ratios pore volume to total volume, void ratio considers pore volume in relation to solid volume and, subsequently, only the numerator changes when void ratio changes, keeping the denominator constant and resulting in better application to scenarios of changing porosity (e.g. Hillel 2002).

3.2. Voids and Porosity

The pore space or voids remain the same regardless of whether water or air occupies it. Additionally, the solid phase creates the void space, but in hydrology this void space becomes the vital parameter in quantifying and understanding fluid movement through porous media. It is, therefore, important to understand the void space geometry before considering the solids and fluids comprising the medium.

Classification of porosity can be based on a number of aspects. Essentially, four important aspects should be considered, whereby an initial classification of porosity is based on the first two aspects, namely type and scale, and where evaluation of the third and fourth poses somewhat more difficulty and will be addressed separately (Dippenaar 2014):

- ***Type*** – primary (textural, soil material) porosity versus secondary (structural, soil mass) porosity to account for the differences in the nature of the void spaces and connectivity
- ***Scale*** – submicroscale, microscale, mesoscale and macroscale porosity to account for variations in porosity with varying scales of consideration (the concept of representative elementary volume as per §3.2.1)
- ***Effective porosity*** allowing the transmission of water as opposed to porosity which cannot contribute to the flow of water
- ***Water saturation*** governing whether and, if so, the rate of water drainage under gravity; concepts of residual saturation and field capacity.

3.2.1. Type and scale of porosity

Primary versus secondary porosity is directly dependent on the soil or rock material versus the secondary processes that altered the primary material after formation.

In terms of the scales of porosity it is important to realise that multiple REVs can exist depending on the scale of investigation. It is, for instance, possible that a sample of 1 cm3 can have a certain porosity which is valid for the volume of investigation, but that a completely different porosity prevails on a regional scale due to, for instance, a significant shear zone which overrides the hydraulic properties of the smaller scales.

Numerous authors (e.g. Dexter and Richard 2009; Dudoignon et al. 2007; Kutílek 2004) evaluated the various scales of porosity. In summary, ***macropores*** typically relate to vertical prism joints or any other pores which are non-capillary; ***mesopores*** are typically due to shrinkage cracking and 100-2000 μm, ***micropores*** are due to the clay-matrix and particle arrangement and are capillary pores; and ***submicropores*** or ***nanopores*** relate to water molecule and flow path inhibiting sized capillary openings. The pore sizes according to these texts roughly correlate as follows: macropores typically relate to coarser than gravel, mesopores fall within the sand and silt range, micropores are typically related to the clay fraction, and submicropores go into the water molecular size range.

Figure 3-2shows typical influences of soil texture and soil structure (the same applicable to rock) over four broadly defined scales of porosity. Although the boundaries are not as clearly defined, it is important to note that different scales of measurement will influence the REV (Box 4) and the voids formed during formation of the material versus those formed at a later stage will influence the pore sizes and interconnectedness. Tertiary porosity resulting from weathering is, however, excluded at this stage.

	Primary / Textural Porosity **Soil Material**	**Secondary / Structural Porosity** **Soil Mass**
Macroporosity	Non-capillary, e.g. Corestones, differential grading and heterogeneity; gravel and coarser	Non-capillary, e.g. Fractures, joints, fissures, piping, dongas
Mesoporosity	Cusp of capillarity, e.g. Grading and variation; sand and silt	Cusp of capillarity, e.g Bedding, foliation, shrinkage cracks, termite nests, root voids
Microporosity	Soil aggregates and capillarity, e.g. Soil grading (notably clay) and effective pore size diameter	Structural capillary pores, e.g. Near-closed structures, laminations, leached zones
Submicroporosity	Effective clogging texture, e.g. Clay content, adsorption and diffusion of water; water molecules	Effective clogging structure, e.g. Joint infilling, precipitates

Figure 3-2. Summary of typical types and scales of porosity.

The porosity can be defined as indicated in Box 4 where V indicates the volume of a three-dimensional space exceeding a single pore or grain in size. With increasing V, porosity fluctuates but gradually stabilizes to a plateau where the porosity remains constant over a representative elementary volume or REV. Increasing the volume of observation yet further leads to a domain of macroscopic heterogeneity where the porosity once again increases or decreases rapidly, thereby exceeding the REV (Bear 1988). This is also shown in Box 4 where the initial volumes of observation are represented by a point in solid grain or void pore space (in this instance indicated in a set of parallel fractures).

3.2.2. Effective porosity, specific yield and storativity

In terms of flow, porosity can be subdivided into essentially two components, namely ***effective*** (or drainable or interconnected) ***porosity*** and ***non-effective*** (or non-drainable or disconnected) ***porosity***. The sum of these two are referred to as the ***volumetric porosity***. The non-drainable porosity can be excluded from hydrological assessments as it cannot contribute to water movement, although it can contribute to diffusion in contaminant transport. Effective porosity is sometimes estimated based on the ***specific yield***, S_Y, referring to that "volume of water that will drain by gravity per unit drop in the water table per unit volume of aquifer" or the drainable porosity. The remaining water attached to the solid surfaces in the voids is referred to as the ***specific retention***, S_R (Weight 2008) and the relationship is shown in Equation 7.

$$\eta_T = S_Y + S_R$$ **Equation 7**

Total porosity is a function of that porosity which can contribute to flow and porosity which cannot contribute to flow. Various terminologies exist, but in essence total porosity is a function of the effective flow porosity, diffusion porosity and residual porosity (Norton and Knapp 1977) or the unconnected porosity and the connected porosity (Tullborg and Larson 2006). The following applies to these types of porosities and can be calculated as shown in Equation 8:

- (Effective) flow porosity (η_F) is the dominant transport of fluids by means of flow
- Diffusion porosity (η_D) is the dominant transport via diffusion though the aqueous phase
- Residual porosity (η_R) relates to no flow takes place due to no inter-pore connection
- Connected porosity (η_C) relates to the pores available for water saturation
- Unconnected porosity (η_N) is the total minus the connected porosity.

$$\eta_T = \eta_F + \eta_D + \eta_R = \eta_N + \eta_C$$ **Equation 8**

To avoid confusion, the subscript F has been kept for the effective flow porosity. In order to simplify the terminology, however, only two concepts are really required, *viz*. the effective porosity η_e referring to the pores through which water can move, versus the unconnected pores η_N where water cannot enter or pass through and which – for all practical purposes – have no influence on the water retention and transmission of the medium Equation 9).

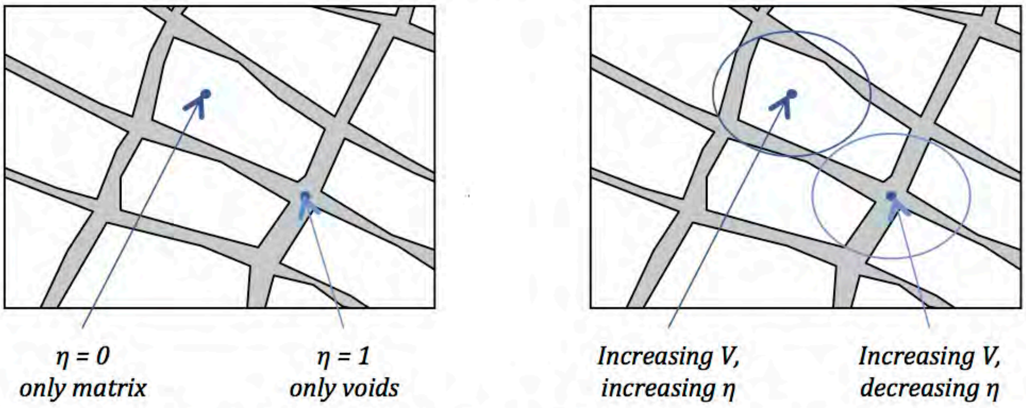
$$\eta_T = \eta_e + \eta_N$$ **Equation 9**

Box 4. Representative Elementary Volume (REV).

BOX 4: REPRESENTATIVE ELEMENTARY VOLUME (REV)

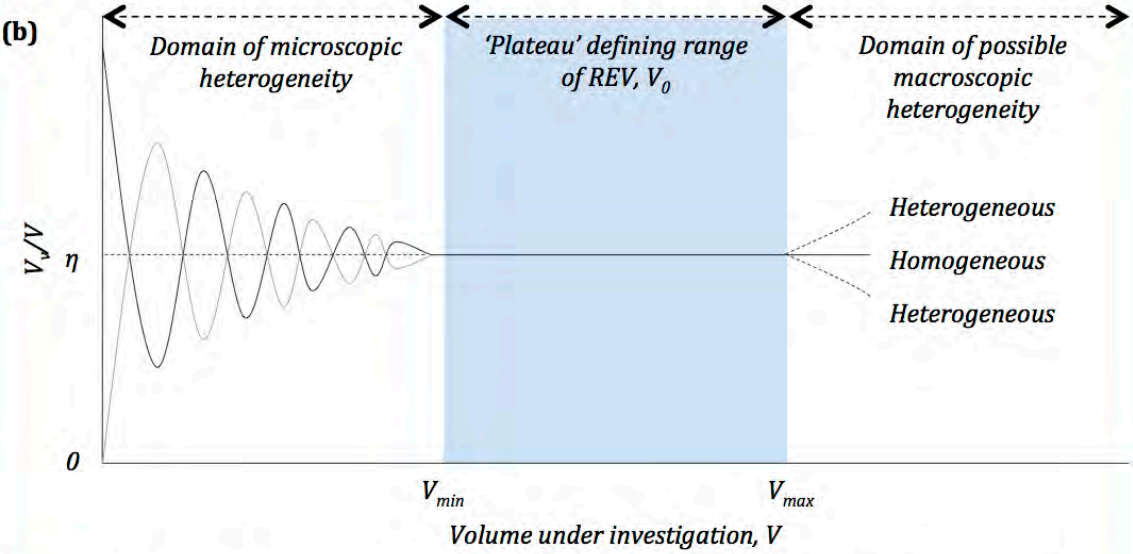
Porosity of a medium is quantified by *V* indicating the volume of a three-dimensional space exceeding a single pore or grain in size. With increasing V, porosity fluctuates and gradually stabilizes to a plateau range where the porosity remains constant over a representative elementary volume or REV. Increasing the volume of observation yet further lead to a domain of macroscopic heterogeneity where the porosity once again increases or decreases.

(a)



This can be conceptualized where the initial volumes of observation are represented by a point in solid grain or void pore space (in this instance indicated in a set of parallel fractures). On increasing these volumes, the porosity changes as both solid and pore space are included with increasing volume of observation.

(b)



This can also be applied with aerial and linear porosities (as opposed to the volumetric porosity discussed above) with the REV being replaced by the representative elementary area (REA) as the area of investigation is adjusted until porosity stabilizes, or the representative elementary length (REL) as the length of a line through the medium is adjusted until the porosity along the route of the line stabilizes

READ MORE & CITED FROM:

Bear 2007

Storativity relates to the amount of water an aquifer can release or store and is calculated as a function of the ***specific yield*** S_Y (Equation 7), ***specific storage*** S_S and saturated aquifer thickness b (Equation 10). The specific yield and storativity is approximately equal for majority of unconfined aquifers as the specific storage becomes almost negligible (Fetter 1994; Weight 2008). The concept of storativity is, however, mostly applied to confined aquifers, whereas specific yield refers to unconfined aquifers.

$$S = S_Y + S_S \cdot b$$ **Equation 10**

In the instance of confined aquifers, the volume of released water becomes dependent on the properties of the aquifer material and water, *viz*. compressibility of the mineral skeleton, α, and the compressibility of water, β (Equation 11).

$$S_S = \rho_W + g(\alpha + \eta \cdot \beta)$$ **Equation 11**

3.2.3. Pore space geometry

The pore space or geometry can often be seen as a result of the packing of the solid phase of the material. This distinguishes – when considering uniform, spherical particles homogenously and isotropically distributed through the bulk of the material – between essentially two packing configurations, viz. cubic and rhombohedral, the latter being significantly denser and less porous than the prior. However, as soon as grain sizes and shapes are allowed to vary, preferential packing scenarios can occur due to, for instance, interlocking grains, clay bridges between coarser particles and redistribution of fine materials due to percolating water. Based on this heterogeneity and anisotropy, void spaces cannot merely be measured and assumed for the bulk of the sample. Two aspects now become relevant: (1) the evaluation of the actual pore space geometry, and (2) the simplification of the pore space geometry to a simpler, more useable parameter.

Pore space geometry can best be understood by starting with basic geometric packing variations of perfectly spherical uniformly distributed grains as shown in Figure 3-3. The cubic packing represents the least dense packing with a porosity of 0.476 opposed to the densest rhombohedral packing with a porosity of approximately 0.260. Importantly, the porosity of a porous medium composed of uniformly distributed spherical grains varies between these two extreme values and is a function of the packing only and not the grain size.

In terms of the actual pore space geometry, one can distinguish between pores and throats with pores being the larger void spaces and throats the narrower connecting void spaces. A pore section diameter can then be determined as the diameter of a circle (or in the instance of the example below, an ellipse) with an area equal to that of the cross-section of the pore. To help with the calculation of this pore space geometry, the feret concept can be used where a feret represents the spacing between two parallel tangents to a void feature in a given direction. The maximum feret refers to the maximum possible distance between two such lines and the minimum feret to the minimum distance or to that distance perpendicular to the maximum feret

(Mathews et al. 1997). Entrance into the pore and therefore the possibility of water entering the pore itself depend on the size of the pore throat (Figure 3-4).

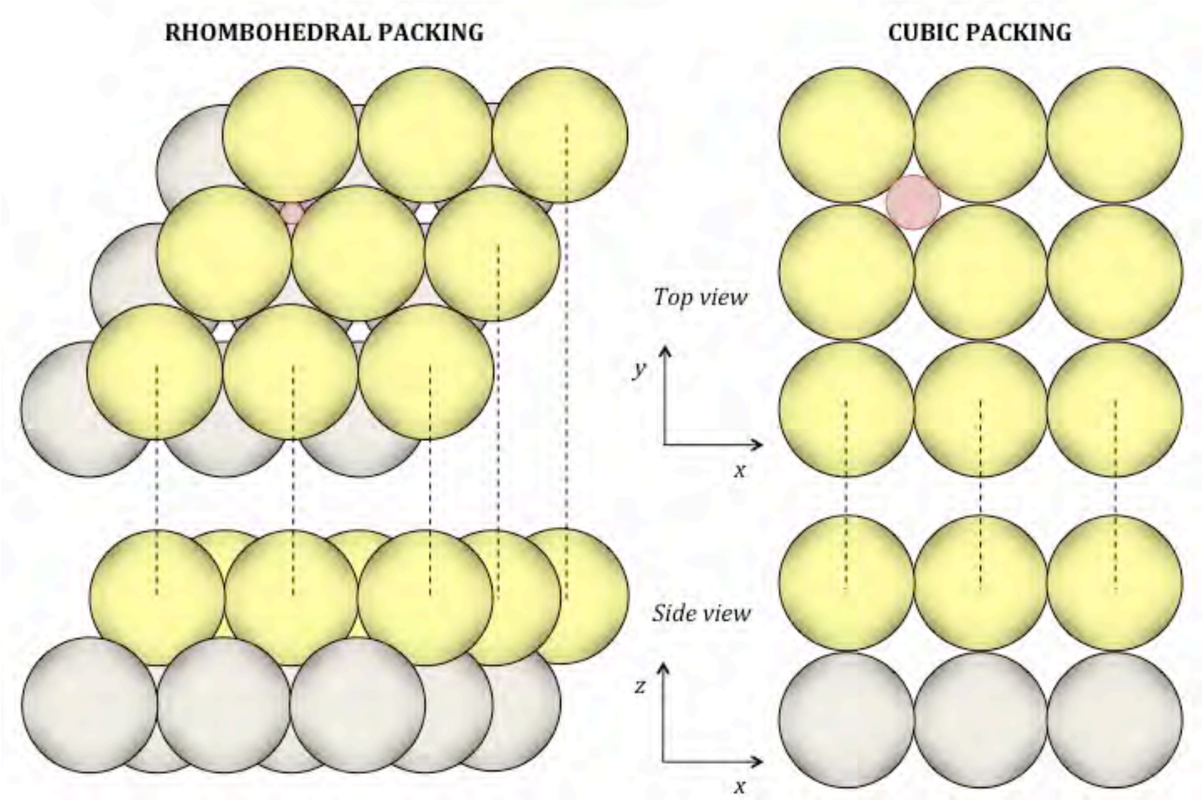


Figure 3-3. Rhombohedral closest packing (left) versus cubic packing (right) of uniform spherical grains (dimensions 3 x 3 x 2) (adapted from Bear 1988).

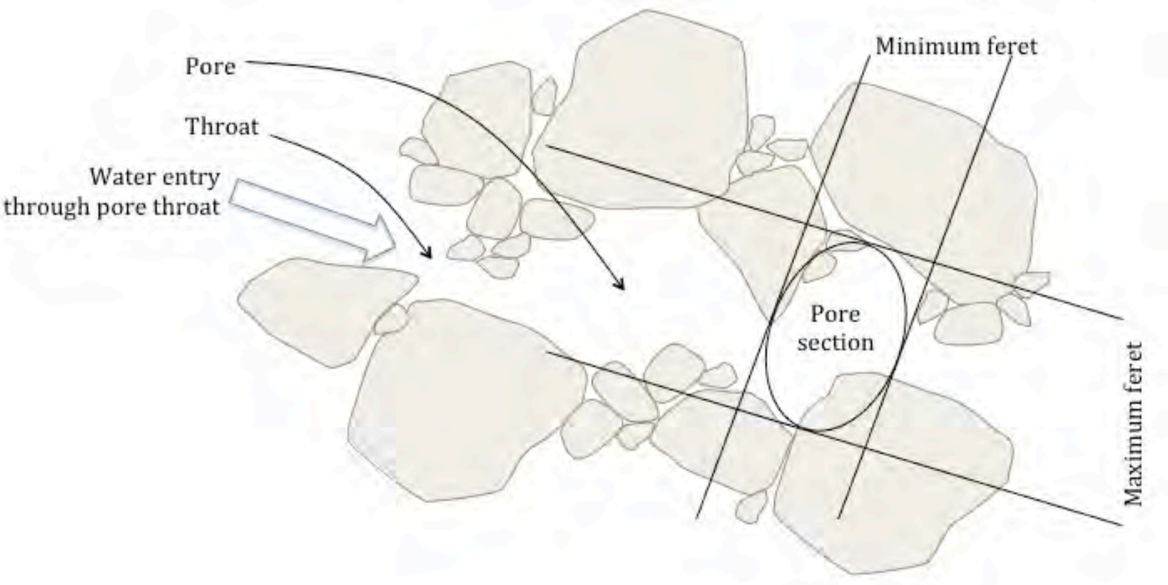


Figure 3-4. Pores, throats and the concept of ferets (adapted from Mathews et al. 1997).

However, grain sizes are rarely if ever uniform in nature and perfect sphericity in perfectly homogeneous isotropic media are very rare. This leads to heterogeneity (inhomogeneity) and anisotropy where the hydraulic properties of the material vary three-dimensionally based on direction (x, y) and location within the sample ([1], [2]) as indicated on Figure 3-5.

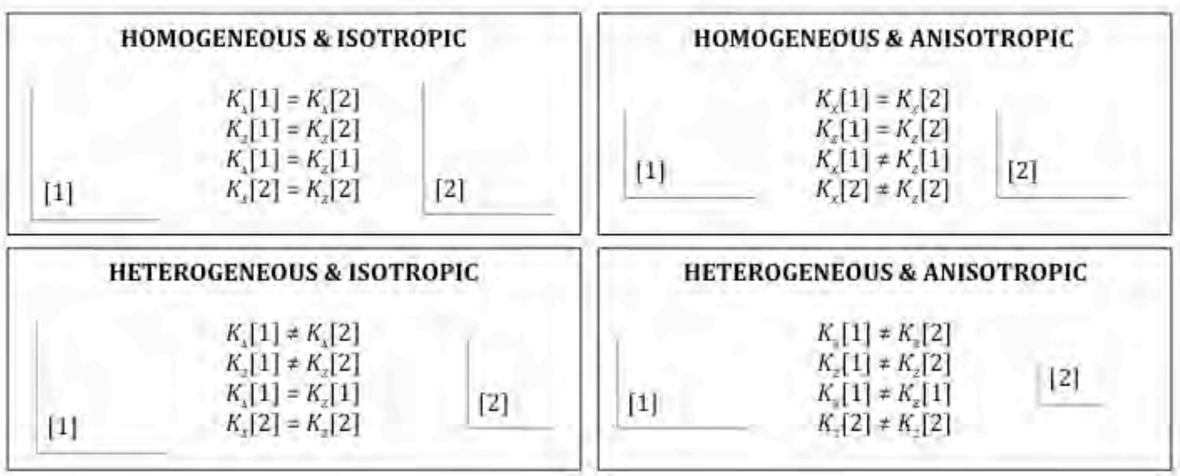


Figure 3-5. Homogeneity and heterogeneity versus isotropy and anisotropy (after Shaw 1994).

Soil scientists have very appropriate distinction between different types of pores (Schaetzl and Anderson 2005):

- ***Packing void*** – voids forming between larger particles which cannot properly pack together
- ***Vugh*** – voids which are unconnected with distinctly irregular shapes and walls and mostly associated with fine-grained soils
- ***Vesicle*** – unconnected mostly rounded voids with smooth walls
- ***Chambers*** and ***channels*** – connecting passages between voids
- ***Planes*** – voids aligned along a plane or an axis.

All of these factors influence the behaviour of a material and possible variations in porosity.

3.3. Earth Materials

A number of aspects require clear distinction when considering the solid phase in terms of hydrology. These include, but are not limited to, the facts that:

- The medium itself changes over the range of organic, unconsolidated surface soils to hard, fresh, intact bedrock, which will indefinitely influence the effective porosity in the medium.
- The effective porosity can be governed by primary pore space or by secondary structures, or by a combination between these.

- The mineralogy will influence the leaching and deposition of clay minerals, as well as the mobilisation and precipitation of ions, both processes which will – over time – change the hydrology in certain horizons and will also affect capillary processes.

When distinguishing between rock and soil in terms of hydrology, the main importance is probably the significant differences between texture and structure that may influence the movement of fluids through the medium. Soil represents that interface between the atmosphere and lithosphere that interacts with the hydrosphere, sustains growth in the biosphere, can be distinguished from inert rock by the presence of organisms, is structurally organised due to pedogenic processes, and has a capacity to respond to changes in the environment (White 1997). However, soil can be defined in one discipline to include certain materials that in others are considered rock due to the application of the classification. Typical definitions for soil as well as the basic terminology pertaining to the vertical distribution of material in the Earth's crust are shown in Box 5, together with detailed combined definitions for soil and rock respectively.

Based on these definitions, a soil scientist or geologist may, for instance, consider a pedogenic horizon as a soil because of its formation through a soil forming process. A geotechnical engineer, on the other hand, will very probably classify this same material as a durable rock, suitable for use in road construction.

Even though Box 5 aims to supply some very broad views of soil as a medium, it is important to note that the vast grey area between the agricultural soil as a growth medium (typically confined to less than the uppermost 1.0 m and composed of solid mineral grains, plant and animal organisms, water with dissolved ions, and air) and the geological bedrock (which can include unconsolidated materials, although mostly related to consolidated mono- or poly-mineral materials). It is clear why an engineer would opt for soil and rock as the two extremes which immediately justifies the material's usability for a certain purpose; similarly, the ecologist or agricultural soil scientist evaluates that portion of the material which is relevant to plant root penetration and water retention. For the geologist and geomorphologist, it becomes an indicator of the deeper and historical processes that shaped the landscape and formed the depositional environments. All definitions are in the end based on the need for defining soil and bedrock as separate entities.

In terms of hydrology and, more importantly, hydrogeology addressing the pathway between the atmosphere and the groundwater (i.e. the complete thickness of the vadose zone), all of these definitions are valid. However, for the sake of clarity, soil will be considered – broadly – to be generally unconsolidated to consolidated, formed in-situ or transported, but no longer distinctly exhibiting the geological structure and/ or minerals of the parent bedrock. Irrespective or strength, bedrock is considered to be the end-point and the soil the connection between bedrock and the processes influencing (or having influenced) it.

Classification of soil also varies by discipline with the soil scientist being interested in the behaviour of the complete plant root zone, whereas the (engineering) geologist may be more interested in the relationship between the transported materials and the weathered bedrock. Classification in South Africa is briefly outlined in Box 6.

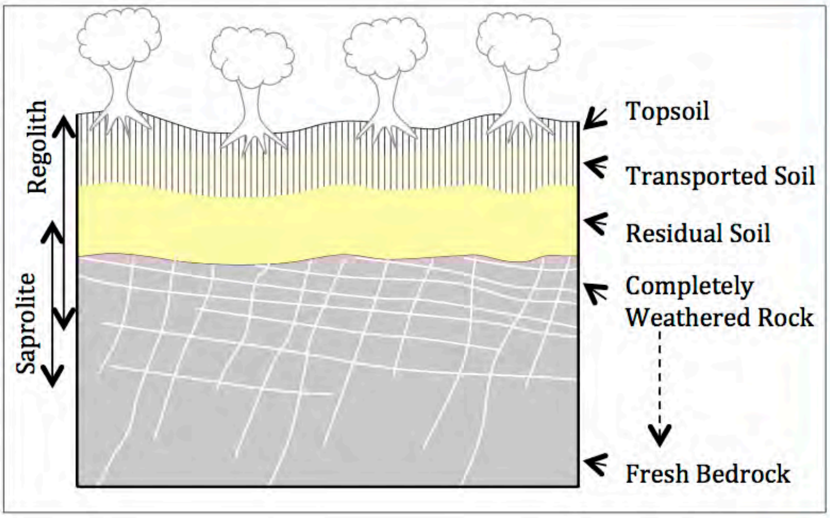
Box 5. Soil and the Vertical Succession of Earth Materials.

BOX 5: SOIL AND THE VERTICAL SUCCESSION OF EARTH MATERIALS

SOIL includes the soil in the plant root zone; the subsoil which, combined with the plant root zone soil, forms the regolith, and includes: transported and residual material; any pedogenic materials, horizons and/ or traces thereof; pore space which is mostly governed by primary or textural porosity with possible influence of secondary porosity; fluids in the pore spaces, comprising any liquid or gas, although mostly water and atmospheric air; as well as all associated organic matter and organisms. Some definitions per discipline are supplied below.

Soil Science / Pedology	Unconsolidated mineral and organic material serving as plant growth medium; influenced by parent material, climate, organisms, topography and time; characterised by successive horizon formation based on morphology, physical composition and biological characteristics.
Geotechnical Engineering / Engineering Geology	Uncemented or weakly cementer mineral particles formed due to weathering of rock; excavatable without blasting, or which disintegrates in water, or which can be manipulated or tolerated for construction.
Hydrology	Storage reservoir which influences a catchment's water balance; uppermost earth materials which can support plant life with sufficient moisture.
Geology	Dependent on origin, transport and composition; fine weathered rock material and surface deposits with varying amounts of organic matter.

ROCK is formed through igneous (plutonic or volcanic), sedimentary (lithification, precipitation or cementation) or metamorphic processes, and can be fresh, unweathered and/ or intact, and progressively become more weathered while still exhibiting the parent rock mineralogy, texture and structure, until completely weathered rock which – although it behaves like soil – still maintains the parent rock's structure.



SOIL PROFILES represent represent this characteristic sequence of materials and are typically described in terms of **SOIL HORIZONS**. The subdivision of a profile into horizons depend on the profiling approach employed. Soil scientists, for instance, will consider horizons to represent materials subjected to the same processes (hydrological, translocation), whereas engineers and geologists subdivide the profile based on origin as this defines it's mechanical and mineralogical properties.

BEDROCK underlies the soil profile at depth and should be incorporated if encountered.

READ MORE & CITED FROM: Blatt & Tracy 1997; Bridges and Van Baren 1997; Craig 1999; Dippenaar 2012; Miller 2000; Rahn 1986; Schaetzl and Anderson 2005; White 1997; Winegardner 1996; Younger 2007

Box 6. Pedological vs. Geotechnical Soil Classification.

BOX 6: PEDOLOGICAL VS. GEOTECHNICAL SOIL CLASSIFICATION

SOIL SCIENCE/ PEDOLOGY

Soil description is primarily based on a ***Descriptive Topsoil*** (organic, humic, vertic, melanic).

Secondarily (in the absence of a descriptive topsoil), a ***Distinctive Subsurface Enrichment*** is used, and includes: in the form of silic (silicic), carbonate or gypsym (calcic), clays (duplex), metal humate (podzolic), iron mottling or cementation (plithic), uniform iron enrichment (oxidic) or reduction in an aquic subsoil or wetland (gleyic).

Finally, should both the above not be sufficiently descriptive or distinctive, classification is based on ***Weak Subsurface Enrichment*** in young soils as young soils in unconsolidated sediments (cumulic), young soils in weathered rock (lithic) or disturbed materials (anthropic).

Within all of these soil groups, a number of soil forms exist based on the soil horizon succession and key indicators.

ENGINEERING GEOLOGICAL/ GEOTECHNICAL ENGINEERING

Moisture: Very dry, dry, slightly moist, moist, wet

Colour: According to standard colour charts

Consistency: Very soft, soft, firm, stiff, very stiff (cohesive soils; excess silt and clay)
Very loose, loose, medium dense, very dense, hard (non-cohesive or granular soils)
Very soft, soft, medium-hard, hard, very hard (rock)

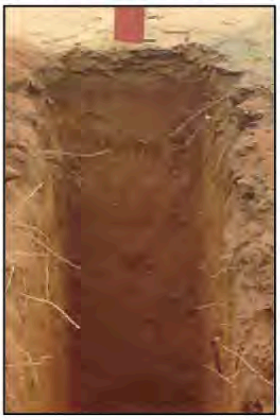
Structure: Intact (none), fractured, jointed, slickensided, shattered, laminated, pinholed, open

Soil Type: Proportions gravel, sand, silt and clay (based on field estimation)

Origin: E.g. colluvium, hillwash, alluvium, lacustrine, aeolian, anthropogenic (transported)
E.g. iron-rich; ferruginized; powder, nodular, honeycomb, hardpan ferricrete
E.g. residual, completely weathered to fresh bedrock

SOIL SCIENTIFIC/ PEDOLOGICAL

HUTTON SOIL FORM
Freely drained soil, aerated in younger solum
Often mottled and with uniform staining
Orthic A underlain by apedal B.



ENGINEERING GEOLOGICAL

Slightly moist, light reddish brown, very loose becoming medium dense with depth, open at surface becoming pinholed with depth, silty SAND. Aeolian.

READ MORE & CITED FROM:

Soil scientific: Fey 2010; Department of Agricultural Development 1991
Engineering geological: SANS 633:2009

Foster (1984) and Foster (2012) present typical hydrogeological characteristics superimposed on a typified weathering profile for crystalline basement in south-eastern Africa. The same generic succession is followed by Koita et al. (2013) for granite in humid Ivory Coast. Although the climate inevitably results in more decomposition and deeper profiles, the proposed horizons provided are consistent with other terminologies with elaboration on the more specific terminology associated with the vertical succession of materials in Box 7.

Rock and soil are both influenced hydrologically by the primary texture (or material) which forms during formation of the material, and the secondary structure (or mass) which is post-formational. For the sake of clarity, these aspects of ***material*** and ***mass*** will be addressed briefly for soil and rock medium.

3.3.1. Soil material, type or texture

Classification of soil texture is explained in Box 8. Particle size analyses refer to the percentage by mass of particles within different size ranges making up the bulk of a disturbed soil sample. For the coarse fraction, this is achieved by passing a soil sample through a series of test sieves, each with a very specific mesh size and subsequently able to allow only material finer than the mesh size to pass through. The mass of the retained soil is determined and a cumulative percentage is calculated for this fraction. The finer materials are determined through sedimentation techniques as a function of the velocity at which spherical particles settle from suspension according to Stoke's Law (Craig 1999).

The ***particle size distribution*** (or ***grading***) is usually presented on a semi-logarithmic plot with the cumulative percentage passing as the ordinate and the particle size as the abscissa as shown in Figure 3-6. A number of important parameters can be determined from the particle size analyses. Of these, the *d*-values refer to the particle size represented by a certain cumulative percentage passing. On Figure 3-6, the most important *d*-sizes are shown as follows:

- d_{10} refers to the finest 10% of the sample by mass (0.03 mm)
- d_{30} refers to the finest 30% of the sample by mass (0.09 mm)
- d_{60} refers to the finest 60% of the sample by mass (0.30 mm)
- I_0 refers the grain size intercept through d_{50} and d_{10} (0.02 mm).

Based on these *d*-values, certain coefficients can be defined, the most important at this stage being the coefficient of uniformity C_U as shown in Equation 12. The greater the value for C_U, the greater the range of particle sizes in the soil and the less uniformly graded the soil is.

$$C_U = \frac{d_{60}}{d_{10}}$$ **Equation 12**

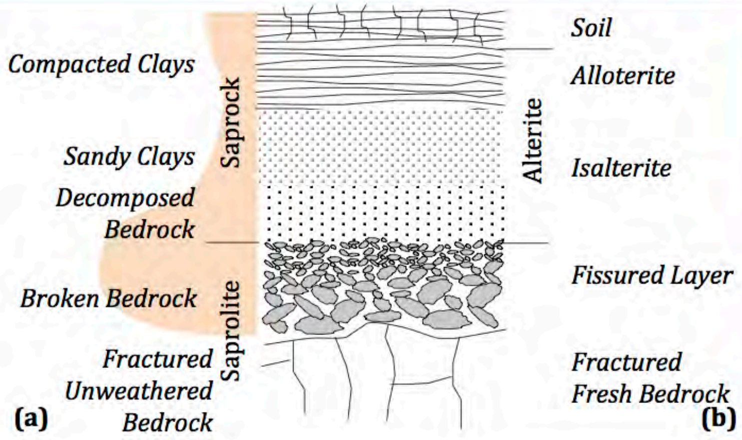
For the example in Figure 3-6, C_U = (0.30 mm / 0.03 mm) = 10. Determination of the d_{10}-fraction is, however, not always possible as many grading analyses do not determine smaller diameters than 0.002 mm.

Box 7. Soil Profiles in Various Earth Sciences.

BOX 7: SOIL PROFILES IN VARIOUS EARTH SCIENCES

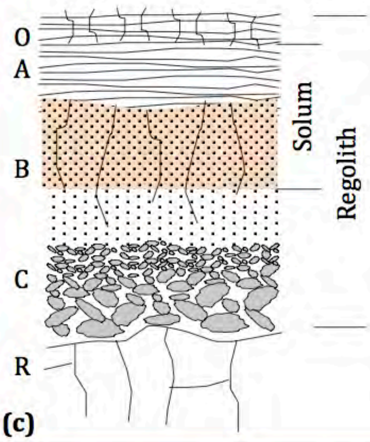
HYDROGEOLOGISTS

- Soil
- Saprolite or altorite
  - Alloterite (clayey material; typically kaolinite-rich)
  - Isalterite (highly weathered with coarse granite debris
- Fissured layer (slightly weathered fissured granite)
- Fractured fresh granite.

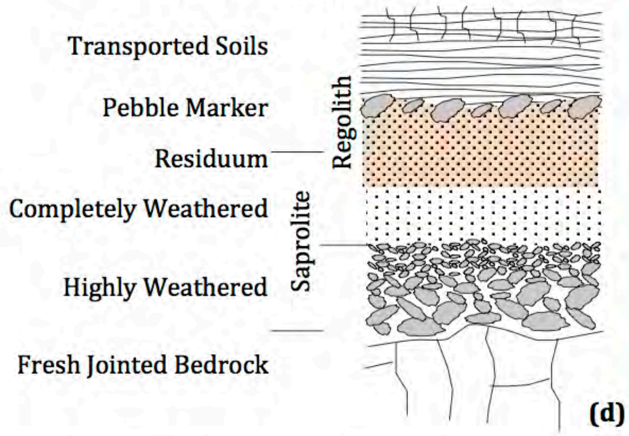


SOIL SCIENTISTS

O1	Partly decomposed litter
O2	Partly decomposed debris
	ELUVIATION
A1	Zone of humus accumulation
A2	Zone of strongest leaching
A3	Transitional to B
	ILLUVIATION
B1	Transitional to A
B2	Zone of maximum illuviation
B3	Transitional to C horizon
C	Parent material; Unconsolidated rock
R	Consolidated bedrock



ENGINEERING GEOLOGISTS



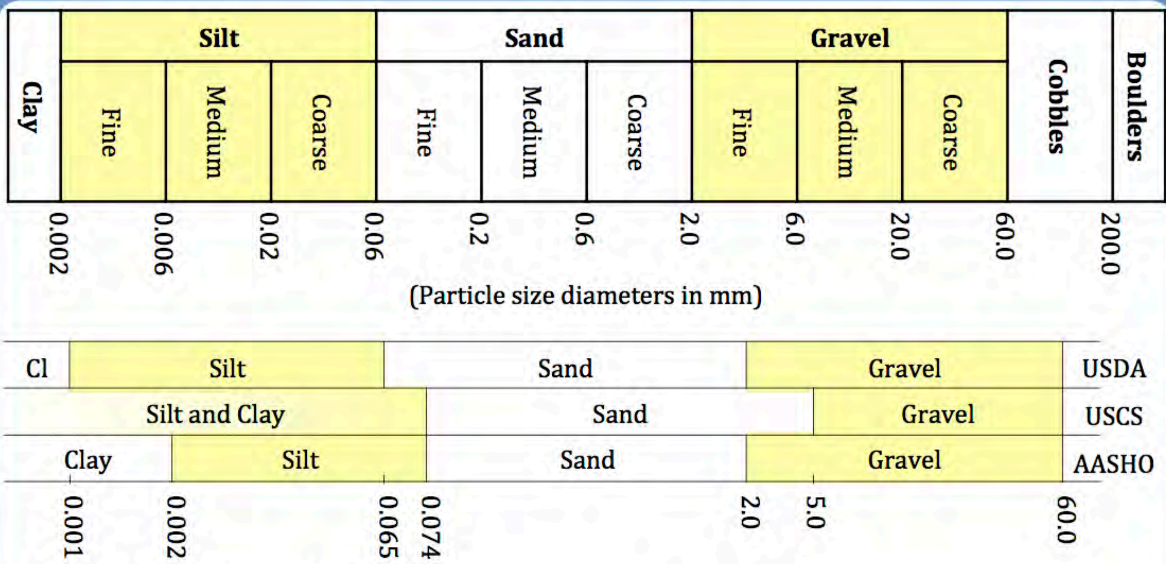
- Transported: soils deposited through erosion agents, e.g. rivers (alluvium), gravity (colluvium; hillwash; talus), wind (aeolian), imported fill
- Pebble Marker: special stone line representing the contact between transported and residual soil
- Residuum: in-situ weathered rock to state of mineralogical, textural and structural change; described in terms of bedrock, i.e. residual granite
- Bedrock: completely weathered (resembling parent rock but comprising soil in terms of mechanical properties), gradually or distinctly changing to highly weathered, mediumweathered, slightly weathered and fresh bedrock.

The shaded portions indicate the common position for pedogenetic enrichment.

READ MORE & CITED FROM: Dippenaar and Van Rooy 2014; Foster 1984, 2012 (a); Hillel 2003 (c); Koita et al. 2013 (b)

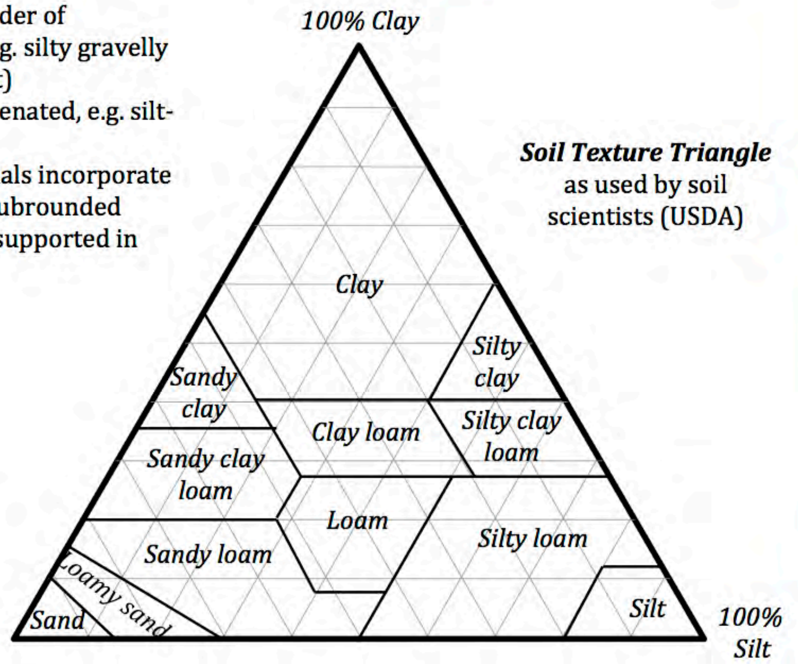
Box 8. Description of Soil Type (Texture).

BOX 8: DESCRIPTION OF SOIL TYPE (TEXTURE)



- Combinations noted in order of increasing prominence, e.g. silty gravelly SAND (sand > gravel > silt)
- Equal combinations hyphenated, e.g. silt-sand (silt = sand)
- Mixtures of coarse materials incorporate specific descriptors, e.g. subrounded cobbles and gravel, clast-supported in silty sand

- *USDA: United States Department of Agriculture*
- *USCS: Unified Soil Classification System*
- *AASHO: American Association of State Highway Officials*



Descriptors for gravels, cobbles and boulders

Blocky:	Length = width = thickness	Matrix-supported:	Clasts supported by matrix
Platy:	Length = width > thickness	Clast-supported:	Clasts in contact;
Elongated :	Length > width = thickness	Subrounded:	All corners rounded off
Bladed:	Length > width > thickness	Subangular:	Corners slightly beveled
Irregular:	Irregular shape	Angular:	Corners sharp or irregular

READ MORE & CITED FROM:

Brink and Bruin 2001; Jennings et al. 1973; SANS 633:2009a; SAICE 2010
Soil Triangle: Brady and Weil 1997; Schaetzl and Anderson 2005

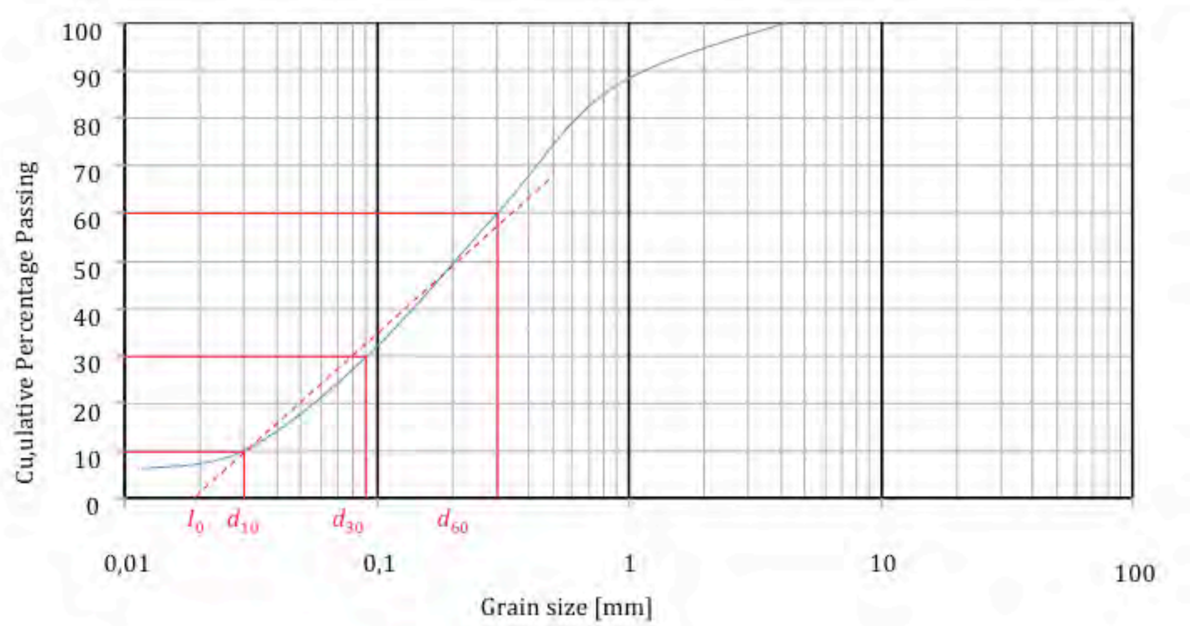


Figure 3-6. **Determining the d-values from particle size distribution data.**

The effective grain size diameter, d_e, can be defined as the diameter of a spherical grain in a uniform porous medium where C_U equals unity and where the hydraulic conductivity is equal to the corresponding natural material comprising varying grain sizes. Depending on the methods in question, the effective grain size (or that grain size diameter controlling the seepage properties of the material) is often estimated based on laboratory results, e.g. $d_e = d_{10}$, $d_e = d_{17}$ or $d_e = d_{20}$ or $d_e = d_{50}$ (the latter, 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. Most sources (e.g. Vuković and Soro 1992) recommend calculating the effective grain size diameter as shown in Equation 13 where d_i is the representative grain diameter comprising a certain fraction f_i of sample. In most analyses, however, an upper and lower boundary of the fraction is available, and Equation 14 or Equation 15 can be used to determine that representative grain diameter d_i where f_i is the fraction of particles between the sieve sizes $d_{i(min)}$ and $d_{i(max)}$.

$$d_e = \frac{1}{\sum_{i=1}^{n}\left(\frac{f_i}{d_i}\right)} \quad or \quad \frac{1}{d_e} = \sum_{i=1}^{n}\frac{d_i}{f_i}$$ **Equation 13**

$$\frac{1}{d_e} = \sum_{i=1}^{n}\left(\frac{\sqrt{d_{i(max)} \cdot d_{i(min)}}}{f_i}\right)$$ **Equation 14**

$$\frac{1}{d_e} = \sum_{i=1}^{n}\left(\frac{d_{i(max)} + d_{i(min)}}{2f_i}\right)$$ **Equation 15**

3.3.2. Rock material

Rock – as opposed to soil – comprises solid matrix as well as secondary porosity in the form of geological structures. Accounting for this anisotropy and heterogeneity within the material poses some difficulty. In general, however, rocks tend to have much lower primary porosity than soils due to consolidation and lithification of sedimentary rocks or the densest-state crystallisation of igneous and metamorphic rocks. Secondary porosity, therefore, tend to have the greatest influence.

Some important parameters in rock material description for hydrological purposes include:

- Origin – the rock type identifies mode of formation (e.g. sandstone and granite formed in distinctly different manners and result in different primary porosity and mineralogy)
- Mineralogy – the rock-forming minerals are more or less susceptible to for example weathering and will determine the secondary minerals forming during weathering. Mineralogy combined with origin also dictates the likelihood of water entering the rock and subjecting of these minerals to weathering.

3.4. Soil and Rock Mass (Structure)

Soil mass refers essentially to unconsolidated materials, but consideration of structure is equally (if not more) significant in rock where secondary structures, typically formed through tectonic deformation, are generally more pronounced and important in the transmission of fluids.

Occasionally, and notably with respect to the classification of aquifer formed in soluble rock, tertiary influences are also addressed and typically relate to significant changes in the rock fabric due to chemical weathering processes such as carbonate dissolution. This mainly applies to karst aquifers (in the dolomite regions in South Africa) and is not included in detail in this text.

3.4.1. Soil mass or structure

In terms of soils, structure refers to the aggregation of particles and is morphologically described according to (1) the ***type*** or form of structural units, (2) the ***size*** of these units, and (3) the ***degree*** or grade of development. Sizes are generally distinguished as fine, medium or coarse and structural development can be weak, moderate or strong. Some generic types include (Stevens and Laker 2012):

- Structureless , i.e. not aggregated, and either single-grained (loose) or massice (hard mass when dray but without clear alignment)

- Blocky, i.e. roughly cubic aggregates, and either angular blocky or sub-angular blocky
- Prism-like, i.e. long vertical axes, and either prismatic or columnar
- Spheroidal, i.e. granular or porous crumb structures.

An alternative approach to soil structure description is based on application to engineering (discussed in §6.1.1) and includes, for instance, intact (*sic*. structureless), fissured, slickensided, microshattered, shattered, granular, pinholed, honeycomb, etc. (SANS 2009a).

3.4.2. Rock mass or structure

Depending on the depth to ground water, bedrock can also form a major part of the vadose zone. The factors controlling flow through rock differ from those controlling flow through unconsolidated porous materials, notably due to the presence of a secondary 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 (also sometimes termed fresh, unweathered and unfractured) 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.

Some important considerations in the description of bedrock include:

- ***Bedding***, i.e. thicknesses of beds or laminations, presence of sedimentary structures such as cross-bedding or ripple marks, etc.
- ***Geological contacts***, i.e. gradual or distinct, orientation of contact, alteration due to contact (e.g. recrystallization due to igneous intrusion), etc.
- ***Jointing***, i.e. direction (dip and dip direction), frequency (no. per metre), aperture, roughness, waviness, infilling, etc.
- ***Structural influences***, i.e. faults, folds, shear zones, intrusions, etc.
- ***Foliation***, i.e. metamorphic textures such as schistosity, gneissosity, etc.

3.5. Tertiary Porosity

As opposed to primary and secondary porosity as a function of the aggregation of particles and the subsequent structural influences thereon, tertiary void space can be formed essentially through chemical decomposition processes. This is most prevalent in the dissolution associated with soluble rock such as dolomite or limestone, but may also exist in distinct weathering and translocation processes in soils, including piping and dispersion.

These weathering voids may, for instance, play significant roles in the vadose zone in karst areas where sinkholes and cave systems may serve as so-called swallow holes forming near-direct routes between the land surface and the groundwater table. In terms of soils, tertiary porosity may be linked to significant voids formed through, for instance, piping, dispersion and leaching.

3.6. Fluid Phase

Essentially two types of fluids can occupy the voids in a porous medium: liquids and gases. For the purposes of hydrogeology, these are almost always (with certain obvious exceptions) water and air. Water has a fundamental property whereby it is at its densest state as liquid and water is therefore practically incompressible. Some important properties of water are explained in Box 9.

As opposed to water, air is highly compressible and air-filled voids can allow entry of water. This behaviour results in water and air moving differently in the same medium. Water will also generally tend to wet the mineral surface, implying that up to a certain moisture content, water will replace air, and exceeding this critical water volume may induce seepage due to cohesion of water molecules exceeding adhesion to mineral surfaces.

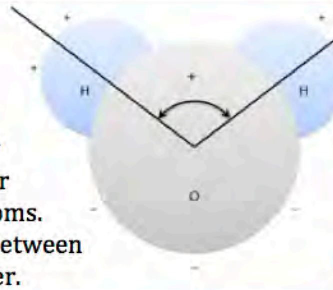
Occasionally, fluids that are immiscible with water coexist in the void space. This in notably eminent in hydrocarbon contaminated sites where non-aqueous phase liquids (NAPLs) infiltrate into the subsurface. The concepts of wettability and capillarity become important here and will be discussed in detail in §4.2.1.

Manmade fluids such as grout (cement-water mixtures) are also often used in engineering for increasing soil strength or reducing permeability. These fluids have characteristic densities and viscosities based on the water:cement ratio and penetrability of the grout mixture is calculated as a function of the earth material's permeability and the properties of the grout itself.

Box 9. Properties of Water.

BOX 9: PROPERTIES OF WATER

WATER, ITS PHASES AND PROPERTIES



(a)

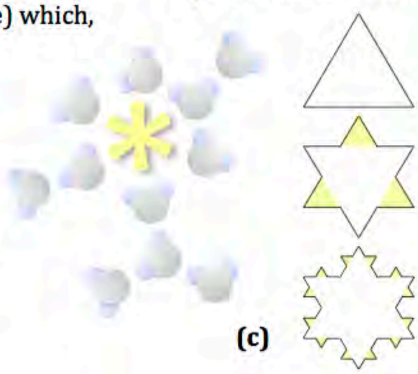
Water comprises of water molecules (H_2O) in the molecule dihydrogen monoxide and minor other trace ions and molecules. In its liquid state, water molecules are closely packed but constantly moving. Water molecules are polar with a more positive charge near the hydrogen atoms and a more negative charge near the oxygen atoms. This results in attraction in the form of hydrogen bonding, notably between the hydrogen atoms of one molecule with the oxygen atom of another. Self-attraction due to this polarity defines water's behaviour in terms of important properties such as viscosity, surface tension and capillarity.

Property	Symbol	Units	Value
Mass density	ρ_W	[M/L³]	1 000 kg/m³
Weight density	$\gamma = \rho_W g$	[F/L³]	9 810 N/m³
Compressibility	β	[L²/F]	4.5 x 10-10 m²/N
Dynamic viscosity	μ	[FT/L²]	1.4 x 10-3 N.s/m²
Boiling point	T_B	[Temp]	100° C
Melting/ freezing point	T_M	[Temp]	0° C
M – mass; L – length; F – force; T – time; Temp - temperature			

Above: some important properties of water.

(b) Water's maximum density occurs in its liquid state around 3.98° Celsius as a liquid. This results in liquid water being practically incompressible and being more dense that its solid form (ice) which, as a result, will float on the liquid.

(c) As a solid, in crystalline mineral state, ice forms hexagonal crystals (indicated by the asterisk, *) which can best be explained at the hand of snow flakes. This is also commonly envisioned at the hand of the Koch Snowflake. The first three iterations using fractal geometry are shown, resulting with each iteration in a more complex snowflake.



(c)

FLUIDITY

An important parameter for fluids including water is fluidity. Being easier to determine in the laboratory, the viscosity is often quantified using Newton's Law of viscosity. The fluidity is related to the dynamic viscosity (μ), kinematic viscosity (υ), fluid density (ρ), specific weight (Υ) and gravitational acceleration (g), and is inversely proportional to viscosity.

$$f = \frac{g}{\upsilon} = \frac{\rho \cdot g}{\mu} = \frac{\gamma}{\mu}$$

Fluidity becomes important when considering fluid mixtures, for example water – air systems or water – petroleum systems. This, together with other parameters such as wettability, define the behaviour of the fluids in the subsurface, including which fluid will imbibe or drain, which fluid will be attracted to the solid mineral surfaces, and which fluid will possibly form immobile phases. These multiphase and/ or variably saturated systems become notably important in contaminant transport.

READ MORE & CITED FROM:

Dippenaar 2013, Fig. (a) and (c); Fitts 2002

4. PARTIAL AND VARIABLE SATURATION

4.1. Moisture below Saturation

Terminology related to moisture contents below saturation and/ or water occurring in the vadose zone are summarised in Box 10 and Box 11. Moisture contents are usually denoted as a fraction or percentage of the void spaces occupied with water, or alternatively in units of per mille (mm/m or ‰). Three main forces affect the energy level of soil water, namely:

- ***Matric forces*** resulting due to the attraction of water to the soil solids or matrix (adhesion) and that is responsible for adsorption and capillarity
- ***Osmotic forces*** resulting due to the attraction of water molecules to ions and solutes
- ***Gravity forces***, which continuously pull the water down vertically.

These three forces define the difference in energy level of water between sites or conditions that can be defined as the ***soil water potential***. Water always moves from a point with high potential to a point with lower potential and the ***total soil water potential*** Ψ_T can be defined as the sum of the ***gravitational potential*** Ψ_g, ***matric potential*** Ψ_m, ***osmotic potential*** Ψ_o and any other possible contributions of additional potentials (Equation 16). A collective term, ***pressure potential***, is often used for the matric potential combined with the submergence potential Ψ_s due to hydrostatic pressures of overlying water in the saturated zone (Brady and Weil 1999).

$$\Psi_T = \Psi_g + \Psi_m + \Psi_o + \cdots \qquad \textbf{Equation 16}$$

Gravitational potential is the product of the height of the water column above a reference elevation h and gravitational acceleration g as shown in Equation 17. The reference point is usually in the soil profile at depth to ensure that gravitational potential of the soil water will be a positive value.

$$\Psi_g = gh \qquad \textbf{Equation 17}$$

Whether actual ***field capacity*** as per Box 10 can be achieved is debatable. Where no impermeable layer is present under a soil column, drainage will continue despite the rate decreasing until an apparent asymptote is reached. For this reason it becomes difficult to measure field capacity, and subsequently it is often considered the matric potential at -0.33 bar moisture percentage (Jury et al. 1991).

Associated with this, the ***residual (displacement) saturation***, S_r, is the minimum saturation under hydrostatic conditions as a function of specific surface area of the soil, pore shape and interactions between solids and soil water. This is shown in Equation 18 as a function of the associated residual water content θ_r, saturated water content θ_{sat}, and a pore-space dependent parameter β; after Brooks and Corey (1964) to estimate unsaturated hydraulic conductivity, and in Equation 21 to determine the effective saturation S_e (from Liu 2004). Low values are typical of granular soils (5-15%) given the inert mineralogy and low specific surface, with higher S_r-values for cohesive soils (Martin and Koerner 1984).

Box 10. Terminology related to Soils below Saturation (Part 1).

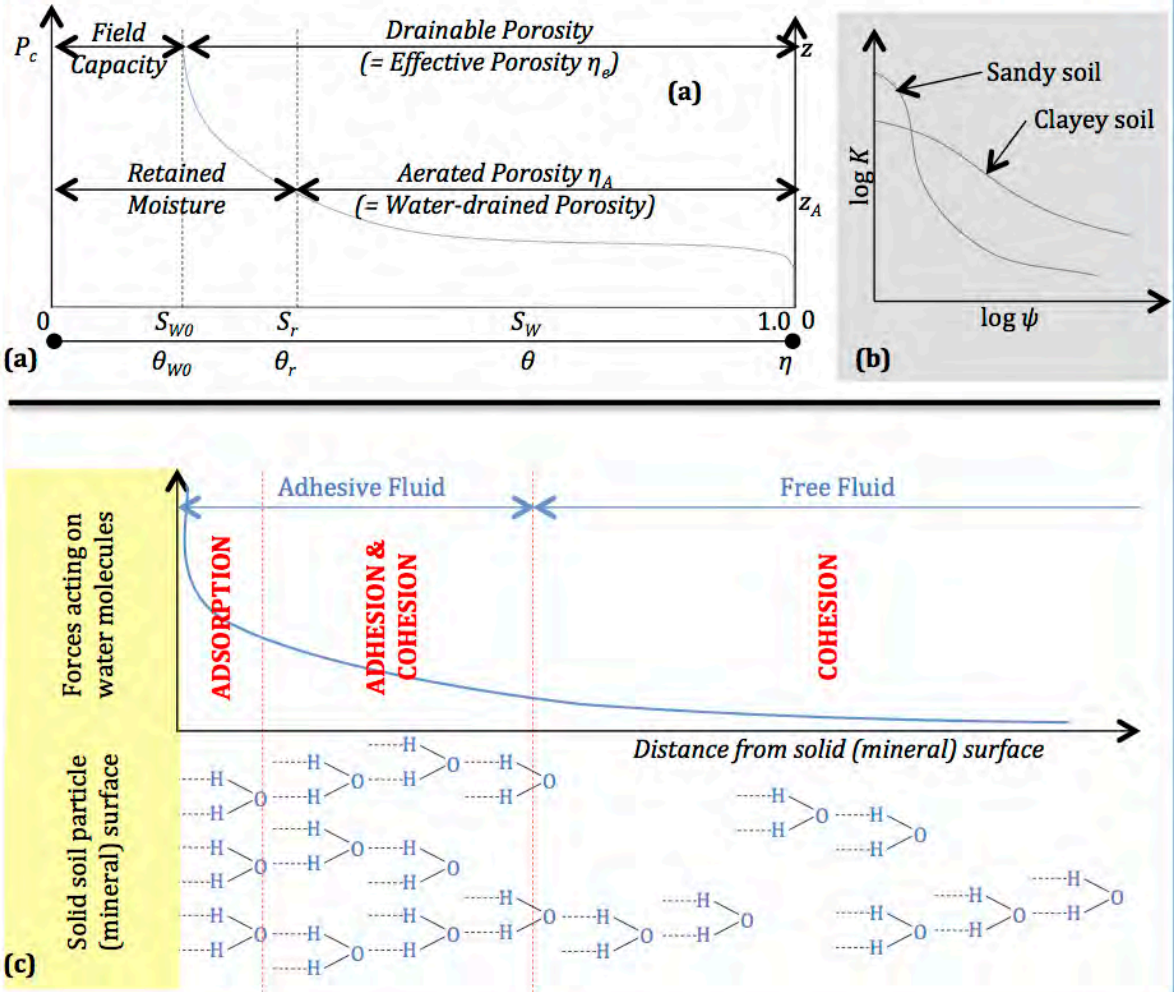
BOX 10: TERMINOLOGY RELATED TO SOILS BELOW SATURATION (PART 1)

FIELD CAPACITY (FC) refers to that moisture content θ the soil can retain after excess water has seeped away under gravity; therefore the volume of water introduced to the subsurface but not available for percolation. At this moisture content, the complete ***effective porosity*** – which is that portion of the pore spaces able to transmit water – is air-filled.

(PERMANENT) WILTING POINT (PWP) is the θ where water becomes unavailable to plants.

PLANT WATER AVAILABILITY (PWA) is the difference between FC and PWP.

Soil texture to a large extent governs the relationship between matric suction and hydraulic conductivity of unsaturated soils (b). Clayey soils, given smaller pore sizes and greater surface area, will behave very different to granular or sandy soils where pore spaces are large and adhesion significantly less. The high conductivity of sand at low suction results in important properties such as its high infiltration rate, as well as its inability with respect to clay to retain water during evaporation. Subsequently, these soils will exhibit very different field capacity and wilting point values.

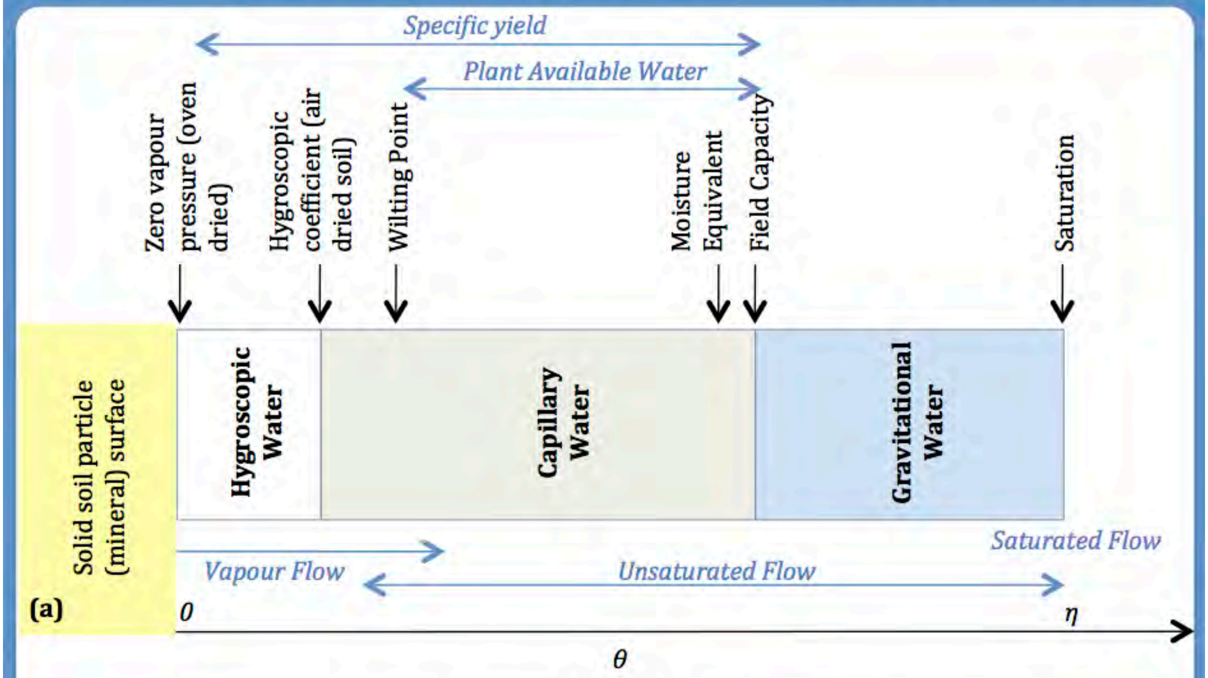


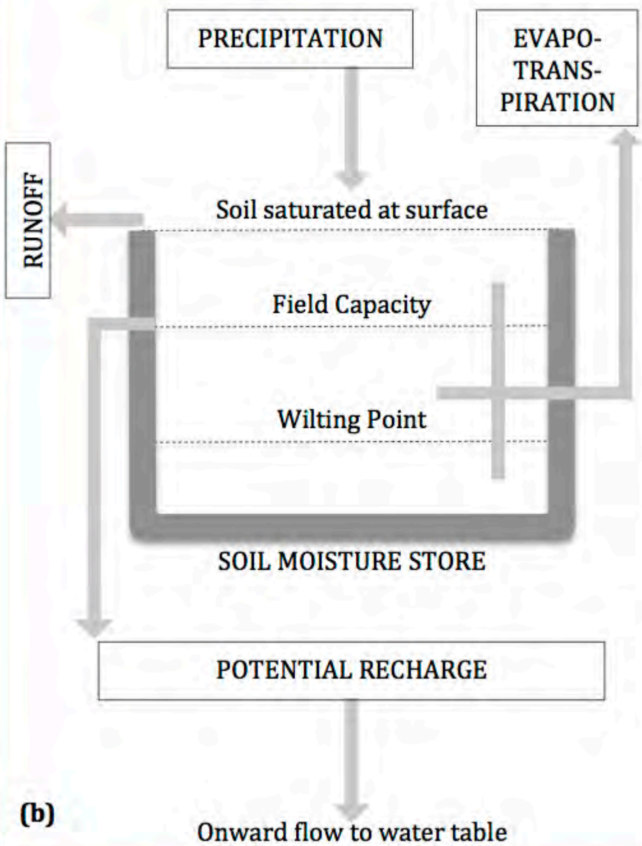
READ MORE & CITED FROM:

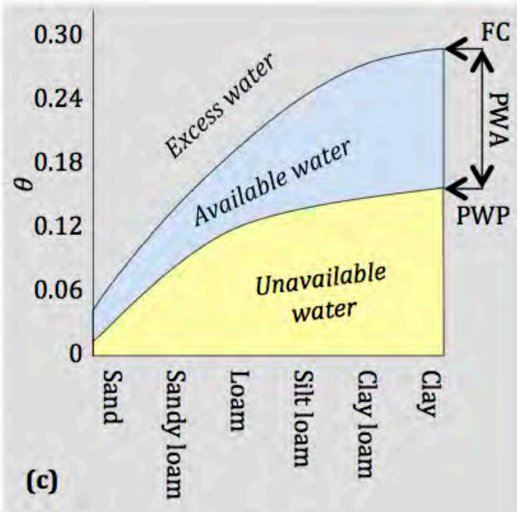
Allaby & Allaby 2003, Bear 2007; FitzPatrick 1983;; Rose 2006

Box 11. Terminology related to Soils below Saturation (Part 2).

BOX 11: TERMINOLOGY RELATED TO SOILS BELOW SATURATION (PART 2)







POTENTIAL RECHARGE refers to water beyond influences of plant roots, evapotranspiration or surface runoff. This water has the potential to eventually recharge the aquifer and is only termed recharge when entering the phreatic surface. However, moisture content below field capacity cannot drain under gravity, and this threshold needs to be surpassed.

READ MORE & CITED FROM: Allaby & Allaby 2003; Bear 2007, Bear & Cheng 2007, Brady & Weil 1997, Doe 2001, FitzPatrick 1983, Hillel 2002; Rose 2006; Schaetzl and Anderson 2005; Todd and Mays 2005; Younger 2005 (b)

$$K(\theta) = K_{sat}\left(\frac{\theta - \theta_r}{\theta_{sat} - \theta_r}\right)^{1/\beta}$$ **Equation 18**

$$S_e = \frac{S - S_r}{S_{sat} - Sr}$$ **Equation 19**

The degree of saturation in soils reaches some limiting value at some given height above the water table. The vadose zone above this level is referred to as the ***discontinuous vadose zone*** and is characterised by water strongly sorbed onto particle surfaces so that it cannot be replaced by air with increasing capillary pressure, but only by evaporation and transpiration (Martin and Koerner 1984a).

4.2. Interaction between Solid and Fluid Phases

4.2.1. Surface tension and wettability

A liquid in contact with a solid surface can, according to Berg (1993 in Doe 2001):

- Spread spontaneously and form a film with extent relating to the mass of available liquid
- Spread on the surface until an equilibrium is achieved with the solid and gas phases, forming a three-phase interface with a contact angle
- Have no interaction with the surface whatsoever.

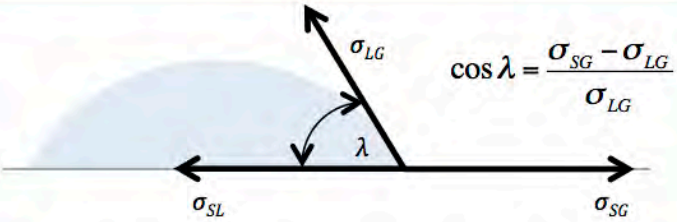
The process eventually occurring is dependent on the wetting properties of both the liquid and the solid surface and eventually affects the occurrence of water in the subsurface. Essentially this depends on the interactions between the water molecules and the mineral surfaces, as well as the interaction between the different water molecules. These two types of interactions can broadly be distinguished as adhesion – the attraction of water molecules to solid surfaces – and cohesion, which refers to the attraction of water molecules to each other (Brady and Weil 1999).

The processes of cohesion and adhesion require work and relate to specific critical angles as shown in Box 12. Equation 20 shows the calculation of the work of cohesion as a function of the surface tension of the liquid. ***Cohesion*** relates to the water's attraction to itself, and WC is the work required to create a unit surface area of liquid; separation of a unit of liquid creates two masses from the initial one mass and subsequently the divided bodies will have twice the initial energy (Doe 2001).

$$W_C = 2\sigma_L$$ **Equation 20**

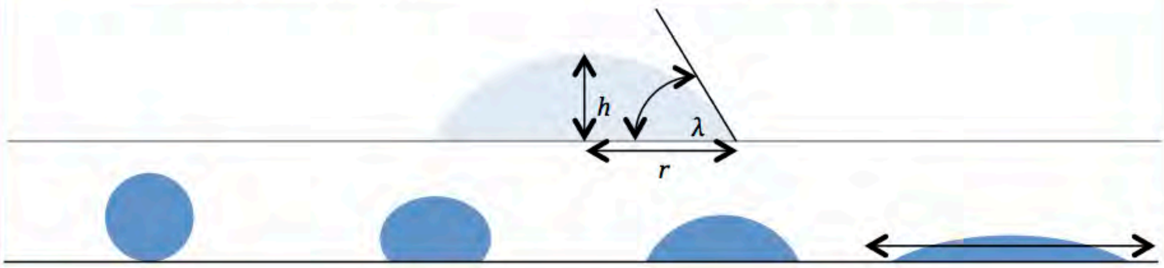
Box 12. Surface Tension, Wettability, Adhesion and Cohesion.

BOX 12: SURFACE TENSION, WETTABILITY, ADHESION AND COHESION



- **ADSORPTION** refers to the water molecules held rigidly at the soil solid surfaces due to, for instance negatively charged mineral surfaces in contact with positively charged polar water molecules; often this refers to a thin film of wetting fluid which is always present on the solid phase.
- **ADHESION** refers to a distance of a few molecular layers where the thermodynamic properties (e.g. density, viscosity) differ from the bulk, free water due to attraction of the charged mineral surfaces; adsorption can therefore be included as the part of adhesive water nearest to the mineral surface.
- **COHESION**, on the other hand, occurs where water molecules are attracted to each other and excludes the effects of the charged mineral surfaces. This water is, freely available to drain under gravity

NON-ADHESION	ADHESION	SPREADING
Drops and Rivulets		Films
Cohesion; no Adhesion	Cohesion > Adhesion	Adhesion > Cohesion
Non-wetting and Hydrophobic	Wetting and Hydrophilic	



Contact Angle:	180°	90°	0°

- No adhesion can occur at $\lambda = 180°$ and this represents a perfectly repellent surface
- Partially repellent surfaces are represented by $90° < \lambda < 180°$ where adhesion can occur and capillary depression occurs
- Wetting occurs at a critical angle of $\lambda = 90°$, differentiating capillary rise from capillary depression and subsequently hydrophilic and hydrophobic conditions, and representing a neutral surface where there is no pressure change across the air-water interface
- Hydrophilic conditions where $0° < \lambda < 90°$ and liquids imbibe into smaller pores, representing a partially wetting surface
- Spreading where $\lambda = 0°$, forming films on solid surfaces rather than drops, representing a perfectly wetting surface.

READ MORE & CITED FROM:

Bear 2007, Bear & Cheng 2007, Brady & Weil 1997, Doe 2001, FitzPatrick 1983

Adhesion, on the other hand, relates the interface between different materials, e.g. water and a solid. W_A here refers to the work required to de-wet or disjoin a unit area of solid-liquid interface, thereby creating two new surfaces with the respective solid and liquid energies and removing the solid-liquid interface as shown in Equation 21 (Doe 2001).

$$W_A = \sigma_S + \sigma_L - \sigma_{SL}$$ **Equation 21**

Wetting W_W also requires work and refers to the work to de-wet a unit area of solid surface, thus creating a solid-gas interface from the initial solid-liquid interface (Equation 22; Doe 2001).

$$W_W = \sigma_{SG} - \sigma_{SL}$$ **Equation 22**

The work of ***spreading***, finally, refers to the work required to create a unit area of solid-gas interface while removing the initial liquid-gas and solid-liquid interfaces, or through differencing the work of cohesion and the work of adhesion as shown in Equation 23 (Doe 2001).

$$W_S = W_C - W_A = (2\sigma_L) - (\sigma_S + \sigma_L - \sigma_{SL}) = \sigma_S - \sigma_L - \sigma_{SL}$$ **Equation 23**

For a threefold phase comprising solid, liquid and gas, the contact angle, λ, of the junction can be related to the surface tensions, σ, according to Young's Law as shown in Equation 24. The subscripts denote the interphases between the solid (S), liquid (L) and gas (G) phases (Doe 2001).

$$cos\lambda = \frac{\sigma_{SG} - \sigma_{SL}}{\sigma_{LG}}$$ **Equation 24**

Incorporating wetting relationships into Young's Law allows Equation 25 to Equation 27 to hold (Doe 2001).

$$W_A = \sigma_{LG} \cdot (1 + cos\lambda)$$ **Equation 25**

$$W_W = \sigma_{LG} \cdot (cos\lambda)$$ **Equation 26**

$$W_S = \sigma_{LG} \cdot (cos\lambda - 1)$$ **Equation 27**

Adhesion is often used synonymously with adsorption, although theoretically distinction should be made between the two concepts (e.g. Bear and Cheng 2010; Brady and Weil 1999).

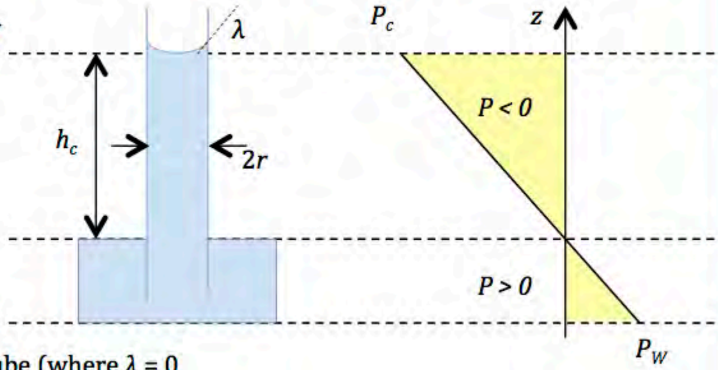
4.2.2. Capillarity

Water can occur in soils as gravitational, capillary or hygroscopic water. ***Gravitational*** water is free flowing and moves vertically downwards under the influence of gravity at a tension of less than 0.1 bar. ***Capillary water*** is held on the soil particles and in the pores at 0.1-31 bar and moves in the direction as determined by the prevailing moisture gradient (Box 13). ***Hygroscopic water*** moves essentially in the vapour phase and is attracted to the soil surfaces at suctions exceeding 31 bar (FitzPatrick 1983).

Box 13. Capillarity.

BOX 13: CAPILLARITY

The importance of the critical angle $\lambda = 90°$ becomes evident when considering capillary rise. If r can be defined as the radius of a tube through which water can flow and ½d indicates the radius of uniform spherical grains forming the solid cubic-packed phase of the system, the capillary rise h_c can be determined as a function of the surface tension of water σ_W and the weight of the water raised (specific weight of water γ_W which equals the product of the water density ρ_W and gravitational acceleration g, and the contact angle between the meniscus and the wall of the tube λ) as shown below and to the right.

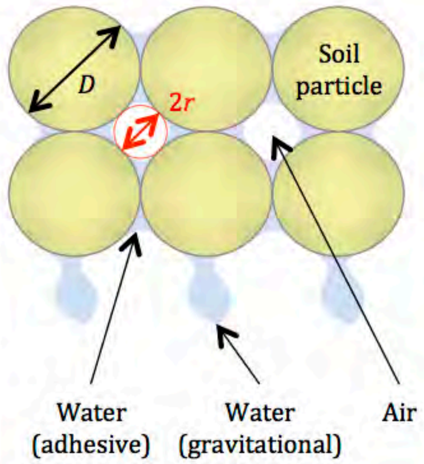


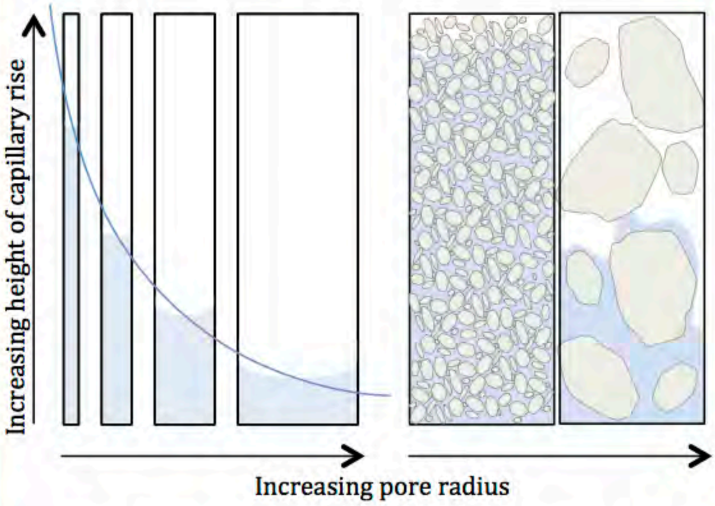
$$h_c = \frac{2\sigma_W}{r \cdot \gamma_W}\cos\lambda = \frac{2\sigma_W}{r \cdot \rho_W \cdot g}\cos\lambda$$

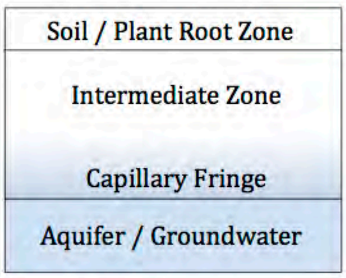
Assuming pure water in a clean glass tube (where $\lambda = 0$ and at 20°C, $\sigma = 0.074$ g.cm^{-1} and $\gamma = 1$ g.cm^3), the height of capillary rise can be estimated as follows:

$$h_c = \frac{0.15}{r} = \frac{0.15}{0.20D} = \frac{3}{4D}$$

With the assumption of uniform spherical grains in cubic packing, $r = 0.20D$ and the equation can be simplified further. This inverse relationship between pore radius and capillary rise is probably best illustrated as shown by the inverse proportional relationship between pore size and height of capillary rise as shown below.







Capillarity gives rise to the capillary fringe: that zone above the water Table where water moves upwards due to suction, wetting the lower portion of the vadose zone. This can result in saturation of the lower capillary fringe; however, the presence of water is due to suction (negative pressure), and therefore the capillary fringe is classified as being part of the vadose zone.

READ MORE & CITED FROM: Bear 2007; Deming 2002; Doe 2011; Fetter 1994; Todd and Mays 2005

In summary, water below the Earth's surface occurs as adhesive or adsorbed (hygroscopic and capillary) water due to some form of attraction to the mineral surface, or pore water (free capillary or gravitation water) where the only molecular attraction forces are between individual water molecules. Pore water or free fluid represents the greatest volume and easiest water to expel. Hygroscopic water is adsorbed onto the solid particle surface and retained by means of surface tension. These films of adhesive water can also occur around solid grains. Absorbed water is internal to each individual solid grain and required the removal of free (pore) and adsorbed (hygroscopic) water before it can be removed.

Soil and rock interact differently with water and, notably, different textural sizes and ions will result in different materials forming. In the vadose zone, interaction between the solid and fluid phases (including any liquids and gases) is mainly due to wettability.

The capillary zone or capillary fringe refers to the area over the water table up to the limit of capillary rise. Capillary action, however, occurs throughout the vadose zone, opposing gravity-driven drainage of water. Capillary action is a function of surface tension, which causes water to be a wetting agent aiming to wet the surfaces of the mineral grains. In this scenario, air becomes the non-wetting agent, which is trapped in the open pores with the least possible contact with the mineral grains.

Capillary action can also occur in the form of capillary fingering and does not necessarily refer to a uniform interface (Lu and Likos 2004). This process results in high capillary rise in certain portions of the subsurface coupled with negligible rise at other positions, and may be a significant contribution to damp issues in construction.

Hagen-Poiseuille's law states the flow through a single vertical pore as a function of the effective pore diameter and includes the dynamic viscosity of water μ_W and the microscopic hydraulic gradient S (Equation 28) (e.g. Das 2008) or as the cross-sectional area a = πr^2 (Equation 29).

$$Q(r) = \frac{\gamma_W S}{8\mu_W} r^2 a$$ **Equation 28**

$$Q(r) = \frac{\pi \rho_W g}{8\mu_W} r^4$$ **Equation 29**

5. MOVEMENT OF WATER IN THE SUBSURFACE

5.1. Mechanisms of Fluid Flow

FitzPatrick (1983) distinguishes between three types of water movement in soil depending on the moisture content and soil properties, *viz*. saturated, unsaturated and vapour flow. ***Saturated flow*** – as the name implies – takes place where all the pores are water filled and are typically associated with the phreatic zone. Movement can be in any direction and, notably when above the phreatic surface, is not limited to lateral movement. ***Unsaturated flow*** entails movement of water over particle surfaces in the presence of large amounts of air in the pores. Movement is essentially vertical under gravity when wet, but becomes more lateral or even vertical upwards when the moisture content goes below field capacity. ***Vapour flow***, finally, is water movement in the vapour phase within in the soil or between the soil and the atmosphere. This movement depends on relative humidity, temperature gradient, size and nature of pores and the moisture content. Heat movement in soil will, however, not be addressed in this text.

Before one can address the movement of water through the vadose zone in more detail, it is important to first address the parameters and equations governing flow in the general subsurface. Distinction is made in the subsections between the classical approaches to quantify flow in general, followed by the movement of water in the vadose zone specifically. Steady movement of water or flow requires a balance between the accelerating and retarding forces. The following forces work to accelerate subsurface water (Kovács 1981):

- ***Gravity*** is by far the dominant accelerating force and becomes accentuated when the specific gravities of water differ due to dissolved salts and/ or temperature
- ***Overburden pressure*** aids in accelerating water due to compression of water from the pores resulting from the reduced volume
- ***Vapour and gas pressure***, notably at great depths, can furthermore have minor influences.

Accelerating forces are typically counteracted (or retarded) by the following (Kovács 1981):

- ***Inertia*** where flow is turbulent (non-Darcy flow)
- ***Friction*** where flow is laminar (Darcy-flow)
- ***Adhesion*** where water molecules are attracted to solid particles due to tension and counteract gravity.

Based on these forces, three distinct scenarios exist where (Kovács 1981):

- Flow is through a ***saturated porous medium*** with an equally distributed pore network with random interconnectivity
- Flow is through a ***saturated fractured or fissured rock***
- Flow is through ***unsaturated porous layers or fractured rocks***.

For saturated porous flow, movement is controlled by primary porosity and gravity dominates the acceleration. Four scenarios can counteract acceleration as follows (Kovács 1981):

- Flow is turbulent and inertia dominates; friction and adhesion are negligible
- Flow is transitional between turbulent and laminar and inertia and friction dominate
- Flow is laminar (Darcy flow) and friction dominates
- Flow is via micro-seepage as a function of adhesion to grains and friction.

For saturated fracture flow, movement is controlled by secondary porosity and once again accelerated predominantly by gravity. However, the conducting channels are usually larger than pores, not equally distributed, and not random but structurally ordered. Adhesion can therefore almost be neglected, as the solid surface area is low compared to the volume of water contained. Flow can be via one of the following scenarios (Kovács 1981):

- One-dimensional and confined to linear channels, conduits and openings (like pipe flow)
- Two-dimensional along contact planes of layers and in fracture zones
- Through interstices of solid rock which resembles primary porosity

Finally, unsaturated flow can be (Kovács 1981):

- Unsaturated porous above water table where the pressure is determined by atmospheric pressure and adhesion dominates due to the extremely high solid surface area compared to the volume of water contained
- Fracture zones above water table which mimics unsaturated porous media, but is significantly less influenced by adhesion due to the lower surface area; infiltration is usually more rapid due to channel flow
- Unsaturated layers at great depth due to degassing of water at depth.

Additional flow regimes in the vadose zone addressed by Martin and Koerner (1984b) include (1) steady vertical seepage, (2) steady flow in the vadose zone parallel to the phreatic surface, (3) development of groundwater mounds under liquid-filled impoundments and (4) wetting front advances through homogeneous media.

5.2. Bernoulli's Law and Hydraulic Head

Box 14 describes Bernoulli's Law and the concept of hydraulic head. The first component relates to the kinetic energy due to the motion of moving water, the second to potential energy due to gravity, and the third potential energy due to the fluid pressure.

Box 14. Bernoulli's Law and Hydraulic Head.

BOX 14: BERNOULLI'S LAW AND HYDRAULIC HEAD

A mass of water flows from a state where $P = z = v = 0$ (pressure, elevation and velocity are zero) to its current state due to mechanical energy in three forms:

- Elastic potential energy required to compress $$E = \frac{1}{2}mv^2$$
- Gravitational potential energy required to elevate $$W = Fz = mgz$$
- Kinetic energy required to accelerate water. $$P = \frac{F}{A}$$

$$E_T = \frac{1}{2}mv^2 + mgz + P$$

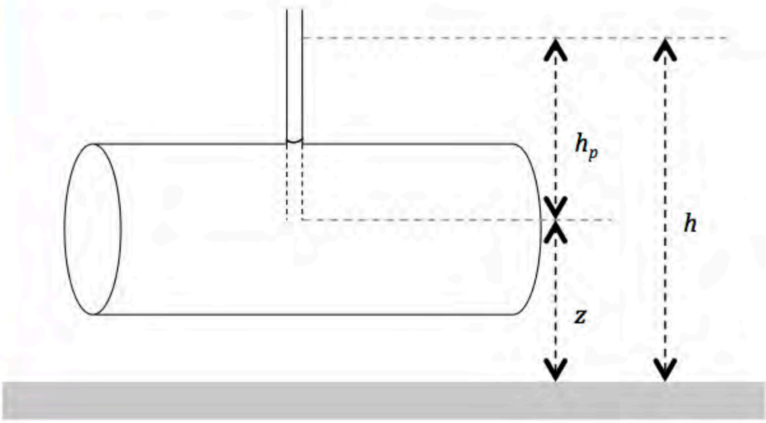
Unit volume: $V = 1$ and $\frac{m}{V} = \rho$

$$E_T = \frac{1}{2}\rho v^2 + \rho gz + \frac{P}{\rho}$$

Bernoulli first quantified this in 1738 to determine the work required to compress, elevate and accelerate a mass of water. Summation of these three parameters yield the total energy and, when converted to unit weight through division by ρg, results in a parameter with units of length. This resultant parameter is called the hydraulic head (h) and can be measured in the field or laboratory with the units of length. The hydraulic head is the sum of the velocity head, elevation head and pressure, is constant, and is calculated as shown.

In all instances, E is the kinetic energy, W the work required to lift a mass and P the pressure or force per unit area. All of these are functions of the mass of the moving body m, velocity of movement v, elevation of the fluid's centre of gravity above a datum z, gravitational acceleration g, applied force F and the cross-sectional area perpendicular to the directed force A.

The hydraulic head refers to the rise of water in a piezometer which is proportional to the total fluid energy at the bottom where the piezometer is open, and subsequently refers to the total mechanical energy per unit weight of water. For stationary water or hydrostatic conditions, the pressure at a given point equals the weight of the overlying water per cross-sectional area where h_p relates to the height of the water column providing the pressure head, and is significantly less influenced by the velocity head due to static. Hydrostatic conditions apply to stationary water, but also to scenarios where only horizontal flow is present without any vertical component.



Hydraulic Head:

$$\frac{v^2}{2g} + z + \frac{P}{\rho g} = h$$

$$h_v + z + h_p = h$$

Hydrostatic Conditions:

$$v \rightarrow 0 \text{ and } h = z + \frac{P}{\rho g}$$

$$P = (h - z)\rho_w g$$

READ MORE & CITED FROM: Driscoll 1989, Fetter 1994, Fitts 2002, Todd and Mays 2005; Younger 2005

At the water table, the pore water pressure is atmospheric and this is taken as the zero datum. In the capillary fringe, pressure heads become negative and ψ denotes the negative pressure heads above the water table. Here, assuming z is positive upwards, z = $-\psi$ and the total hydraulic head h = 0 (Rose 2006) in combination with stationary water where $v \rightarrow 0$ as per Equation 30. The suction head, $-\psi$ is often used to address the extent to which the pore water pressure is less than atmospheric pressure and is often (yet confusingly) denoted by h. In general context, the suction head is the positive pressure head so that suction head ($-\psi$) equals the elevation head (z) and the negative pressure head ($-\psi$) = $-(\psi)$ as per Equation 31.

$$h = h_p + z = \psi + z \quad \textbf{Equation 30}$$

$$(-\psi) = z = -(\psi) \quad \textbf{Equation 31}$$

5.3. Darcy's Law and Associated Parameters

The term seepage applies to moisture moving through a porous material. Engineers and geologists tend to interchange the symbols used, with engineers often utilising k for hydraulic conductivity (or coefficient of permeability) and K for (intrinsic) permeability. Similarly, Q and q as discussed hereafter are also often interchanged. For the sake of consistency, the hydrogeologically notations will be used where K represents hydraulic conductivity and k the intrinsic permeability. The concepts pertaining to Darcy's Law and the important parameter, hydraulic conductivity, are discussed in Box 15. For unsaturated conditions, K_{unsat} is determined through so-called characteristic curves of moisture content and pore water pressure.

Darcy's law applies under small enough groundwater velocities to ensure laminar flow. This is characterised by high viscous forces, small velocities and momentum, and the absence of swirls or eddies. Turbulent flow, on the other hand, is characterised by eddies. Distinction between these two parameters can be based on the so-called ***Reynolds number*** R_e as a function of the fluid density ρ, flow velocity v, mean pore or grain size d and dynamic viscosity μ (Equation 32 and Figure 5-1). Where R_e is less than some unspecified value between one and 10, flow in granular media can be considered laminar and Darcy's law applies (Fitts 2002).

$$R_e = \frac{\rho \cdot v \cdot d_e}{\mu} cos\lambda = \frac{2\tau_W}{r\rho_W g} cos\lambda \quad \textbf{Equation 32}$$

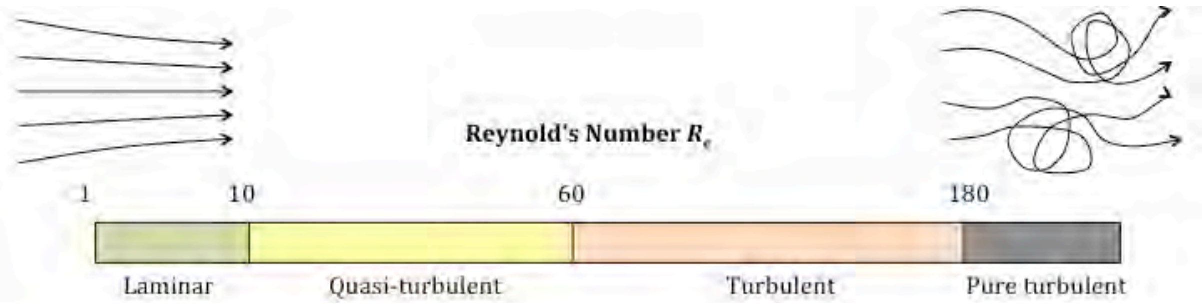


Figure 5-1. The Reynolds number showing the occurrence of laminar and turbulent flow (e.g. Bear 2007; Fitts 2002; González de Vallejo and Ferrer 2011).

Box 15. Darcy's Law and Associated Parameters.

BOX 15: DARCY'S LAW AND ASSOCIATED PARAMETERS

The **(HYDRAULIC) CONDUCTIVITY**, coefficient of permeability or constant of proportionality, *K*, is a measure of the resistance of the soil to the flow of water and has the units of velocity [L/T]. 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.

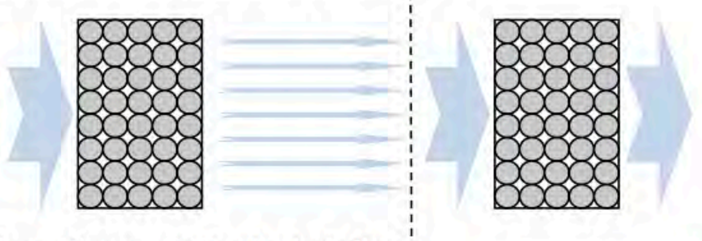
The **(INTRINSIC OR ABSOLUTE) PERMEABILITY**, *k*, on the other hand, is defined as the soil property allowing seepage of fluids through interconnected void spaces and has the units of area [L^2]. Permeability applies to any fluid and not necessarily water and is a function of *K*, the fluid density ρ, gravitational acceleration *g*, and the fluid's dynamic viscosity μ.

DARCY'S LAW defines the hydraulic conductivity as a function of *K*, the hydraulic gradient *i* and the cross-sectional throughflow area *A*. The hydraulic gradient *i* is calculated as the change in hydraulic head, *dh*, over the change in distance, *dl*, between the two points of observation. The equation is negative, seeing that the head h decreases in the direction of flow.

$$Q = -K \cdot i \cdot A = -K \frac{dh}{dl} A \qquad K = \frac{k \cdot \rho \cdot g}{\mu} \text{ and } K(m.s^{-1}) \approx 9.77 \cdot 10^6 \cdot k(m^2)$$

The **DARCY VELOCITY** or **SPECIFIC DISCHARGE**, *q*, and the **AVERAGE LINEAR FLOW VELOCITY**, *v*, are calculated as shown below. For the latter, not the complete cross-section is available to flow, but rather flow is limited to that cross-sectional area occupied by interconnected voids, i.e. η_e. Calculation of *v* effectively removes the porosity and determines a flow rate through an area comprising only the open voids (cross-sectional through-flow area is $A \cdot \eta_e$), whereas *q* assumes flow through a cross-sectional area which includes porosity (cross-sectional through-flow area is *A* which includes open voids as well as solid grains) and, therefore, $q < v$.

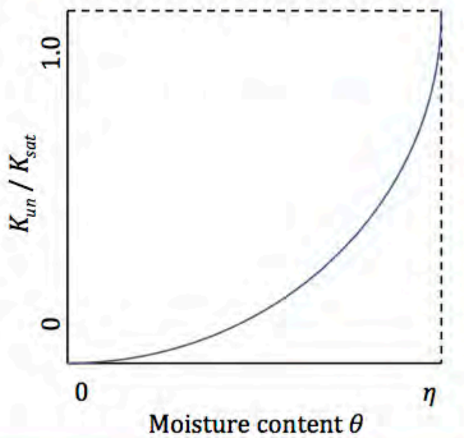
$$v = \frac{q}{\eta_e} = \frac{q}{A \cdot \eta_e}$$



$$q = \frac{Q}{A} = K \cdot i$$

For saturated conditions, *K* is a constant value including the intrinsic properties of the porous medium and water. At saturation, $\theta = \eta$ and $K_{un} = K_{sat}$. However, *K* is a function of θ and, where $\theta < \eta$, unsaturated K_{un} is not equal to the saturated K_{sat}.

For unsaturated flow, the moisture or water content and the moisture or pore water pressure need incorporation. The hydraulic head *h* is measured as a height relative to a datum but, for unsaturated flow, the head is a function of the soil suction (or suction head) Ψ and *K* is a function of θ. At a fixed porosity with increasing soil moisture content θ, the hydraulic conductivity *K* increases and Ψ decreases.



READ MORE & CITED FROM: Das 2008; Deming 2002; Driscoll 1989; Fetter 1994; Fitts 2002; Kiely 1998; Todd and Mays 2005; Younger 2005

Water flow through rock or soil is at varying velocities and in varying directions, and not true to the simplified volume-averaged descriptors such as specific discharge or linear flow velocity. Applying Darcy's law, small-scale variations are overlooked in favour of these volume-averaged descriptors in what is referred to as the continuum or macroscopic approach where the medium is transposed from an irregular, complex one to a continuous, homogenous medium. For this reason, consideration of the representative elementary volume (REV) becomes increasingly important (§3.2.1).

In certain scenarios, differing K-values will exist for the x, y and z-directions. In such a situation, q can be determined for each direction separately and based on a distinct corresponding K-value as shown in Equation 33 and Equation 34.

$$q_x = -K_x \frac{dh}{dx} \; and \; q_y = -K_y \frac{dh}{dy} \; and \; q_z = -K_z \frac{dh}{dz}$$ **Equation 33**

$$q = \sqrt[2]{q_x^2 + q_y^2 + q_z^2}$$ **Equation 34**

Unsaturated flow is typically estimated by means of Darcy's Law applied to unsaturated conditions where hydraulic conductivity becomes a function of water content or saturation (Equation 35) or the Richards's equation where suction and gravity require incorporation (Equation 36), or rewritten in vertical, one-dimensional coordinates (Equation 37; Karamouz et al. 2011; Ruan and Illangasekare 1999).

$$q_v = -K(\theta)\frac{dh}{dx} = -K(\theta)\frac{d}{dz}(h_c + z) = -K(\theta)\left(\frac{dh_c}{dz} + 1\right)$$ **Equation 35**

$$q_v = -K(\psi)\nabla h$$ **Equation 36**

$$\frac{d\theta}{dh}\frac{\delta h}{\delta t} = \frac{\delta}{\delta z}\left(K\frac{\delta(h+z)}{\delta z}\right)$$ **Equation 37**

5.4. Unsaturated Flow

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). This is explained in Box 16 where 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 concentrates the flow of water non-uniformly in the subsurface layers (Glass et al. 1988).

Box 16. Mechanisms of Water Movement in the Vadose Zone.

BOX 16: MECHANISMS OF WATER MOVEMENT IN THE VADOSE ZONE

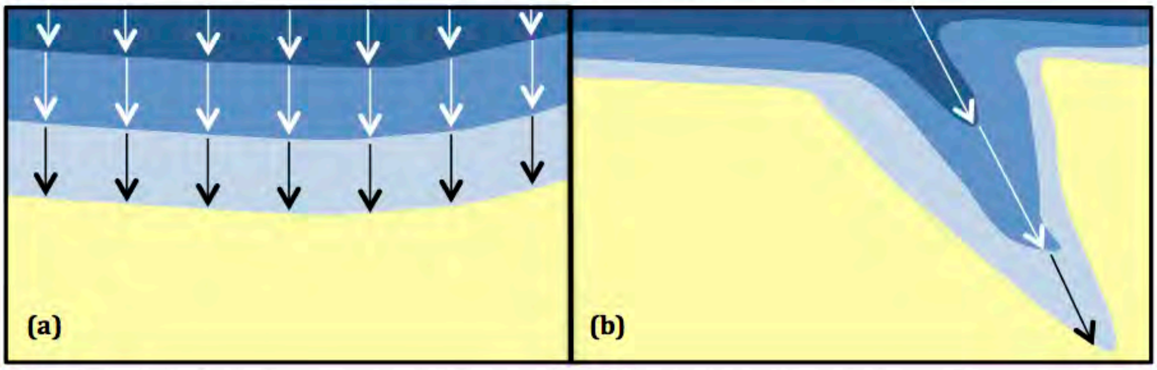
Water movement in the vadose zone is influenced by wetting front instability, fluid retention and release due to capillary and gravity actions competing, and small changes in boundary conditions such as temperature and pressure. This leads to so-called episodic, intermittent, pulsating or threshold-like flow behaviour in the vadose zone, which acts as purging events. One can, therefore, consider the competition between capillarity and gravity as a competition between the forces of retardation and acceleration in the vadose zone, respectively trapping and mobilising water. Water movement in the unsaturated zone generally occurs vertically due to gravity (infiltration and percolation) or laterally due to an aquiclude or aquitard (interflow), and is not always a constant and continuous process. Interflow water often daylights on surface in the form of wetlands, whereas deep percolating waters may eventually become recharge

PISTON, TRANSLATORY, EPISODIC, INTERMITTENT, PULSATING or **THRESHOLD-LIKE FLOW** entails precipitation stored in the vadose zone to be displaced vertically following infiltration of a subsequent precipitation event, thereby not affecting the distribution of moisture, but only the depth. The terms piston, translatory, episodic, intermittent, pulsating or threshold-like flow can be used synonymously and depend on the addition of moisture from surface to push the wetting front downwards

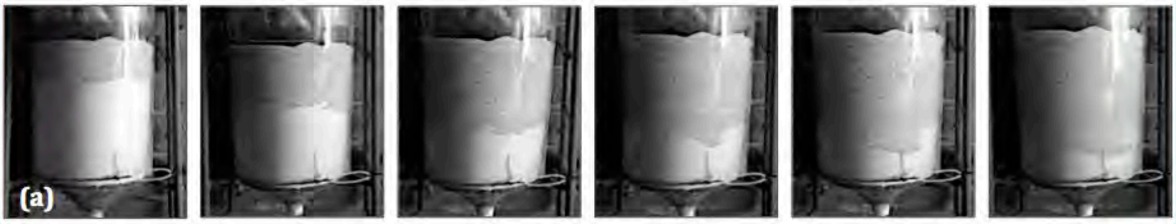
PREFERENTIAL FLOW resulting in **FINGERING** or **UNSTABLE FLOW** concentrates flow through macropores, preferred pathways or due to changing soil texture rather than wetting the complete medium.

(a) Three subsequent translatory flow events, progressively pushing the wetting front downwards

(b) Preferential flow in the form of fingering through macropores and/ or structures.



(c) Movement of a wetting front in medium-grained sand at ten-second intervals. Note how the shape of the wetting front remains fairly constant.



READ MORE & CITED FROM: Beekman & Xu 2003, Glass et al. 1988, Podgorney & Fairly 2008

Often, movement is not in the form of a downward-pushing wetting front. Fingering occurs, often despite homogeneity of materials, due to water cohesion resulting in preferred pathways. This preferential flow may vary with different events, or may be preferential flow due to macrospores that represent structural heterogeneities with differing porosity to the surrounding material.

Flow (***seepage***), wetting (***imbibition***) and drying (***drainage***) in unsaturated media become increasingly complex as explained in Box 17 and Box 18. ***Retention curves*** or ***characteristic curves*** relate water saturation to capillary pressure and are a function of soil texture and structure. Initially saturated soils will drain to a moisture distribution based on its retention curve and can be approximated by means of the specific yield. More development in soil-moisture characteristic curves is well documented and includes, for instance, Das et al. (2005), Dexter (2004), Van Genuchten (1980)

Berkowitz (2002) accentuates the issues of partially saturated flow through fractured systems, noting that uncertainty is high and that open questions to be addressed include:

- How field-scale fluid flow and solute migration in such systems can be understood and with which quantitative modelling approaches
- How does one account for fast flow behaviours in certain field sites?
- Through which additional experiments can these partially saturated systems canbe understood better (both conceptually and quantitatively)?

Three studies are cited (Dahan et al. 1998, 1999, 2000 in Berkowitz 2002), finding that less than 15% of fracture openings transmitted 100% of percolating water at one site, and less than 20% of fracture openings transmitted more than 70% of the percolating water at another site. Additional consideration of film flow on rough fractures is presented by Liu (2004).Work is presently underway to address some of these issues by means of geotechnical centrifuge modelling.

5.5. Subsurface Translocation Processes

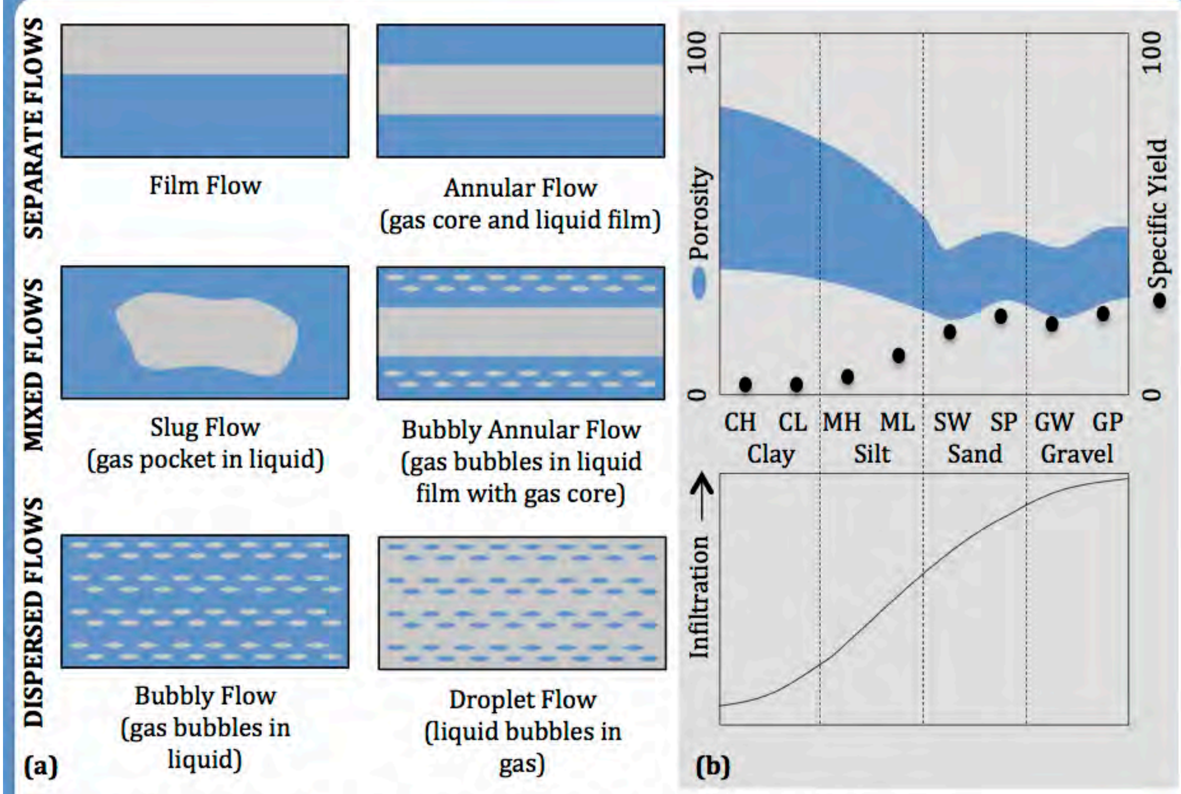
Translocation here is defined as the subsurface movement of fine minerals (e.g. clay minerals) and ions with moving subsurface water.

5.5.1. Water and Clay Minerals

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***. These so-called clogging microstructures alter the soil material and soil mass as well as the seepage behaviour (Figure 5-2). Leaching of clay minerals from a generally coarse-grained soil with percolating water can furthermore lead to a change in soil structure to a so-called collapsible fabric.

Box 17. Unsaturated Flow.

BOX 17: UNSATURATED FLOW

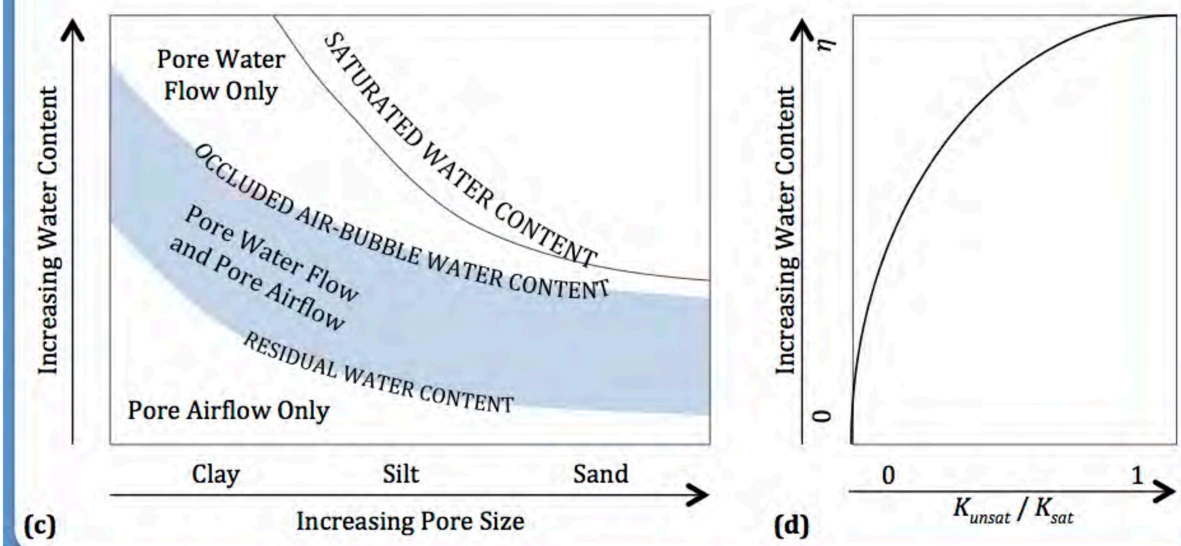


(a) Flow mechanisms of water–air systems through fractures or macropores.

(b) Influence of soil texture on porosity, specific yield and infiltration rate.

(c) Influence of water content and soil texture (pore size) on water flow and airflow

(d) Influence of water content on the relative hydraulic conductivity K_{unsat} / K_{sat}.



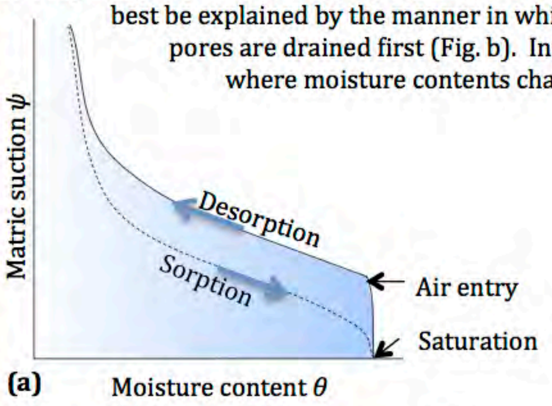
READ MORE & CITED FROM:

Fitts (d); Indraratna & Ranjith 2001 (a,b); Lu and Likos (c)
Martin and Koerner 1984b

Box 18. Characteristic Curves and the Hysteresis Effect.

BOX 18: CHARACTERISTIC CURVES AND THE HYSTERESIS EFFECT

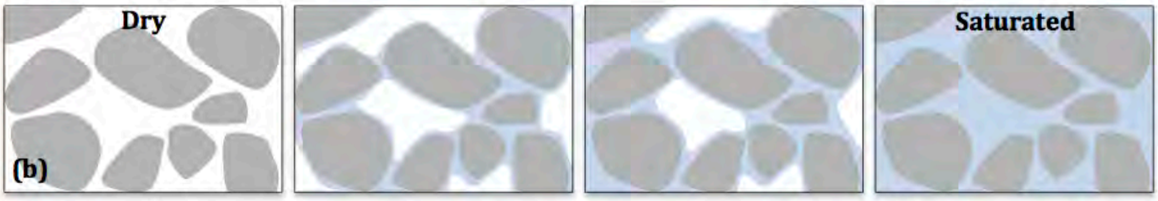
Characteristic curves comprise the ***main branches*** (Fig. a), including the extremes of (i) saturation of a dry soil (sorption) and (ii) drying of a saturated soil (desorption; soil-moisture release). This can best be explained by the manner in which smaller pores are wetted first and larger pores are drained first (Fig. b). Intermediate scenarios are called ***scanning curves***, where moisture contents change between these extremes. Two processes result:



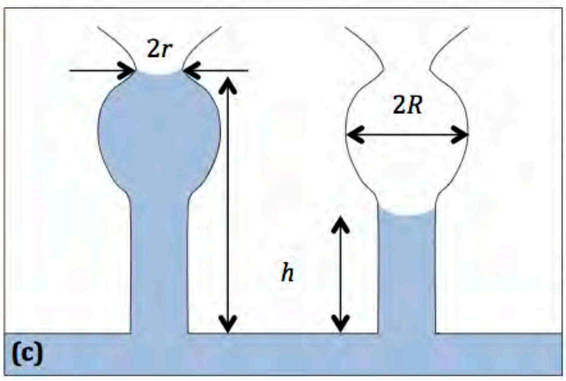
- Drainage curves or moisture-release curves result from water draining from pores and depend on the narrow radii of the connecting throats. The process is quicker when saturated depending on the pore radius.
- Imbibition or wetting curves depends on the maximum diameter of the large pores. The process of sorption or rewetting requires greater suction for smaller pores.

Equilibrium at a certain suction may be obtained with different values of saturation, and, for a given capillary pressure, a higher saturation is obtained when a sample is being drained than during imbibition.

Characteristic curves are not constant and depend on the soil texture, as well as whether the soil is being wetted or dried. In terms of soil texture, clays will always have higher moisture content at the same matric suction due to the greater surface area and its porosity. At the same moisture content, clays will always have higher suction due to, once again, the surface area and the smaller pore sizes compared to granular materials.



The difference in matric suction at the same moisture content for a wetting and drying soil can be ascribed to pores emptying in a different order than they are filling and by air entrapment during wetting. For instance, when wetting, large pores may fill first and cause air to be trapped in small pores.



Hysteresis can be ascribed to:

- Geometric non-uniformity of individual pores (irregular shapes of voids and smaller throats connecting these voids; ink-bottle effect (Fig. c)
- Contact angle resulting in greater curvature with an advancing meniscus than in receding one causing grater suction in desorption than in sorption for same water content
- Entrapped air resulting in lower water content in newly wetted soil
- Differentially changing soil structure including swelling and shrinking.

READ MORE & CITED FROM:

Fitts 2002; Hillel 2003; Martin and Koerner 1984a; Schaetzl and Anderson 2005

Clay translocation down hillslopes often result in the formation of so-called duplex soils, often associated with gully heads and seep lines. With terms such as plinthite referring to accumulation of ions, duplex soils are characterised by the enrichment in clay minerals, often with associated decrease in permeability.

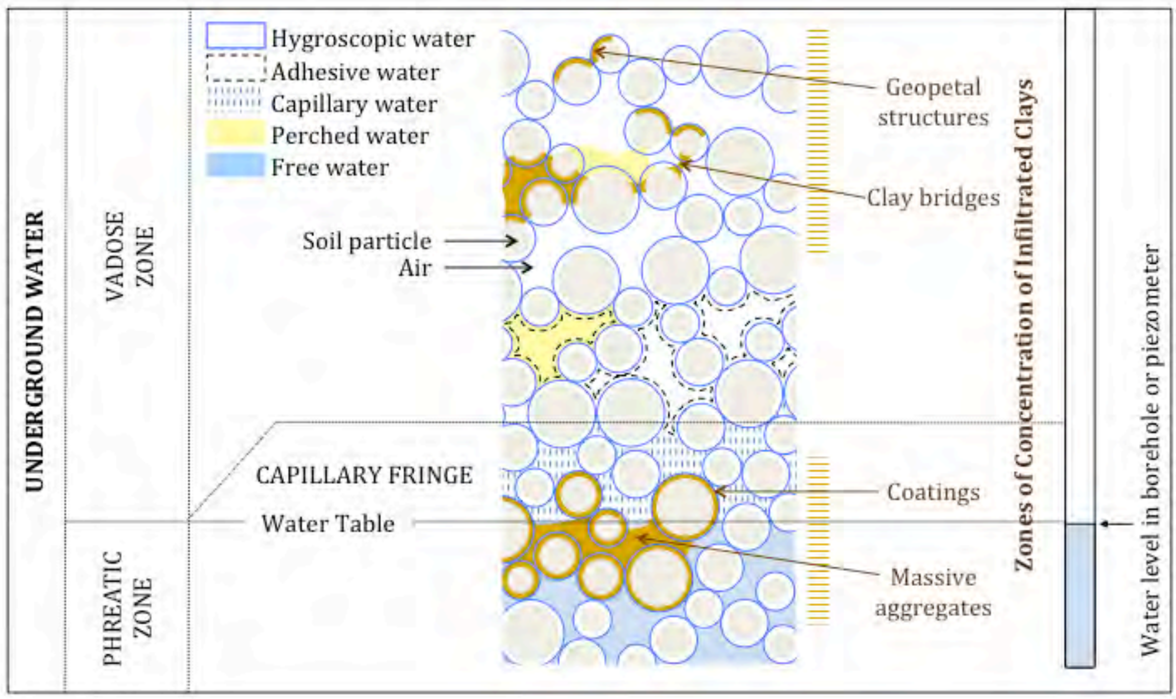


Figure 5-2. Vertical distribution of water in the crust and the concomitant clogging structures (adapted from Moraes and de Ros 1990, Shaw 1994, Skolasinska 2006).

5.5.2. Water and Pedogenesis

Perched water tables or fluctuating ground water levels can lead to the development of pedogenic soil horizons that lowers the permeability and the subsequent vertical percolation. The process of pedogenesis is influenced by the subsurface, down-slope drainage of water until a point on the slope is reached where precipitation of transported ions commences. This is then referred to as the zone of pedogenesis and includes ***pedocretes*** such as laterite, ferricrete, calcrete, silcrete or other pedogenic materials based on the available ions and the climatic conditions (Box 19).

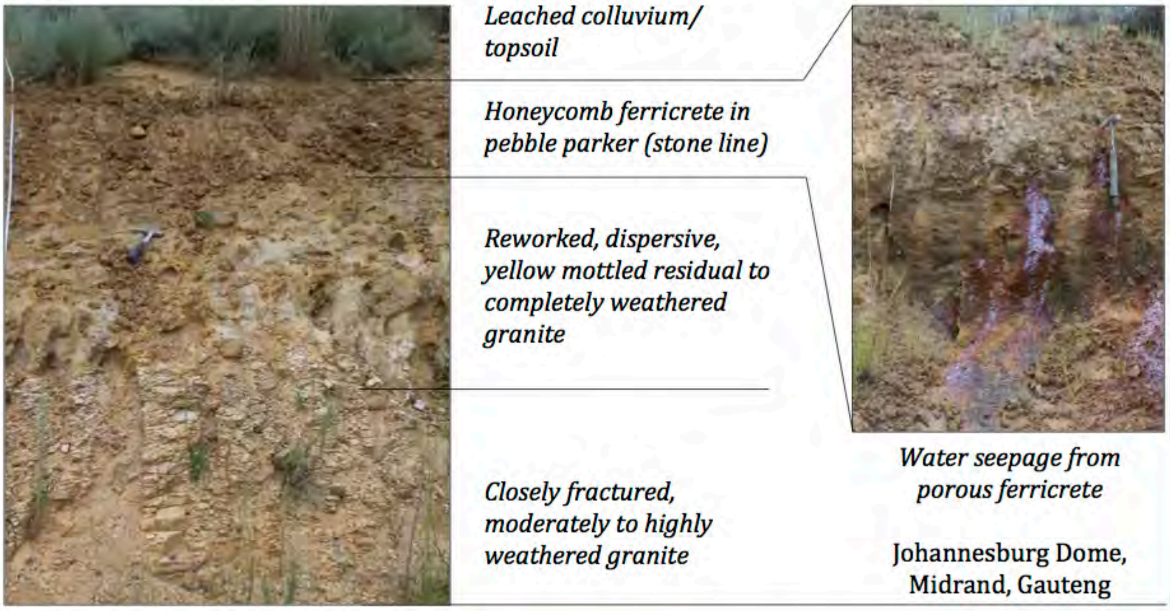
This soil horizon can be either a ***pedogenetic pedocrete*** (due to percolating water from surface and the precipitation of mobilised elements above a less permeable horizon) or a ***groundwater pedocrete*** (due to seasonal fluctuations in ground water level or ground water perching and the concomitant precipitation of elements dissolved in ground water) as shown in Box 19 (McFarlane 1976).

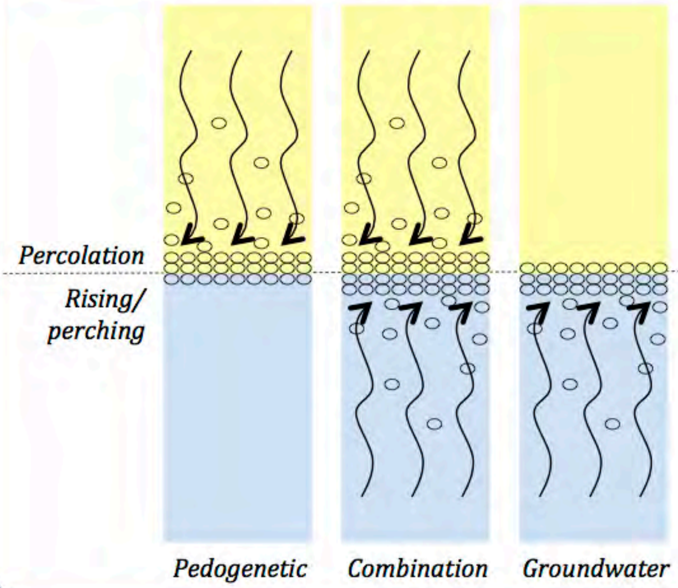
Box 19. Pedogenesis: Formation and Classification.

BOX 19: PEDOGENESIS: FORMATION AND CLASSIFICATION

Pedogenesis refers to the induration of soil through the precipitation of authigenic minerals within an existing material. The phases of pedogenesis are:

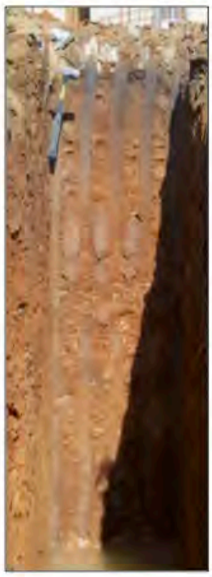
- Enriched soil (iron-rich, calcium-rich, silica-rich, gypsym-rich)
- Highly enriched (ferruginized, calcified, silicified, gypsified)
- Powder pedocrete (powder ferricrete, calcrete, silcrete, gypcrete)
- Nodular/ Glaebular pedocrete (nodular or glaebular ferricrete, calcrete, silcrete, gypcrete)
- Honeycomb pedocrete (honeycomb ferricrete, calcrete, silcrete, gypcrete)
- Hardpan pedocrete (hardpan ferricrete, calcrete, silcrete, gypcrete)





Left: pedocretes can either form through percolating or rising water, or a combination of both..

Right: ferruginization in Karoo Supergroup sandstone in Ermelo, Mpumalanga



READ MORE & CITED FROM:

McFarlane 1976

An alternative term, ***duricrust***, refers to any hard, generally impermeable crust on surface, or within the upper horizons of a soil, notably forming in extreme climates (semi-arid or humid tropical) and includes calcrete, ferricrete (ferruginous laterite), aluminocrete (bauxite) and silcrete (Blatt and Tracy 1997).

Soil scientists often refer to ***pans*** such as duripan (for silica cemented), fragipan (for any dense, brittle) or placic (for very hard Fe and Mn cemented) materials, which can be defined as cemented or densely packed materials resulting in relatively impermeable horizons. As opposed to this, the term ***plinthite*** refers to a highly weathered mixture of iron and aluminium sesquioxides and quartz, occurring as red mottled and that changes into hardpan (a hardened soil layer in the lower A or B horizons caused by cementation) upon alternate wetting and drying cycles (Brady and Weil 1999). The pedocretes, however, are almost always referring to cemented materials, whereas the pans in soil sciences often involve compacted materials.

Part 2: Methods and Guidelines

Dippenaar, M. A.

6. METHODOLOGIES TO QUANTIFY RELEVANT PARAMETERS

6.1. Profile Description

6.1.1. Soil profile description

Soil profiles in South Africa (for engineering purposes) are described according to the MCCSSO system described in draft SANS 633 (2009) and involve the parameters in the sequence of the acronym:

- ***Moisture*** – dry to wet
- ***Colour*** – based on primary and secondary colour with additional comments on discolouration (notably mottling)
- ***Consistency*** – very loose to very dense for non-cohesive soils; very soft to very stiff for cohesive soils
- ***Soil structure*** – e.g. intact, open, voided, jointed, foliated, open root channels, shattered, slickensided, etc.
- ***Soil type*** – estimated clay, silt, sand and gravel fractions in ascending order of dominance
- ***Origin*** – transported (e.g. colluvium, alluvium, pebble marker), pedogenic materials (ferricrete) residual (in-situ weathered bedrock) and bedrock (completely weathered to fresh).

Additional descriptors are also noted, including seepage from profile sides, sidewall instabilities, termite or ant burrows, root channels, reason for the final depth of the profile (e.g. existing excavation; depth of backactor refusal; excavation unstable) and any other noticeable and relevant natural and manmade features.

Proper description of the distribution (both vertically and spatially) of earth materials continues to prove the most fundamental and severely important in the acquisition of data. Also probably the initial stage of investigation, it provides the first in-depth view into the subsurface at fairly low cost.

The approaches of soil profile description or logging provided by the engineering geological and soil scientific disciplines provide a detailed methodology to envisage the (a) behaviour of soils in terms of its hydraulic properties, (b) recent historical hydrological processes resulting in depletion, enrichment, mobilisation, precipitation and/ or deposition of ions or fines, (c) likely flow paths, clogging horizons and plant root depths and (d) prevailing or in-situ moisture content variation.

Elaboration on the MCCSSO system for engineering geological soil classification in shown in Box 20 with additional elaboration on different soil texture classification systems in Box 8.

Box 20. MCCSSO: Moisture, Colour, Consistency and Structure.

BOX 20: MCCSSO: MOISTURE, COLOUR, CONSISTENCY, STRUCTURE

1. MOISTURE

Dry	No moisture detectable
Slightly moist	Moisture just discernable
Moist	Moisture easily discernable Soil at optimal moisture content
Very moist	Close to saturation but no seepage evident
Wet	Soil saturated with seepage Generally at or below water table

2. COLOUR

Predominant colour with secondary patterns (if applicable), e.g.
Light reddish brown mottled black

Colours: pink(-ish), red(-ish), orange, yellow(-ish), brown(-ish), olive, green(-ish), blue (bluish), purple, grey(-ish), black, white

Tones: very light, light, dark, very dark

Secondary Descriptors:

Speckled	Patches of colour < 6 mm
Mottled	Patches of colour < 60 mm
Blotched	Large irregular patches of colour > 60 mm
Banded	Approximately parallel bands of varying colour
Streaked	Randomly orientated streaks of colour
Stained	Local colour variations along discontinuities

3. CONSISTENCY: NON-COHESIVE SOILS

Very loose	Crumbles easily when scraped with geological pick
Loose	Small resistance to penetration by sharp end of pick
Med. dense	Considerable resistance to penetration by sharp end of pick
Dense	Repeated blows with pick for excavation
Very dense	Power tools required for excavation

3. CONSISTENCY: COHESIVE SOILS

Very soft	Easily moulded by fingers; pick head can be pushed in up to the shaft
Soft	Easily penetrated by thumb; pick can be pushed in 30 mm; moulded with effort
Firm	Indented by thumb with pressure; pick can be pushed in 10 mm
Stiff	Slight indentation by pushing pick point into soil; hand pick excavation
Very stiff	Slight indentation by blow with pick point; power tool excavation

4. STRUCTURE

Intact	Without structure
Fissured	Fissile discontinuities
Slicken-sided	Smooth, glassy, often striated discontinuity surfaces
Micro-shattered	Sand-sized fragments due to closely spaced fissures; usually stiff to very stiff
Shattered	Above but gravel-sized
Granular	Non-cohesive; random
Pinholed	Voids or pores < 2 mm
Honey-combed	Voids or pores > 2 mm

READ MORE & CITED FROM: Brink and Bruin 2001; Jennings et al. 1973; SANS 633:2009a; SAICE 2010

6.1.2. Rock description

Description of rock is also discussed in SANS 633 (2009a) and incorporate indications of mineralogy and rock type, degree of weathering, jointing, other structural influences or fabric, as well as any evident discolouration or mottling. For sensible application to flow, special emphasis is placed on the joint continuities, apertures, infilling, roughness and waviness as these all will govern to which extent water can move through the fractures. Universally accepted weathering descriptors are as follows:

- ***Completely weathered rock*** resembles soil where the material is discoloured and some of the original rock fabric may be preserved.
- ***Highly weathered rock*** is friable, discoloured and often pitted due to washing out of altered minerals during drilling or excavation. The original rock fabric is preserved, albeit opened due to weathering.
- ***Medium weathered rock*** shows slight discolouration from the discontinuities, the latter which may also include filling of altered materials. The rock fabric has been preserved, the rock is not friable and some grain openings may be evident.
- ***Slightly weathered rock*** shows staining on discontinuities with possible thin filling. The colour generally resembles the unweathered state, although some surface discolouration may extend into the rock from the discontinuities.
- ***Unweathered rock*** (intact; fresh) shows no visible signs of alteration, although discontinuity planes may be somewhat stained.

Details regarding the importance of discontinuity surveys and important considerations in describing rock mass are available in Box 21 (e.g. Anon. 1977). Additional input from the classical approaches to discontinuity surveys are added for weathered rock to incorporate relic structures and those related to soils in the classification.

6.1.3. Improved earth scientific profile description

In order to maximise the information obtained from description of material successions, a multi-disciplinary approach is beneficial. Inclusions of principles from both soil science and geology will significantly improve the profile log and will aid in better application of the information. The paradigm shifts in profiling detailed below are recommended for improved information from soil profile descriptions. These "paradigm shifts" are summarised in Figure 6-1 and discussed below. Credit should be given to each individual specialist field for their contributions to material descriptions. However, given the huge disciplinary overlap in the field of vadose zone hydrology, it becomes imperative that the specialist is also able to deduce information from other specialists' data.

Box 21. Rock Mass Description and Discontinuity Survey.

BOX 21: ROCK MASS DESCRIPTION AND DISCONTINUITY SURVEY

1. TYPE OF STRUCTURE

0	Fault zone
1	Fault
2	Joint
3	Cleavage
4	Schistosity
5	Shear
6	Fissure
7	Tension crack
8	Foliation
9	Bedding

- Note dip and dip direction/ strike (°)
- Persistence (metres extent of structure)

2. APERTURE (mm)

1	Wide (> 200)
2	Mod. wide (6 200)
3	Mod. narrow (20–60)
4	Narrow (6–20)
5	Very narrow (2–6)
6	Ext. narrow (< 2)
7	Tight

- Address the consistency in the aperture.

3. INFILLING - NATURE

1	Clean
2	Surface staining
3	Non-cohesive
4	Inactive clay
5	Swelling clay
6	Cemented
7	Chlorite, talc, gypsum
8	Other – specify

4. INFILLING – COMPRESSIVE STRENGTH (1–6: kPa; 7–12: MPa)

1	Very soft (< 40)
2	Soft (40–80)
3	Firm (80–150)
4	Stiff (150–300)
5	Very stiff (300–500)
6	Hard/ very weak (600–1250)
7	Weak (1.25–5)
8	Mod. weak (5–12.5)
9	Mod. strong (12.5–50)
10	Strong (50–100)
11	Very strong (100–200)
12	Ext. strong (> 200)

5. ROUGHNESS

1	Polished
2	Slickensided
3	Smooth
4	Rough
5	Defined ridges
6	Small steps
7	Very rough

6. WAVINESS

1	Wavelength (m)
2	Amplitude (m)

7. WATER

1	Dry
2	Damp
3	Seepage
4	Flow < 10 ml/s
5	Flow 10–100 ml/s
6	Flow 0.1–1 l/s
7	Flow 10–100 l/s
8	Flow > 100 l/s

- Note environmental conditions as moisture may change over time and with precipitation events.

ADDITIONAL CONTRIBUTIONS:

More types of structures exist in rock, depending on its degree of weathering, mineralogy and deformation history. Specification of such can be included additionally to include, for instance, gneissossity, laminations, cross-bedding, ripple marks and other relic structures. Soil structures possibly present in completely to highly weathered rock can also be noted and includes, for instance, krotovinas (infilled root voids/ burrows), open root channels, pinholes, slickensides and shattering.

Mineralogical specification of the rock and infill material will also aid in addressing the properties.

READ MORE & CITED FROM: Anon. 1977

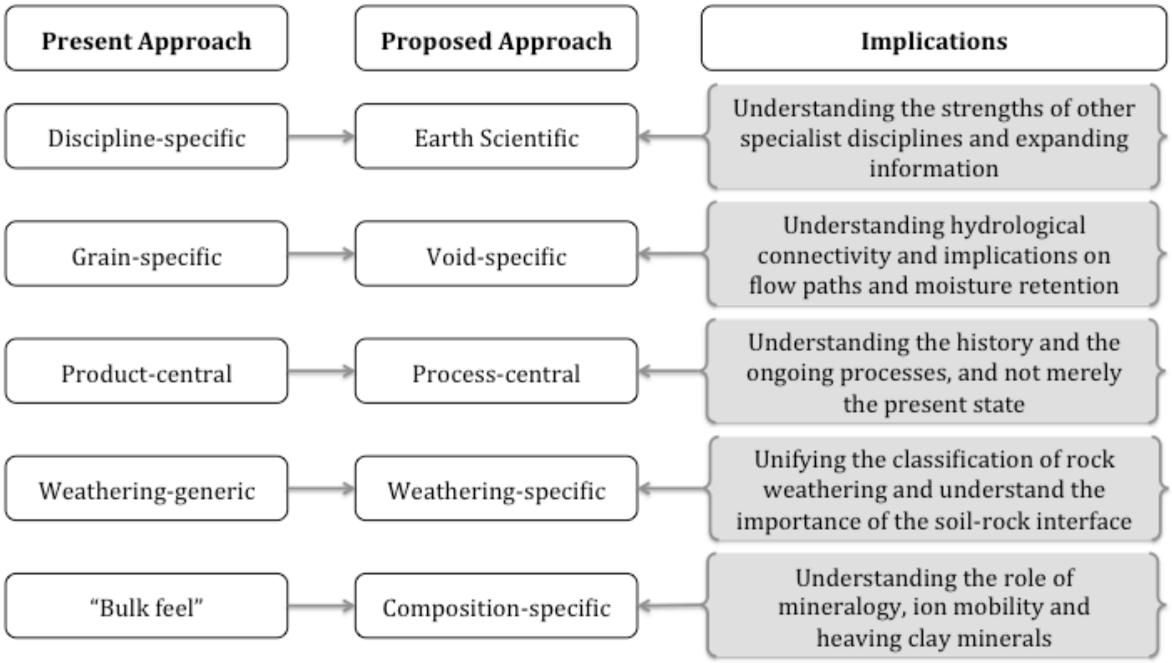


Figure 6-1. Proposed paradigm shifts for an improved earth scientific profiling methodology for applications in vadose zone hydrological studies.

Profiling should be ***earth scientific*** rather than solely geological, soil scientific or pedological. The MCCSSO parameters provide a sensible guideline for interpretation of site materials notably with respect to engineering application. However, the parameters are useful to most applications, provided that the investigator properly understands the classes associated with each parameter. The inclusion of soil origin is a notable strength of the system, especially given the lack of agreement on concepts such as saprolite, regolith and weathered rock, and should be expanded to other disciplines. In the same reasoning, however, the detailed assessment of notably soil structure in soil science clarifies the issues related to the continuity and orientations of soil structures (notably macropores) and the interactive soil taxonomy of pedologists improve understanding of the complete catena system and the soil hydrology (e.g. Bouma 2006; Le Roux et al. 2011).

Profiling should be ***void-specific*** and not solely grain-specific. Soil texture (type) and structure and generally described as a function of the clay minerals and granular fractions, and often exclude significantly coarse fractions such as gravels, pebbles, cobbles and boulders. These large inclusions are often practically impermeable with distinct flow paths around the surface, or indicate a different origin that may imply different consolidation and mineralogy. When logging soil profiles, the shape, size, connectivity and continuity of voids should be noted. Additionally, potentially changing porosity and void space (due to, for instance, heaving clays, consolidation or leaching) should be noted and the granular packing will contribute significantly to estimating the porosity based on visual observation solely. The implications on interflow and hysteresis, for instance, are addressed based on the attached case studies in later sections, and inclusions of such information will be beneficial to a wider range of applications of the same profile descriptions.

Profiling should be ***process-central*** and not product-central. Proper understanding of the processes forming the characteristic soil profile is more important than logging the present state without cognisance of the changing system and the continuing processes changing the soil succession. Discolouration should be noted very clearly and a separate horizon should be noted where mottling or staining frequency or size change, or when soil colour changes. The earth scientist should also be able to ascribe the process to the cause, including but not limited to (a) mottling due to periodical inundation of the horizon, (b) colour due to waterlogged or reducing conditions, (c) discolouration indicates an upward, downward or lateral flow waterlogging, or (d) discolouration is primarily a function of the source rock mineralogy.

Profiling should be ***weathering-specific*** and not weathering-generic. Hydrogeologists notably classify weathered rock as that rock at depth where a zone of more transmissive material is present for the transmission of water. However, rock weathering descriptors are standardised as per §6.1.2 and weathered zones at depth should not be described in a manner contradicting generic geological classifications. Proper understanding of the origin of soils will distinguish between transported soil, residual soil and weathered bedrock. It is imperative that the earth scientist logging the material properly understands the difference between these three origins and can clearly identify saprolite and regolith in a soil profile. As a rule of thumb, South African soils typically have a characteristic pebble marker indicating the boundary between transported and residual soils.

Profiling should be ***composition-central*** and not “bulk feel”-central. Minerals and crystals should be noted as the prior determines the nutrients and weathering products, and the latter the shapes of the grains. Processes are governed by the availability of ions and the ease of preferential weathering. Potentially expansive and inert clay minerals should be noted specifically and secondary minerals should be included in both the soil and rock horizons to address weathering and translocation of fines in the profile. Pedogenetic horizons should be addressed in the dual manner (discussed in §5.5.2) incorporating both the enrichment and the original origin (e.g. nodular ferricrete in residual granite), thereby giving an indication of the mobile ions and the parent mineralogy.

6.2. Porosity

6.2.1. Quantifying porosity

For homogeneous spherical grains of equal diameter in a densest packing, porosity is not a function of the grain-size diameter, but solely of the packing of these grains. Porosity for such materials can vary only between a maximum of 0.476 for cubic (unstable) packing to a minimum of 0.260 for rhombohedral (stable) packing. These values obviously vary distinctly based on deviations from spherical grains (e.g. platy minerals), varying grain sizes and structural porosity.

Despite the porosity being essentially a function of the packing of the grains, two other aspects need to be considered:

- As per Poiseuille's equation, flow rate is dependent on pore radius and water may, therefore, move at different rates through materials of the same porosity.
- Total porosity may not always be available for flow, and evaluation of effective porosity becomes problematic.

Porosity is often estimated based on the uniformity coefficient according to Istomina (1957 in Van Schalkwyk and Vermaak 2000) as shown in Equation 38. This is, however, only applicable to soils with fairly uniform fractions and cannot be applied when clay is present in the soil.

$$\eta = 0.255 \cdot (1.83)^{C_U}$$

Equation 38

Another means of determining porosity in the laboratory is the density relationships at saturation ($V_V = V_T$) compared to oven-dried ($V_V = V_A$) as shown in Equation 39.

$$\eta = \frac{V_V}{V_T} = \frac{V_W}{V_T} = \left(\frac{V_W}{1} \cdot \frac{V_V}{V_T}\right)$$

Equation 39

Probably a more accurate method of determining porosity is through quantitative mineralogical composition as supplied through X-Ray Diffraction (XRD). Fractions (f_M) of minerals are obtained, the sum totalling one. Densities of these individual minerals (ρ_M) are readily available in published literature (e.g. Deer et al. 2000). These results can be used to determine an average solid phase density (ρ_S) which relates to the bulk dry density of the sample (ρ_B) as shown in Equation 40. The benefit of this method is its incorporation of the distribution of minerals with varying density, and not only the textural changes from particle size distribution. Application of the density relationships proved successful in evaluating interflow through ferricrete in an ephemeral hillslope wetland underlain by Lanseria Gneiss in VZSA1 (§11).

$$\eta = 1 - \frac{\rho_B}{\rho_S} \text{ where } \rho_S = \sum f_M \cdot \rho_M$$

Equation 40

Numerous authors have evaluated trends in the quantification of porosity (Box 22). These are discussed by Dippenaar (2014) and briefly include:

- Basic relationships as discussed above
- Density relationships
- Empirical relationships
- Visual, remotely sensed and porosimetry methods
- Random and densest packing simulations
- Geometric and fractal models
- Changing porosity.

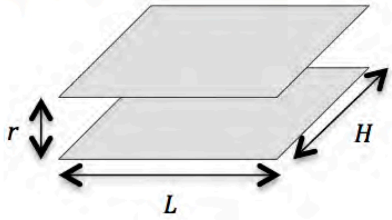
Box 22. Visualizing and Simplifying Complex Porosity.

BOX 22: VISUALISING AND SIMPLIFYING COMPLEX POROSITY

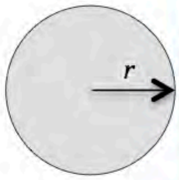
IDEALISED PORE SPACE GEOMETRIES

Idealised pore space geometries represent the pore radii and its influence on capillarity through simplification of actual pore space geometries. Shown to the right are three as well as the calculation of the volume V and area A.

CYLINDER
$V = \pi r^2 L$
$A = 2\pi rL$
$V/A = r/2$



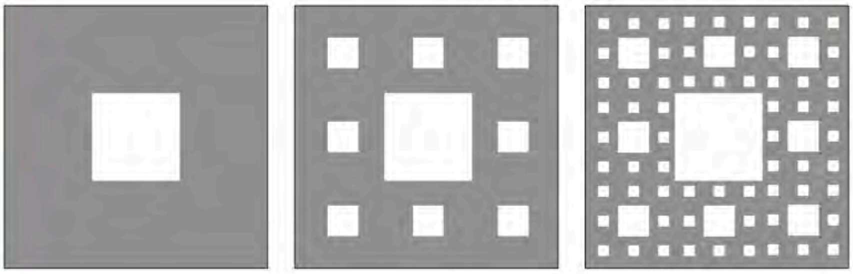
PARALLEL PLATES
$V = LHr$
$A = 2LH$
$V/A = r/2$



SPHERE
$V = 4/3\pi r^3$
$A = 4\pi r^2$
$V/A = r/3$

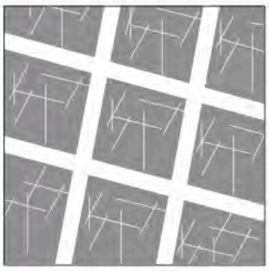
FRACTAL MODELS

Henceforth, grey = matrix; white = pore space)

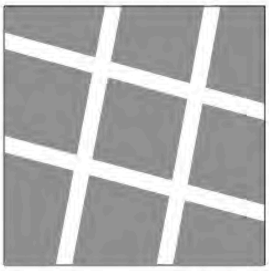


Fractal models such as the Serpieński carpet (left) or the three-dimensional Menger sponge aim to account for infinitesimal pores.

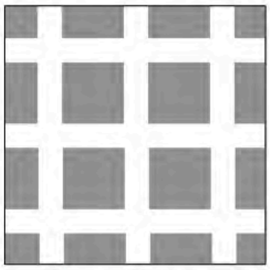
SIMPLIFICATIONS OF FRACTURE SYSTEMS



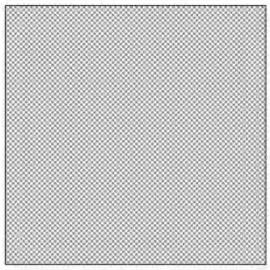
Natural fractured porous medium



Non-homogeneous



Dual porosity



Equivalent continuum

RANDOM DENSEST PACKING SIMULATIONS

True porosity is the porosity of randomly packed material in a container where the container's walls do not influence the porosity and which is inversely proportional to the size of the container. These simulations mostly use spherical beads and eventually aim to simulate increasing container size to lower the influence of the container walls on the estimation. Note the increased porosity adjacent to the container walls, as well as the random densest packing of uniform spheres (left).

READ MORE & CITED FROM: Dippenaar 2014; Giménez et al. 1997; Furukawa et al. 2000; Hilfer 2000; Samardzioska and Popov 2005; Straughan 2010; Vita 2011

6.2.2. Changing porosity of problem and pedogenic soils

Porosity is not always constant and may change over time, either permanently or temporarily, and either gradually or suddenly. The causes for this change in porosity (or the related parameter void ratio) can be natural or induced (anthropogenic) and will influence the hydrological behaviour of the materials.

Movement associated with problem soils (broadly and informally termed to imply any soil with required engineering mitigation measures prior to construction) are typically in the vertical direction and result in a volume increase or decrease. Such soils are for the sake of this study grouped under the direction of movement, being (1) swelling/ shrinking, (2) settlement or (3) differential movements associated with these, and are discussed in Box 23 and Box 24.

The influence of ferricrete (ferrous pedocrete) as identified at VZSA1 is shown in Figure 6-2. Cementation may – at different stages of pedocrete behaviour – result in either more or lesser porous horizons.

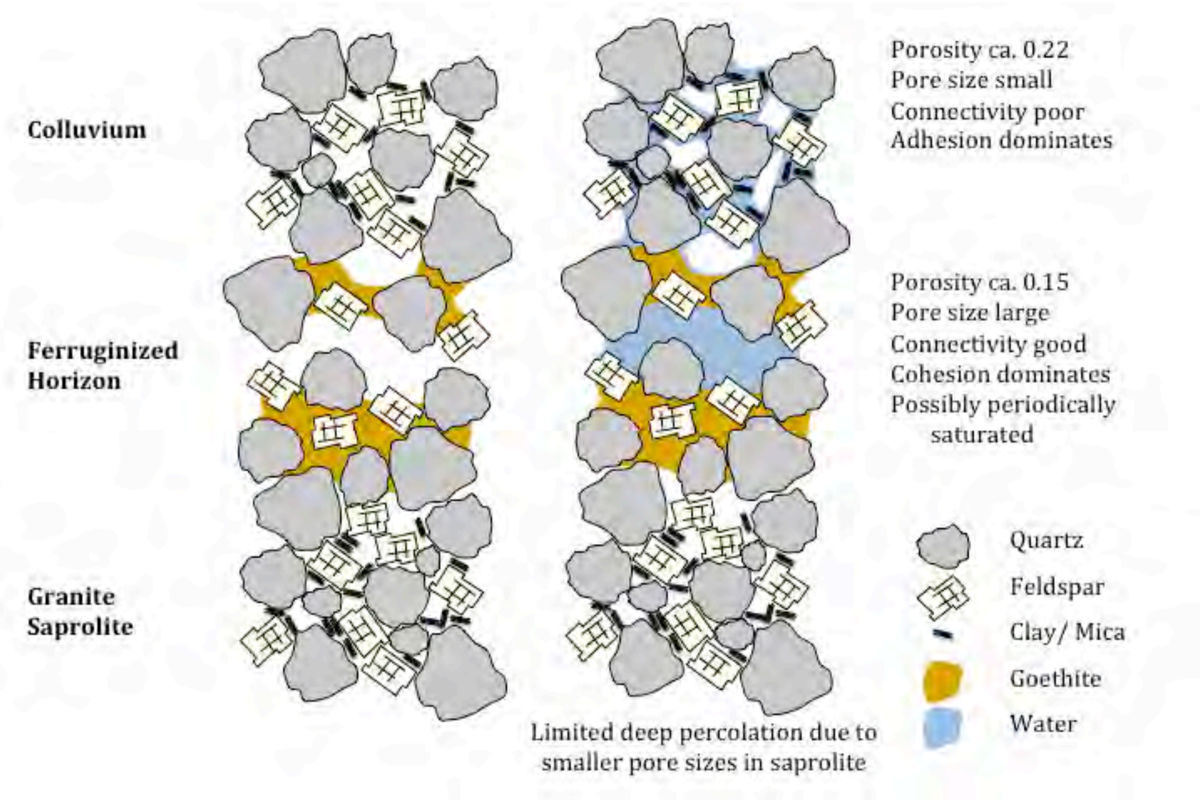


Figure 6-2. **Inferred dry and near-saturated conditions for the typical ferruginized granitic soil profile at VZSA1.**

Box 23. Problem Soils.

BOX 23: PROBLEM SOILS

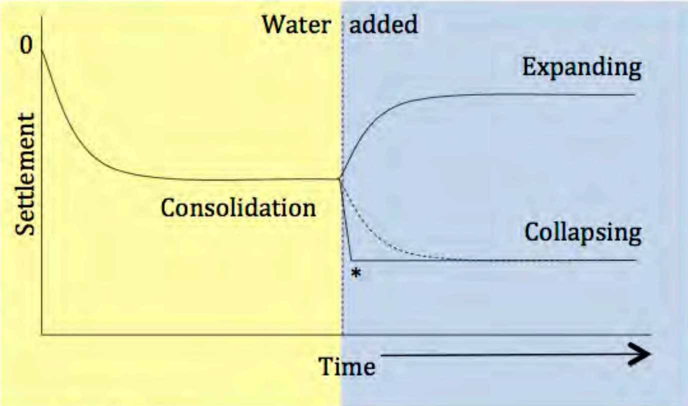
Changing moisture conditions, together with changes in applied load at surface, may induce surface movement. This affects infrastructure, resulting in, for instance, subsidence of structures, cracking of foundations and structures and water entering excavations and foundations. Typical problem soil behaviour includes:

EXPANSIVE SOILS:

- These are fine-grained soils depicting specific clay mineralogy which results in changes in volume due to changes in moisture content, resulting in heaving or swelling on wetting (increase in volume) or shrinkage due to drying (decrease in volume).
- The behaviour is quantified by the heave or shrinkage, referring to the anticipated surface movement in an expansive soil horizon due to periodical changes in moisture content.

SETTLEMENT AND VOLUME DECREASE:

- Settlement refers to the downward vertical movement of a structure following distribution and redistribution of stresses and loads on the soil.
- Collapsible soils are soils with collapsible soil structure, evident from open texture with a low density, that will settle suddenly or rapidly following a combination of increase in applied load and soil moisture content.
- Compressible soils are those experiencing gradual settlement due to volume decrease following an increase in applied load.
- Subsidence relates to the vertical downward movement of a structure's foundation due to loss of support beneath its foundation.



DIFFERENTIAL MOVEMENT (applying to both settlement and heave) refers to soil which result in non-uniform vertical displacement due to uneven settlement or heave below different portions of a structure.

Clay mineralogy influences its ability to heave (expand) and shrink, requiring a 2:1 clay mineral. Consolidation or compaction is a readjustment of soil particles into a denser state, whereas collapse is a sudden further reduction due to loss of cohesion between sand grains.

Engineering Geological Investigations rate different portions of a site in terms of its likelihood to heave, settlement, collapse or other geological concerns. These so-called H, S and C classes are a requirement prior to township development and have to be addressed for each new application. Recommended foundation options are supplied for these classes and is based on the anticipated movement.

In terms of vadose zone hydrology, the implication of varying porosity are obvious. Permanent or temporary changes in porosity will inevitably change the hydraulic conductivity of the subsurface materials. Especially in area being developed, it becomes increasingly important to envisage the future porosity of the materials for proper mitigation against water damage.

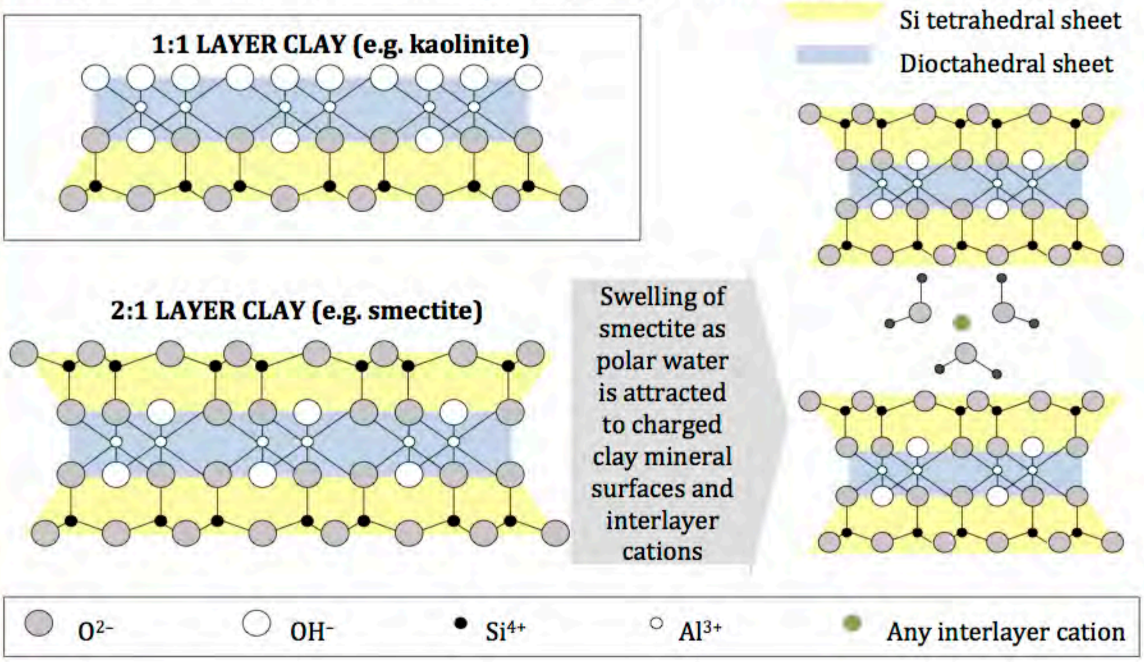
READ MORE & CITED FROM: Das 2008; Knappett and Craig 2012; Mathewson 1981; National Department of Housing 2002; SANS 634:2009

Box 24. Mechanisms of Heave, Consolidation and Collapse.

BOX 24: MECHANISMS OF HEAVE, CONSOLIDATION AND COLLAPSE

CLAY MINERALOGY AND HEAVING

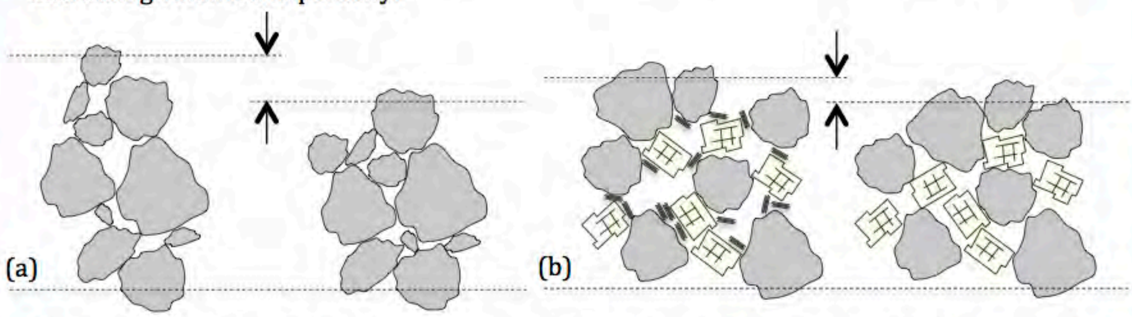
2:1 layer clays are prone to expansion on wetting and shrinkage on drying. This results in lower porosity as volume increases, or increased porosity, likely as dessication cracking, on drying.



SETTLEMENT OF NON-EXPANSIVE SOILS

(a) Consolidation settlement is a gradual process resulting from the soil grains readjusting into denser packing. This typically happens due to overburden pressure, loading or draining of soil moisture and results in a decrease in volume and porosity.

(b) Collapse settlement, on the other hand, entails the further densification of an open-structured soil as cohesive fines are washed out. These clay bridges maintained the open structured, but on loading and wetting, are washed out and the soil grains readjust into a dense packing, thereby decreasing volume and porosity.



Both these mechanisms result in a permanent volume change with the notable difference being the mechanism (densification or removal of clay bridges) and the rate of the readjustment.

READ MORE & CITED FROM:

Das 2008; Knappett and Craig 2012; Mathewson 1981; Schaetzl and Anderson 2005

6.2.3. Considerations with respect to porosity

Porosity is more than merely the ratio of voids to total volume. Numerous aspects influence porosity and the ability of water to move through such pores. Some important influences are shown for a granitic (quartz, feldspar and mica or clay, the latter due to feldspar weathering) soil medium in Figure 6-3, viz.:

a) Cubic packing of fairly uniform near-spherical grains
b) Tetrahedral or rhombohedral packing of fairly uniform near-spherical grains
c) Random packing of fairly uniform grains of variable shape
d) Cubic packing of fairly uniform near-spherical grains of finer texture
e) Elongated grains
f) Elongated clay platelets or micas
g) Coarse quartz and finer feldspar in a randomly packed mixed texture material
h) Varying grain size, grain shape and random densest packing
i) Clogging of pores by precipitates or fines
j) Open collapsible structure due to leaching of fines
k) Open structure due to animal burrows or plant roots.

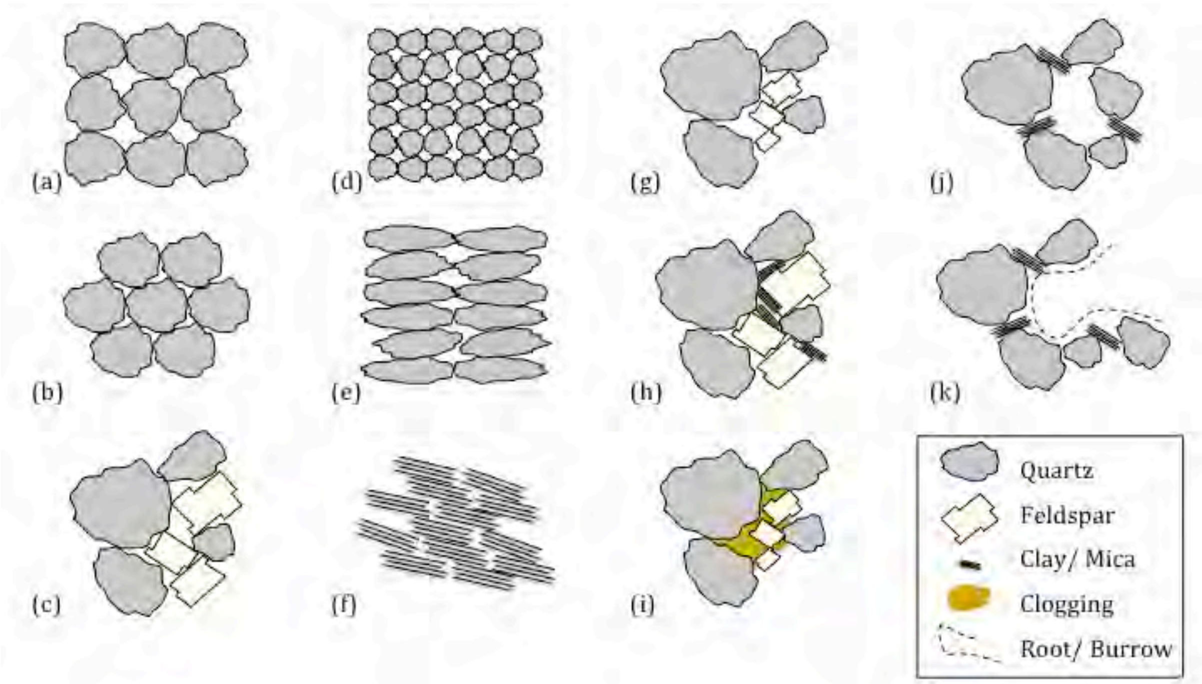


Figure 6-3. **Porosity influenced by (a) cubic, (b) rhombohedral/ tetrahedral and (c) random packing; influence of grain shape ((d)-(f)), variable grain size ((g)-(h)), clogging structures (i) and large open voids due to (j) leaching or (k) plant roots or animal burrows.**

Porosity is governed by the packing and distribution of different sized and shaped soil particles. From a simple packing of uniform spherical particles where porosity is solely a function of the packing, porosity can vary significantly as soil texture becomes more variable (comprising clay, silt, sand and gravel) and pore spaces become clogged with finer particles.

Additionally, porosity is not the only consideration. The sizes of the pore spaces and throats contribute to the hydraulic conductivity of the material and the likelihood of flow occurring at lower moisture contents, as well as the processes of imbibition and drainage. The pore sizes, as opposed to the porosity per se, are a function of the particle size distribution.

The connectivity of pore spaces results in the effective porosity and specific yield. Good connectivity (both in continuity and throat diameters) is required to allow movement of water.

6.2.4. Bias in the quantification of porosity

As with most other parameters, quantification of porosity is easily influenced by the human error and the heterogeneity and anisotropy of earth materials. Laboratory porosity or bulk density determination is dependent on retrieval of an intact and representative sample, which can be removed with a fair amount of ease. In unconsolidated, uncemented or non-cohesive materials, this becomes difficult and selective sampling of limited intact samples, which are not too dense for easy removal, will inevitably supply biased results.

The incorporation of mineral densities is believed to increase the accuracy of the porosity estimates as it incorporates the particle size distribution and the individual mineral densities. However, as the bulk dry density is required, the same problems as noted above apply. It is furthermore exacerbated by the same bias where readily removable materials (e.g. loose quartz sand; soft clay) are more likely to be sampled than those requiring excavation effort (e.g. hardpan ferricrete; rock fragments; very stiff dry clays).

6.2.5. Advances in the quantification of porosity

Proper quantification and understanding of porosity with respect to the vadose zone require specific considerations as shown in Figure 6-4. Although a significant oversimplification of the complexity of porosity, incorporation of all these aspects will improve hydrological interpretation.

Specific issues pertaining to the quantification of porosity have been identified and include (Dippenaar 2014):

- Changing porosity from consolidation (permanent) and shrinkage-heave (temporally variable)
- Fracture porosity and the influence of spacing, directions, apertures, weathering, precipitation and continuity
- Leaching processes changing porosity over time.

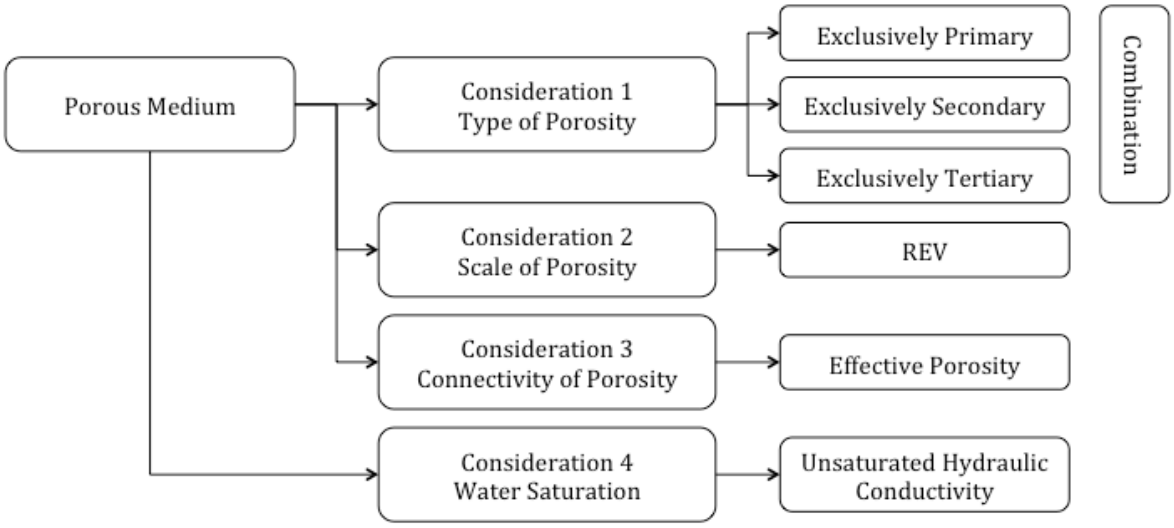


Figure 6-4. Evaluation of porosity in a porous medium for application in vadose zone hydrological studies (Dippenaar 2014).

6.3. Grading-based Empirical Hydraulic Conductivity Estimation

The basic principles of the empirical grading-based hydraulic conductivity estimates, a comparison of the parameters for some of the methods, and their ranges of application are supplied in Box 25. The hydraulic conductivity is estimated by multiplying the constant relationship with the porosity function and the effective grain size function, and the units are in accordance with the input parameters. Evaluation of such methods is well published in, for instance, Cheong et al. (2008) and Odong (2008).

6.3.1. Development of empirical approaches

Estimating hydraulic conductivity from soil particle size distribution is typically based on the effective grain size diameter (d_e often assumed to be d_{10}), the uniformity coefficient (C_U) and the porosity (η). Hazen (1911; 1930) proposed an empirical relationship for fairly uniform sand (C_U < 5), where c is a constant value between 1.0 and 1.5 as shown in Equation 41 and a second temperature-dependent variation in Equation 42.

$$K\left(\frac{cm}{s}\right) = c \cdot d_{10}(\text{mm})$$ **Equation 41**

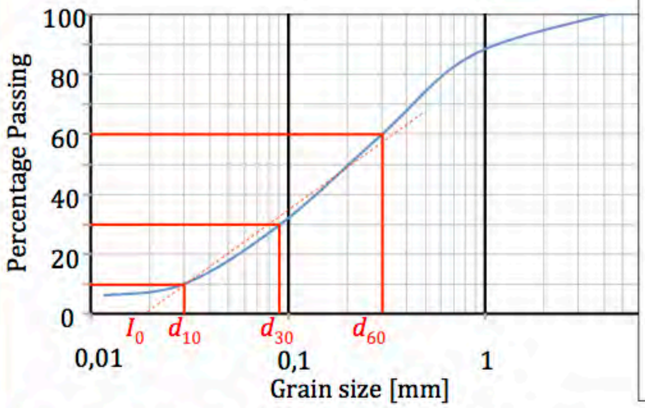
$$K = \left(4.6{\times}10^{-3} + 4.6{\times}10^{-2}(\eta - 1)\right)(0.70 + 0.03 \cdot T)d_{10}^2$$ **Equation 42**

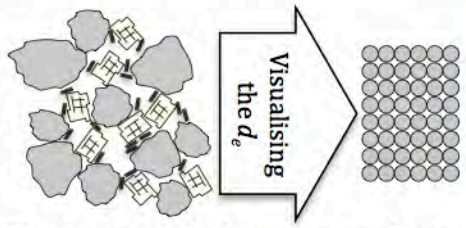
A theoretical solution was proposed by Kozeny and Carman, the derivation of which is taken from Das (2008). The Hagen-Poiseuille equation can be adjusted to incorporate the hydraulic radius r_H, calculable as the ratio of area to wetted perimeter ($\pi r^2/2\ \pi r = r/2$) as shown in Equation 43 or for two parallel plates as shown in Equation 44.

Box 25. Empirical Hydraulic Conductivity Estimation.

BOX 25: EMPIRICAL HYDRAULIC CONDUCTIVITY ESTIMATION

The effective grain size diameter is selected as the upper limit of a given fraction of material which, when the material is composed of uniform spherical grains, the diameter of those grains equal the effective grain size diameter d_e and the hydraulic conductivity is comparable to the natural non-uniform material. Most sources take this value of d_e as d_{10}; i.e. the particle size correlating to the upper limit of 10% on the cumulative particle size distribution plot. This value is determined as shown below and has the units of length.





The dimensionally homogeneous form comprises:

$$K = \underbrace{C}_{\text{constant function}} \cdot \underbrace{f(\eta)}_{\text{porosity function}} \cdot \underbrace{f(d_e)}_{\text{effective grain size function}}$$

Numerous methods exist, mostly based on limited experimental results and within very specific limits of applicability. Some of these methods, reformulated to the dimensionally homogeneous form and indicating ranges of applicability in terms of C_U, d_e and texture, include the following (where K is estimated by multiplying C, $f(\eta)$ and $f(d_e)$):

Approach	C	$f(\eta)$	$f(d_e)$	C_U	d_e	Texture
Hazen	$(g / v)\ (0.0006)$	$(1 + 10\ (\eta - 0.26))$	d_{10}^2	< 5	0.1 – 3	Clean, coarse-grained
Kozeny-Carman	$(g / v)\ (0.0083)$	$\frac{(\eta^3)}{(1+\eta)^2}$	d_{10}^2			Coarse-grained
Amer & Awad	$(0.0093)\ (C_U)^{0.6}$	$\frac{(\eta^3)}{(1+\eta)^2}$	$d_{10}^{2.32}$	1 – 21	0.137 – 0.548	
Shababi, et al.	$(1.2)\ (C_U)^{0.735}$	$\frac{(\eta^3)}{(1+\eta)^2}$	$d_{10}^{0.89}$			Medium to fine sand
Kenney et al.	$(g / v)\ 0.05$	1	d_5^2	1.04 – 12		Grains 0.074 – 25.4 mm
Slichter	0.1012	$\eta^{3.287}$	d_{10}^2			
Beyer	$(0.0045)\ \log(500/C_U)$	1	d_{10}^2	1 – 20	0.06 – 0.6	
USBR	0.0036	1	d_{20}^2			
Terzaghi	$(g / v)\ 0.0009$	$\frac{(\eta - 0.13)}{(1-\eta)^{0.35}}$	d_{10}^2			Coarse sand

READ MORE & CITED FROM:

Amer and Awad 1974; Carrier 2003; Das 2008; Fitts 2002; Hazen 1911;Kenney et al. 1984; Odong 2002; Shababi et al. 1984; Van Schalkwyk and Vermaak 2000; Vukovic and Soro 1992

$$Q(r) = \frac{1}{2}\frac{\gamma_W S}{\mu_W} r_H^2 a$$ **Equation 43**

$$Q(r) = \frac{1}{3}\frac{\gamma_W S}{\mu_W} r_H^2 a$$ **Equation 44**

Through simplifying above equations for the shape factor C_S (≈ 2.5 for granular soils), tortuosity factor T (≈ $2^{0.5}$) and microscopic hydraulic gradients S, the Kozeny-Carman function as applicable to coarse-grained soils is a function of the void ratio or porosity as per Equation 45 (Das 2008). An alternative derivation as a function of a shape factor (SF = 6.0 for spherical; 6.1 for rounded; 6.4 for worn; 7.4 for sharp; and 7.7 for angular (Fair and Hatch 1933) or SF = 6.6 for rounded; 7.5 for medium angularity; and 8.4 for angular (Loudon 1952) and the effective grain size as determined as the fraction fi between sieve sizes $d_{i(min)}$ and $d_{i(max)}$ (Equation 46) (Carrier 2003).

$$K = \frac{1}{C_S S_S^2 T^2}\frac{e^3}{(1+e)}$$ **Equation 45**

$$K = 1.99\times10^{-4}\cdot\left(\frac{100\%}{\Sigma\left(\frac{f_i}{d_{i(max)}^{0.404} - d_{i(min)}^{0.595}}\right)}\right)^2\cdot\left(\frac{1}{SF}\right)^2\cdot\frac{e^3}{(1+e)}$$ **Equation 46**

6.3.2. Standardisation to dimensionally homogenous form

Empirical methods based on soil grading are generalized to a dimensional homogeneous form for easier application. This, adapted from Vuković and Soro (1992), is a function of (Equation 47):

- g / ν = gravitational acceleration / kinematic viscosity; $\nu = \mu / \rho$ (dynamic viscosity / density)
- C = sorting coefficient
- $f(\eta)$ = porosity function
- d_e = effective grain diameter.

$$K = \frac{g}{\nu}\cdot C\cdot f(\eta)\cdot f(d_e) = \frac{\rho g}{\mu}\cdot C\cdot f(\eta)\cdot f(d_e)$$ **Equation 47**

Hazen's relationship between hydraulic conductivity and the effective grain size diameter is shown in the generalised format in Equation 48.

$$K = \frac{g}{\nu}\cdot(6\times10^{-4})\cdot[1+10(\eta-0.26)]\cdot d_{10}^2$$ **Equation 48**

The Kozeny-Carman equation was transposed to this more convenient standardisation of grading-based conductivity relationships as shown in Equation 49 (e.g. Vuković and Soro 1992; Odong 2007).

$$K = \frac{g}{\nu} \cdot (8.3 \times 10^{-3}) \cdot \left[\frac{\eta^3}{(1-\eta)^2} \right] \cdot d_{10}^2$$ **Equation 49**

With respect to the Kozeny relationship (Vuković and Soro 1992), calculation of the effective grain size can also be calculated from grain size distribution results rather than the d_{10} assumption. Fitts (2002) depict the standardised form of the Kozeny-Carman equation with respect to the d_{50}-value (Equation 50).

$$K = \frac{g}{\nu} \cdot \left[\frac{\eta^3}{(1-\eta)^2} \right] \frac{\cdot d_{50}^2}{180 -}$$ **Equation 50**

Terzaghi's formula (1925 in Das 2008) applies to coarse-grained sands and is shown in the dimensionally homogenous form in Equation 51. C_T varies based on grain shape between 1.07 x 10^{-4} for smooth grains to 6.1 x 10^{-3} for coarse grains.

$$K = \frac{g}{\nu} \cdot (C_T) \cdot \left[\frac{\eta - 0.13}{\sqrt[3]{1-\eta}} \right]^2 \cdot d_{10}^2$$ **Equation 51**

Amer and Awad (1974; also Das 2008) applied these relations during experimental validation and reach a relationship as a function of a constant C_1 as shown in Equation 52 with the constant assumed to be 0.0093 and with effective application where $0.137 < d_{10} < 0.548$ and $1 < C_U < 21$. The ratio of gravitation acceleration to kinematic viscosity is included in the constant value term.

$$K = C_1 . d_{10}^{2.32} \cdot C_U^{0.6 \cdot} \frac{e^3}{(1+e)}$$

Equation 52

$$K = (9.3 \times 10^{-3} \cdot C_U^{0.6}) \cdot \left[\frac{\eta^3}{(1+\eta)^2} \right] \cdot d_{10}^{2.32}$$

A subsequent relationship by Shababi et al. (1984) is also written as a function of the uniformity coefficient and is effective for medium to fine sand samples (Equation 53).

$$K = \left(1.2 \cdot C_U^{0.735}\right) \cdot \left[\frac{\eta^3}{(1+\eta)^2} \right] \cdot d_{10}^{0.89}$$ **Equation 53**

Where the soil material comprises coarse grains of 0.074-25.4 mm diameter and $1.04 < C_U < 12$, the hydraulic conductivity is estimated based on the d_5-value only according to Kenney et al. (1984, in Das 2008; Van Schalkwyk and Vermaak 2000) (Equation 54).

$$k = 0.05 \cdot d_5^2$$

Equation 54

$$K = \frac{g}{\nu} (0.05) \cdot d_5^2$$

Slichter (Vuković and Soro 1992) uses the d_{10}-value and has different porosity functions for different porosity values. With an error of approximately 5%, K can be estimated based on Equation 55.

$$K = 0.1012 \cdot \eta^{3.287} \cdot d_{10}^2$$ **Equation 55**

Beyer (Vuković and Soro 1992) incorporates the uniformity coefficient and the d_{10}-value and is independent on porosity with applicability where $0.06 < d_{10} < 0.6$ and $1 < C_U < 20$ (Equation 56).

$$K = (4.5 \cdot 10^{-3}) \cdot log\left(\frac{500}{C_U}\right) \cdot d_{10}^2$$ **Equation 56**

Vuković and Soro (1992) also address the USBR equation, employing the d_{20}-value, water temperature of 15° C and ignoring porosity as per Equation 57.

$$K = 0.0036 \cdot d_{20}^{2.30}$$ **Equation 57**

6.4. Efficacy of Empirical Porosity and Hydraulic Conductivity Estimates

Data from VZSA 1 (ephemeral hillslope wetland on Lanseria Gneiss, §11) are shown in Figure 6-5, superimposed on the ranges of applicability of the respective empirical methods for hydraulic conductivity estimation. As most methods require fairly uniform materials predominantly of sand fraction, bulk of the methods is not applicable to the materials analysed. The resulting hydraulic conductivities are, therefore, also not considered representative and empirical methods fail when applied to non-uniform materials of varying grain sizes.

The same data, for five empirical approaches and field percolation tests, are shown in Table 6-1 and Figure 6-6. Note the range of values per method over orders of magnitude, in comparison to field percolation tests showing little variation. This can be ascribed to the reliability of the empirical approaches on a single grain size diameter (d_{10}) and uniform materials, whereas field methods include for site conditions.

Table 6-1. Correlation between empirical K-values and field percolation tests (m/s) (VZSA1).

Approach	Beyer	USBR	Kozeny	Shababi	Slichter	Percolation
Arith. Mean	2.10E-02	1.20E-02	9.00E-05	6.10E-05	4.00E-05	1.17E-04
Minimum	8.00E-08	8.40E-10	2.00E-09	2.30E-06	9.40E-10	1.55E-05
Maximum	4.30E-01	3.60E-01	1.50E-03	3.60E-04	6.80E-04	2.56E-04

Table 6-2 shows the porosities by soil horizon as calculated using Istomina's approach and density relationships (using published mineral densities from Deer et al. 1996) for VP01-VP07. Seven empirical methods are also indicated, comparing the calculated hydraulic conductivities for all materials using the two different porosity calculations.

Both Istomina's relationship as a function of the uniformity coefficient and the density relationships were applied to evaluate the different methods. The exact same soil samples were used for the calculations to ensure correlation between results. Incorporation of mineral density yielded more variable results which closer resemble the field descriptions of the materials. Most porosity values calculated through Istomina's method average around 0.26 with little variation between different soil horizons.

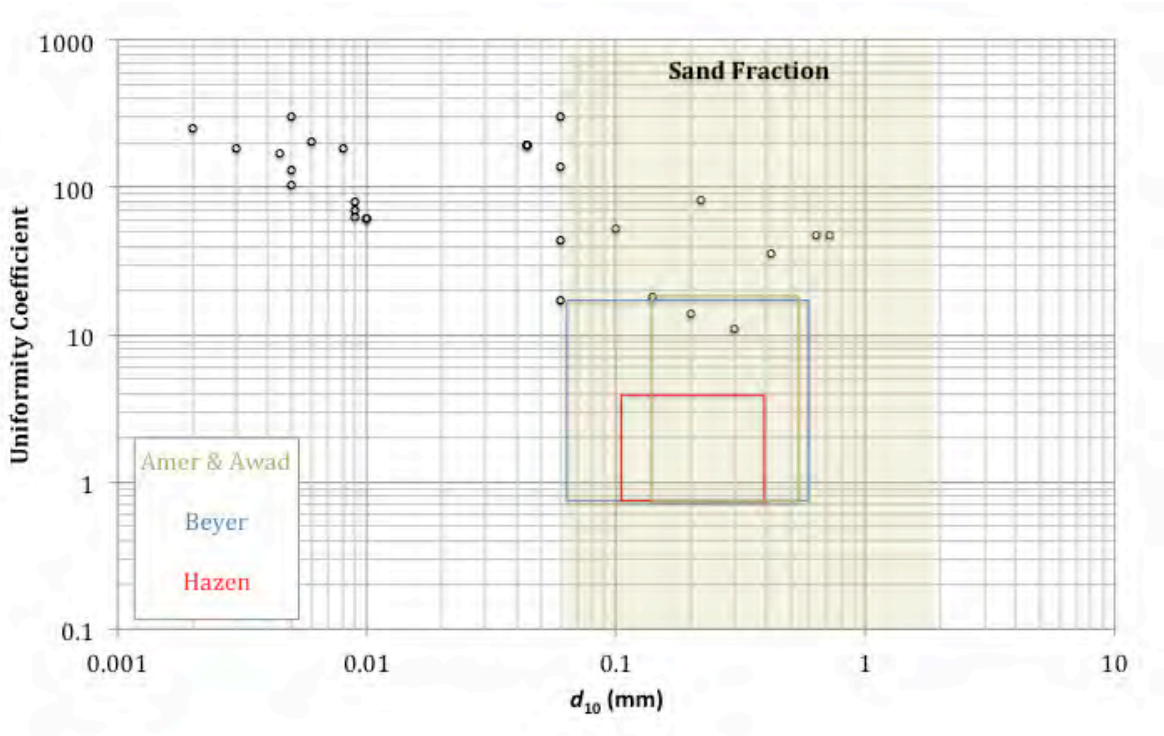


Figure 6-5. **Ranges of applicability of empirical methods and data (VZSA1).**

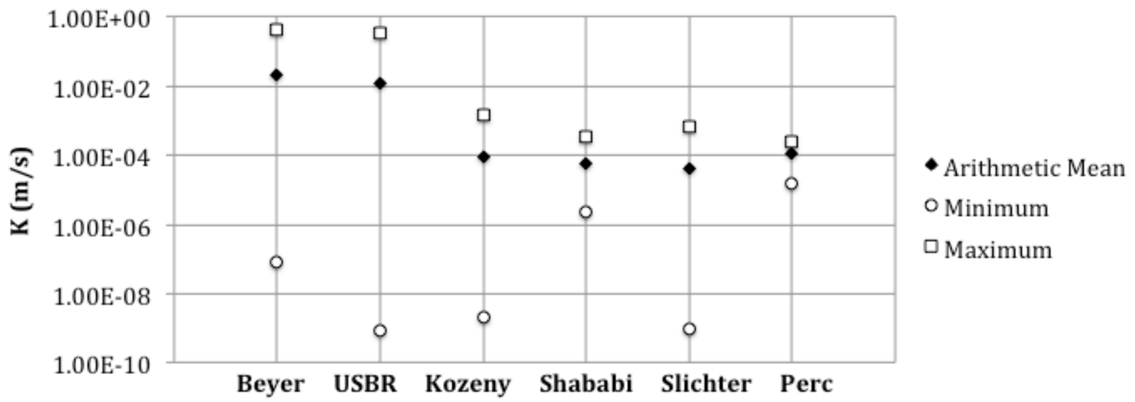


Figure 6-6. **Correlation between results of empirical estimates (Beyer, USBR, Kozeny-Carman, Shababi et al. and Slichter using density-relation porosity) and field percolation testing (Perc) to estimate hydraulic conductivity (VZSA1).**

Table 6-2. Calculated porosities and K-values summarized based on porosity function (VZSA1).

Horizon	Istomina's Approximation			Density Relationships		
Porosity (-/-)	**Arithmetic Mean**	**Std Dev**	**n**	**Arithmetic Mean**	**Std Dev**	**n**
Colluvium	0.26	0.00	3	0.22	0.04	3
Ferruginized Horizons	0.26	0.00	3	0.15	0.05	3
Residual Granite	0.26	0.00	8	0.23	0.08	8
Completely Weathered Granite	0.26	0.00	3	0.15	0.06	3
Fractured Granite	0.27	0.01	5	0.15	0.02	5
Hydraulic Conductivity (m/s)	**Arithmetic Mean**	**Std Dev**	**n**	**Arithmetic Mean**	**Std Dev**	**n**
Amer & Awad	3.55E-12	1.13E-11	22	3.71E-12	1.10E-11	32
Beyer	3.09E-03	7.94E-03	32	3.09E-03	7.94E-03	32
Hazen	1.19E-04	6.89E-04	27	2.81E-04	7.28E-04	32
Kozeny	8.58E-05	2.92E-04	27	1.24E-04	3.18E-04	32
Shababi et al	5.95E-05	9.25E-05	23	6.93E-05	8.57E-05	32
Slichter	3.84E-05	1.31E-04	27	5.59E-05	1.43E-04	32
Terzaghi	3.69E-05	1.44E-04	27	6.11E-05	1.59E-04	32
USBR	1.67E-03	6.67E-03	40	1.67E-03	6.67E-03	40

Regarding the porosity, it is important to note that the colluvium and residuum have higher porosity (0.22-0.23), whereas the ferricrete in-between and the granite saprolite (residual, weathered and fractured) have lower porosity. The colluvial materials were described as pinholed, suggested an open structure. However, the ferricrete shows large connected void spaces rather than homogenously and isotropically distributed pores. This meso- to macroporosity in the ferricrete results in cohesion rather than adhesion and water is allowed to move. In the microporosity in the colluvium and residual, this process may be controlled by adhesion and imbibition rather than free flow until certain moisture contents are exceeded.

Hydraulic conductivities estimated based on empirical approaches are shown in Figure 6-7 and are based on the data summarised in Table 6-2. Of the numerous methods employed, only the depicted eight supplied results falling within the reasonable scale. Excluded methods yielded zero values, negative values or Excel™ errors due to, for instance, zero-value denominators. The Amer & Awad approach were also excluded as it supplied estimates in the 10^{-12} m/s range which fall completely outside of the reasonable average values as depicted for the remaining seven methods. Little variation exists in hydraulic conductivities calculated using these empirical approaches when varying only the two porosity functions. Density relationships generally showed marginally lower K-values, although always still well within the same order of magnitude.

Density-relationships were used in further calculations and comparisons, under the reasonable assumption that it is based on actual data and, therefore, represent the site materials better. Although the empirical methods are obviously fairly insensitive to the highly variable porosities, yielding fairly similar hydraulic conductivity values, the density-relationships better account for the available porosity which can contribute to the understanding of the system well beyond its use in empirical approximations.

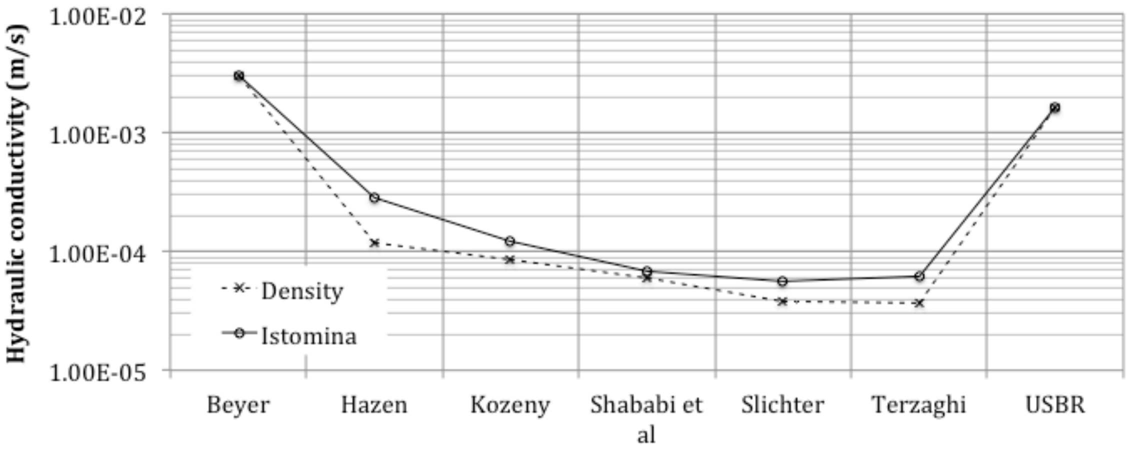


Figure 6-7. **Correlation between empirical hydraulic conductivity estimates calculated by means of density-relation and Istomina porosities (VZSA1).**

For uniform material, such as the crushed tailings from VZSA2 (§12), empirical approaches are more applicable given the fairly uniform grain size of the tailings material. Laboratory permeability testing yielded an average hydraulic conductivity of 4.0 x 10^{-9} m/s. Tailings material was consolidated under hydrodynamic compaction and is assumed to mimic natural conditions. The porosity was assumed to be 0.22 and the material was initially assumed homogeneous (C_U = 1) as the tailings are crushed to 86 µm. This, however, made estimation of the d_e-values difficult, seeing that only the mean grain size (d_{50}) is available, and as different methods employ the d_5, d_{10} or d_{20} grain sizes. For comparative purposes, hydraulic conductivities were calculated using the mean grain size as equal to the d_e as this will be the case in completely uniform materials. To incorporate for possible deviations in grading, a second calculation assumed d_e = 10% d_{50}, regardless of whether the 5%, 10% or 20% cumulative grain size was used. This latter approach resulted in K-values approximately two orders of magnitude smaller and closer to the laboratory value of 4 x 10^{-9} m/s (Table 6-3).

Table 6-3. **Correlation between empirical K-values for uniform tailings material using the mean grain size diameter (d_{50}) and 10% of d_{50} (VZSA2).**

Approach	d_e = 0.086 mm = d_{50}	d_e = 0.0086 mm = 0.1d_{50}
Amer & Awad	4.0E-13	1.3E-15
Beyer	3.3E-04	4.8E-06
Hazen	2.9E-05	2.9E-07
Kenney, Lau & Ofoegbu	4.1E-03	4.1E-05
Kozeny	1.2E-05	1.2E-07
Shababi, Das & Tarquin	6.3E-05	4.9E-06
Slichter	5.6E-06	5.6E-08
Terzaghi	7.2E-06	7.2E-08
USBR	2.4E-06	1.2E-08

Empirical methods prove useful as a quick estimate. However, the following should be duly noted prior to using the estimated values:

- Material should comply with the recommended ranges of applicability as defined by the respective methods (Box 25).
- Empirical estimates are almost always higher than laboratory or field values. Depending on the efficacy of the relevant method, the estimated value may be orders of magnitude higher than laboratory or field values with no true indication of the degree of error. These estimates should, therefore, be considered too high.
- Given the cost and effort of grading analyses, simple field tests or laboratory permeability tests are considered to be significantly more reliable and the overuse of empirical estimations should be avoided, wherever possible.
- The relationship between porosity and an effective grain size diameter makes sense. The problem is not in the concept or in the relationship experimentally derived by the respective authors, but rather in the extrapolation of the methods to scenarios where they should no longer be relevant.
- The use of calculated porosities rather than estimated porosities (e.g. based on packing only, or according to methods such as Istomina) appear to yield more reliable results.

6.5. Laboratory Permeability Methods

Hydraulic conductivity can be determined in the laboratory by means of constant-head tests, falling-head tests and indirectly from consolidation tests. The determined K represents the hydraulic conductivity parallel to the sample axis as calculated by inducing flow through a saturated sample and solving for K according to Darcy's Law. In all instances, the soil specimen is confined between two porous plates, essentially to maintain the structure and compaction in the column (Box 26).

In the constant-head test, the volume water collected V after time t is used to calculate the hydraulic conductivity as a function of the length of the sample L, difference in head over the test sample h, cross-sectional area of the sample A, and the time t required to collect the water volume V as shown in Equation 58 (Das 2008).

$$V = Q \cdot t = K \cdot \frac{h}{L} \cdot A \cdot t$$

$$K = \frac{V \cdot L}{t \cdot h \cdot A} = \frac{Q \cdot L}{h \cdot A}$$

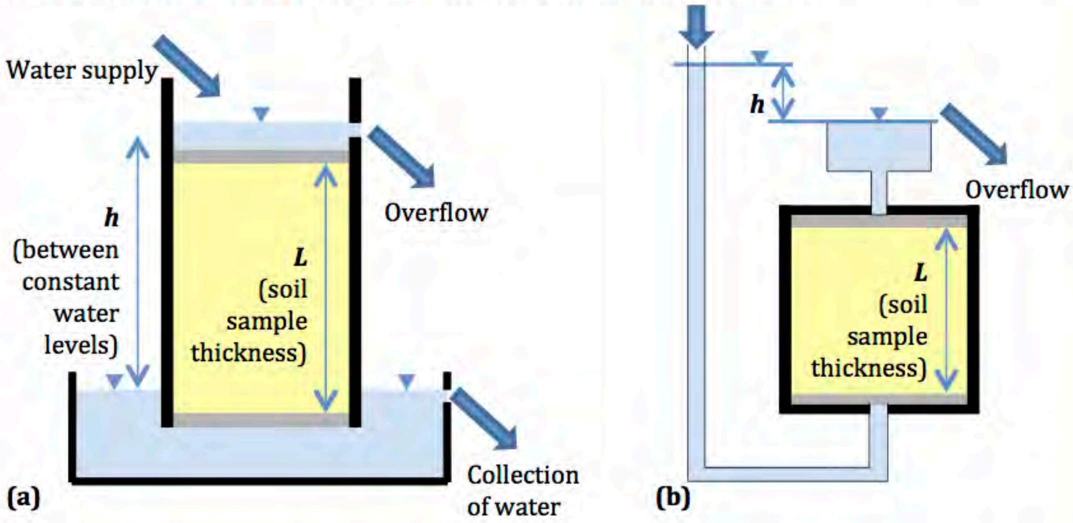
Equation 58

In the falling-head test, the hydraulic conductivity is calculable as a function of the cross-sectional areas of the stand-pipe a and soil sample A, length of the specimen L, and head difference (between h_2 and h_1) at any time t as shown in Equation 59 (Das 2008; Fitts 2002).

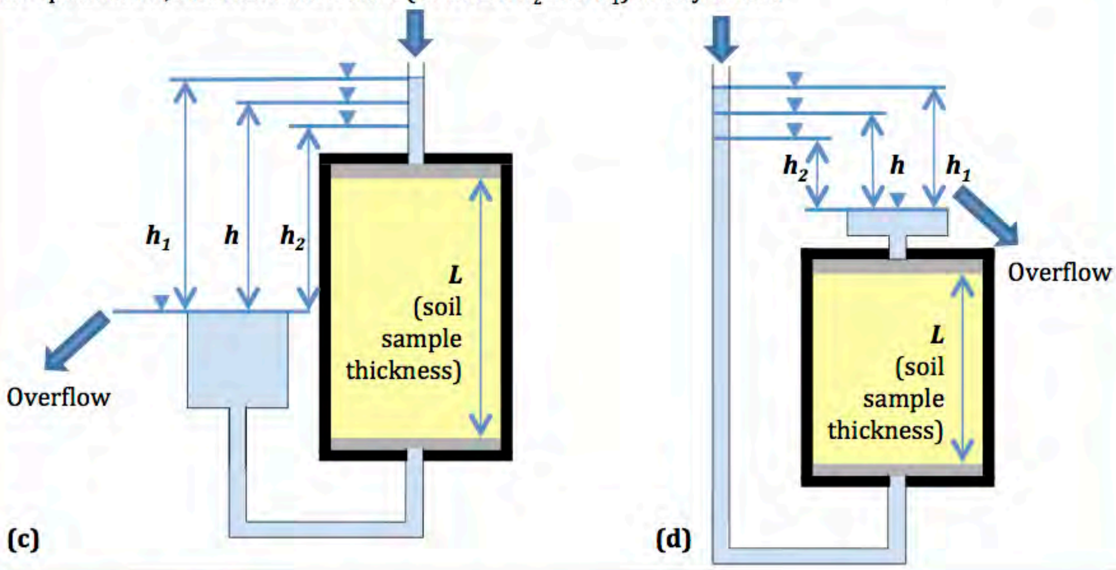
Box 26. Constant-head and Falling-head Permeability Tests.

BOX 26: CONSTANT-HEAD AND FALLING-HEAD PERMEABILITY TESTS

The **CONSTANT HEAD PERMEABILITY TEST** is used for higher permeability granular materials and entails a cylindrical mould containing the soil sample. The water flow through the sample is controlled by adjusting the supply and maintaining a constant head difference between the supply and outflow. The volume water collected V after time t is used to calculate the hydraulic conductivity as a function of the length of the sample L, difference in head over the test sample h, cross-sectional area of the sample A, and the time t required to collect the water volume V.



The **FALLING HEAD PERMEABILITY TEST** – more suitable for fine-grained soils – comprises the sample inside a tube with a standpipe attached to the top of the specimen supplying water to the sample. The initial head difference h_1 is measured for time t = zero and water is allowed to flow through the sample until a final head difference h_2 at time $t = t$. The hydraulic conductivity is then calculable as a function of the cross-sectional areas of the stand-pipe a and soil sample A, length of the specimen L, and head difference (between h_2 and h_1) at any time t.



READ MORE & CITED FROM: Das 2008; Fitts 2002; Knappett and Craig 2012

$$Q = K \cdot \frac{h}{L} \cdot A = -a \cdot \frac{dh}{dt}$$

$$\int_0^t dt = \int_{h1}^{h2} \frac{a \cdot L}{A \cdot K}$$ **Equation 59**

$$K = \frac{a}{A} \cdot \frac{L}{(t_1 - t_0)} ln\left(\frac{h_1}{h_2}\right) = 2.303 \cdot \frac{a \cdot L}{A \cdot dt} \cdot log\left(\frac{h_1}{h_2}\right)$$

6.6. Geotechnical/ Civil Engineering Centrifuge Modelling

A centrifuge essentially comprises a loading frame for testing of soil samples. Modelling is based on replicating an event which can be compared to what might happen and the model is often a scaled version. Scaling laws therefore become increasingly important, as well as replication of true conditions such as stratification and stresses. Rotation accelerates Earth's gravity so that a model which is subjected to an inertial field *N* times *g* will depict a vertical stress at depth h_m equal to that in the prototype according to $h_p = Nh_m$. Some such scale effects addressed in particular include (Taylor 1996):

- Particle size is not scaled *N* times, which results in lower allowed acceleration as scaling of particle sizes will react differently to stresses and moisture. A critical ratio exists between average grain diameter and model dimensions.
- Inertial radial acceleration (proportional to the radius of rotation) results in varying depth in the model with direction towards the centre. A lateral acceleration has to be compared with the vertical acceleration and the Coriolis acceleration needs to be addressed.

When considering seepage in a geotechnical centrifuge, some issues persist, notably the interpretation of the hydraulic gradient and the validity of hydraulic conductivity when accelerated at rates exceeding gravitational acceleration. This implies that *K* also require to be scaled *N*-times, or alternatively that *K* is accepted as a constant value, but that the hydraulic gradient *i* is scaled *N*-times as a zero gravitational field will yield no flow despite the presence of a gradient, as gravity is the main accelerating force (Taylor 1996).

Some important considerations are discussed by Phillips (1996) and include:

- Containers should be longer with respect to the depth to minimise boundary effects
- The effective stress profile (Box 33) will govern the model's behaviour
- Artificial materials, pluviated samples or undisturbed samples can be used, provided that they mimic the natural material's stiffness, strength, and mechanical properties.

Further discussion on the application with respect to fluid movement, heat transport and contaminant transport through porous media is supplied by Culligan-Hensley and Savvidou (1996). Important with respect to fluid and contaminant transport modelling is that – as flow is being modelling – is the change of material properties being mimicked in the model. The parameters to be kept identical between model and prototype include:

- Reynold's number (incorporating fluidity and characteristic length of medium; §5.3)
- Peclet number (incorporating the free diffusion coefficient of a contaminant in solution)
- Rayleigh numbers (to address hydraulic instability due to variable fluid density)
- Inter-region transfer number (heterogeneous media)
- Capillary effects number (incorporating capillary head and surface/ interfacial tension).

Some important consideration for such fluid or contaminant flow and transport models include (Culligan-Hensley and Savvidou 1996):

- Fluid flow may not be laminar with viscous forces predominant and with Reynolds number below 10 as required for validity of Darcy's Law
- Contaminant dispersion cannot be confirmed to be similar in model and prototype
- Given centrifuge time-scales which may vary from field time-scales, rapid linear equilibrium laws may differ between model and prototype (e.g. surface reactions; adsorption).

The geotechnical centrifuge of the University of Pretoria is shown in Figure 6-8

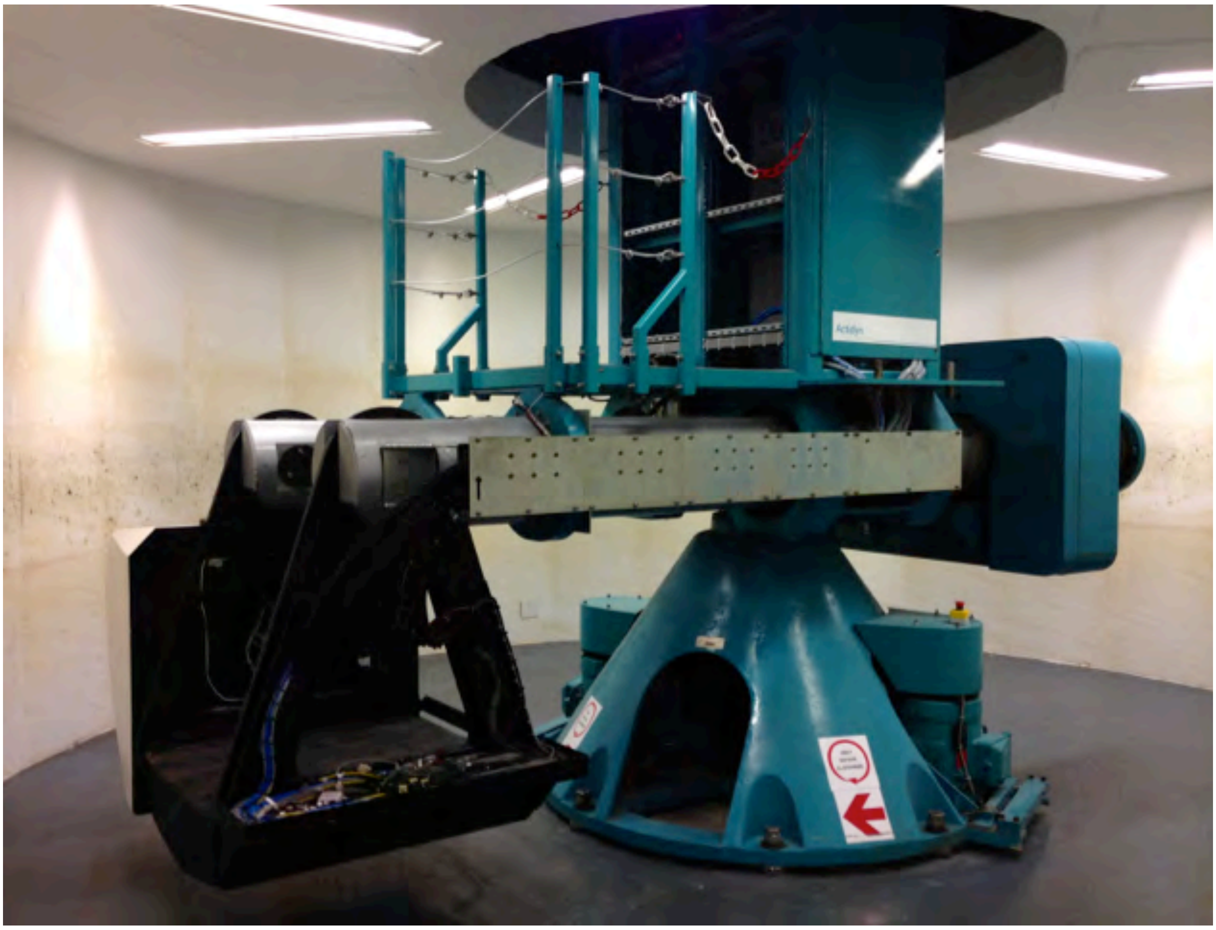


Figure 6-8. Geotechnical centrifuge of the University of Pretoria (© Jones 2014).

6.7. In-situ Methods

6.7.1. Percolation tests and infiltration tests

Various authors describe approaches to percolation testing from auger holes (e.g. Jenn et al. 2007c). In South Africa, one such a method is documented in SANS 10252-2 (1993) on drainage installations for buildings. Similarly, the double ring infiltration test (DRI) is a well-documented and widely applied method to estimate infiltration into the subsurface. The methods used in the percolation and DRI tests are described in Box 27. A Guelph permeameter or disk infiltrometer can also be installed in the auger holes to conduct a constant head or falling head test at a specified depth for wider application.

A number of issues should be noted when using these tests. As these tests estimate a saturated vertical hydraulic conductivity, the application to unsaturated conditions is uncertain. Whether actual saturation can be achiever should be noted as the wetting front can move at any moisture content exceeding field capacity, and therefore does not require complete saturation. Furthermore, the hydraulic gradient cannot readily be estimated as saturation is variable, lateral dispersion will inevitably occur and the depth of the wetting front cannot readily be determined. Estimating the hydraulic gradient as unity incurs obvious limitations on the data accuracy and should be duly noted.

Finally, these tests are subjected to bias as they are typically conducted in areas that are open for installation of the DRI (e.g. non-vegetated patches or looser, flatter soil) or where hand auger penetration is easy for the percolation test. This intrinsically suggests the possible presence of granular materials or macropores and the estimated values may be higher than natural.

6.7.2. Tensiometers

A number of other field approaches exist to quantify hydraulic properties. The tension disk tensiometer is often used on surface and relates infiltration rates to suction in a porous ceramic plate. As the use of these has been well documented in a number of publications, notably in the Vadose Zone Journal (e.g. Šimůnek and Van Genuchten 1996), it has been excluded from this study.

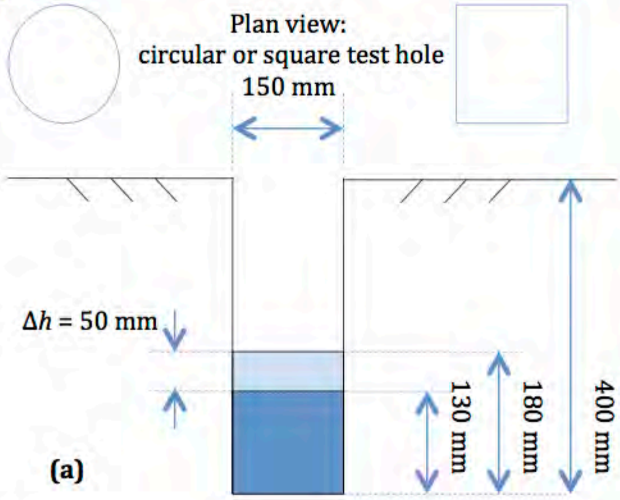
An example of a ceramic tip tensiometer is shown in Figure 6-9. Water from the measurement tube aims to equilibrate with soil moisture and the suction is detected using the pressure gauge.

Box 27. Field Percolation and Double Ring Infiltration Tests.

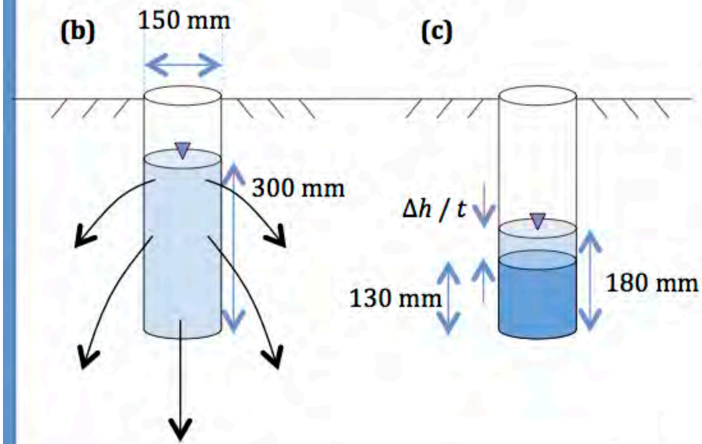
BOX 27: FIELD PERCOLATION AND DOUBLE RING INFILTRATION TESTS

PERCOLATION TEST SANS 10252-2 (1993)

A wide variety of specifications for easy percolation tests from auger holes or shallow excavations are available. Most of these follow interpretation according to Darcy's law and entail the excavation of a test hole with specified dimensions (whether circular to allow excavation by means of hand auger or square to allow excavation by means of shovel). All of these tests are then based on a constant-head or falling-head test in the test hole. The set-up for a standard South Africa method is shown here.



(a) A trial hole is excavated with the given dimensions, the sides are scarified and gravel is placed at the bottom.

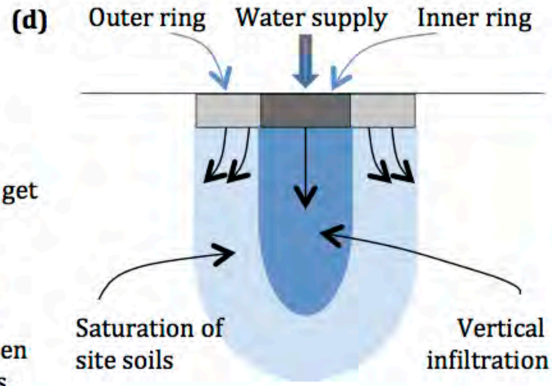


(b) Water is addedd to 300 mm from the base and allow to drain away completely three times or for at least 8 hours prior to conducting the test.

(c) The rate of drop of the water level between heights 180 mm and 130 mm is measured. When the rate of water level change becomes constant, the final data can be used to determine the percolation rate as the final change in head divided by the time taken for this drop to take place. In units of length per time, this amounts to the hydraulic conductivity if the hydraulic gradient is assumed to be unity.

DOUBLE RING INFILTROMETER (DRI)

The DRI entails two rings with differing diameter, employed to characterise infiltration into the subsurface. The water level is kept constant in the outer ring (typically 1 000 mm diameter), serving to get the soils near saturation. A constant-head test is conducted in the inner ring (typically 300 mm diameter). Volumes water added per time is related using Darcy's Law to calculate the vertical saturated hydraulic conductivity. Accuracy is estimated between 50 and 75% due to inadequate saturation of site soils.



READ MORE & CITED FROM: ASTM D 3385-94; SANS 10252-2 1993; Gartung and Neff 1999; Jenn et al. 2007c; Reynolds and Elrick 1986; Dippenaar et al. 2010

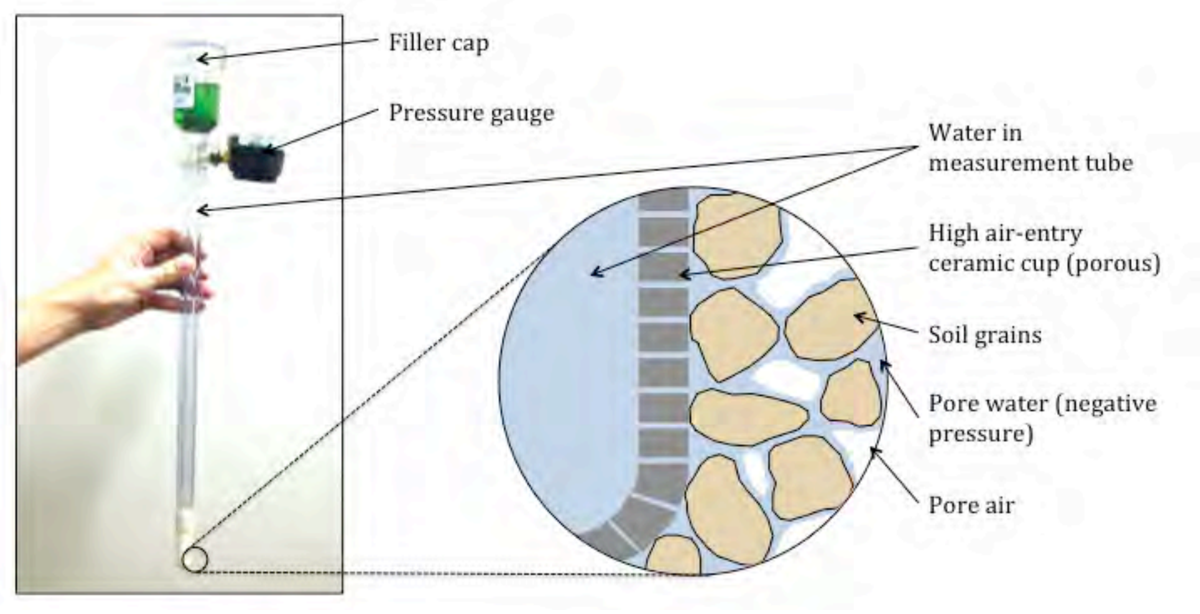


Figure 6-9. Irrometer moisture indicator (left; supplied by CalAfrica) and detail of the ceramic tip of the tensiometer (right; after Lu and Likos 2004).

6.8. Soil – Moisture Characteristic Curves

Although not applied in the accompanying case studies as the focus was on flow regimes, the geological materials and the intermediate vadose zone, characteristic curves are used to relate moisture content to matric suction as explained in Box 18. This can then be applied to estimate hydraulic conductivity for a medium at variable saturation, provided that the saturated hydraulic conductivity is known.

6.9. Modelling

Compilation of a model is dependent on a high quality initial conceptual model. The compilation of a quality conceptual model is discussed in §7, including the acquisition of proper material descriptions to ensure validity of the conceptual model. Assessment of modelling accuracy is not the intention of this study and has this been excluded.

Analytical or numerical modelling follows. Depending on the software employed and the understanding of the earth system modelled, these methods can supply viable results for long-term planning, monitoring and mitigation. Software packages typically solve unsaturated equations such as the Richards' equation.

6.10. Published Values

Numerous authors have published typical saturated hydraulic conductivities for different geological materials. Relating this to unsaturated hydraulic conductivities are, however, more difficult. This section aims to supply some such published values from other sources. Some published values for soil and rock are shown in Table 6-4. Note that values have been rounded to the nearest order of magnitude and the smallest possible ranges were used from the sources (Younger 2007; Karamouz et al. 2011 summarised from Domenicao and Schwartz 1990, Freeze and Cherry 1979, Fetter 1994, Narasimhan and Goyal 1984).

Table 6-4. Published saturated hydraulic conductivities for soil and rock material.

Soil Material	K_{sat} range low (m/s)	K_{sat} range high (m/s)	Average (m/s)
Clay	1.00E-11	1.00E-06	5.00E-07
Clay - silt (> 20% clay)	1.00E-09	1.00E-06	5.01E-07
Clay (unfissured)	1.00E-09	1.00E-06	5.01E-07
Glacial till	1.00E-11	1.00E-05	5.00E-06
Sand	1.00E-05	1.00E-04	5.50E-05
Clay - silt	1.00E-06	1.00E-03	5.01E-04
Sand (very fine)	1.00E-06	1.00E-03	5.01E-04
Silt	1.00E-06	1.00E-03	5.01E-04
Sand	1.00E-05	1.00E-01	5.00E-02
Gravel	1.00E-04	1.00E-01	5.01E-02
Sand - gravel	1.00E-03	1.00E-01	5.05E-02
Sand (clean)	1.00E-03	1.00E-01	5.05E-02
Gravel (clean)	1.00E-01	1.00E+00	5.50E-01
Gravel	1.00E-03	1.00E+01	5.00E+00

Rock Material	K_{sat} range low (m/s)	K_{sat} range high (m/s)	Average (m/s)
Crystalline rock (dense)	1.00E-13	1.00E-09	5.00E-10
Shale	1.00E-12	1.00E-08	5.00E-09
Crystalline rock (plutonic)	1.00E-09	1.00E-07	5.05E-08
Shale	1.00E-08	1.00E-07	5.50E-08
Tuff	1.00E-08	1.00E-06	5.05E-07
Lava	1.00E-08	1.00E-06	5.05E-07
Limestone	1.00E-06	1.00E-06	1.00E-06
Dolomite	1.00E-06	1.00E-06	1.00E-06
Sandstone	1.00E-09	1.00E-05	5.00E-06
Limestone	1.00E-08	1.00E-05	5.01E-06
Dolomite	1.00E-08	1.00E-05	5.01E-06
Sandstone	1.00E-05	1.00E-05	1.00E-05
Crystalline rock (fractured)	1.00E-08	1.00E-03	5.00E-04
Basalt (indurated, fresh)	1.00E-06	1.00E-02	5.00E-03
Karst (limestone)	1.00E-03	1.00E-01	5.05E-02
Karst	1.00E-02	1.00E-01	5.50E-02
Basalt (voided)	1.00E-01	1.00E-01	1.00E-01

6.11. Supporting Methods

Additional methods employed in general site investigation and analysis for a variety of other disciplines may add valuable insight to the behaviour of the vadose zone. As too numerous such methods exist, some applied in the case studies are discussed below.

6.11.1. Foundation indicator tests

Particle size analyses and Atterberg limits are determined as foundation indicator tests to supply basic parameters relevant to founding. The test comprises the following (as will be discussed later):

- Grading through sieves to 0.074 mm fraction and hydrometer to 0.002 mm fraction
- Grain size distribution and soil texture
- Moisture content – consistency relationships (Atterberg Limits), namely plasticity index, linear shrinkage and liquid limit
- Grading modulus and uniformity coefficient to address material grading
- Estimated soil activity based on clay fraction and plasticity
- AASHO and Unified soil classification.

6.11.2. Cation Exchange Capacity

The cation exchange capacity (CEC) of a soil is a measure of the amount of exchangeable cations (such as Ca^{2+}, Mg^{2+} and K^{+}) a soil can adsorb at a specific pH (Allaby and Allaby 2003). Cations held by electrostatic forces can be readily exchanged with cations in the soil solution, therefore, the higher the CEC of a soil, the greater its capacity to retain sufficient amounts of these ions. Negatively charged sites in a soil can also be occupied by cations such as H^{+} and Al^{3+}, which causes the soil to be acidic. Cation exchange mainly takes place on the surfaces of clay minerals and organic matter and is measured in either meq/100 g (milliequivalents of charge per 100 g of dry soil) or $cmol_c$/kg (centimoles of charge per kilogram of dry soil) (Ross and Ketterings 2011).

6.11.3. X-Ray Diffraction and X-Ray Fluorescence Spectroscopy

The samples for X-Ray Diffraction (XRD) used in the presented case studies were prepared for XRD analysis using a back loading preparation method. The samples are prepared as pressed powder briquettes.

6.11.4. Toxicity Characteristic Leaching Procedure

Toxicity Characteristic Leaching Procedure (TCLP) is used to establish the mobility of inorganic and organic components in a liquid, solid or multiphase waste (EPA 1992). Sample is leached for a fixed period in diluted acetic acid. The solution is filtered after the extraction process and the pH value is measured before analysis. The solution obtained from each sample is analysed for trace elements using Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS). The ions analysed in each solution typically include Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, Ge, Hg , K, Li, Mg, Mn, Mo, Na, Ni, Pb, S , Sb, Se, Si, Sn, Sr, Th, U, Ti, Tl, V, W, Zn, Zr and results are expressed as milligrams of each element per 1 000 ml of solution.

6.11.5. Acid-Base Accounting

Acid-Base Accounting (ABA) is a static test which assesses the potential of a rock to produce or neutralise acid. This test is used as a first approximation of the acidity or alkalinity of leachate produced by the rock in the presence of fluids. Components analysed in an ABA test are as follows:

- Acid Generating Potential (AGP) – this test determines the amount of acid that could potentially be generated by the rock material, calculable as the product of sulphur percentage present as sulphides and a factor of 31.25. AGP is expressed as kg of $CaCO_3$ per ton of rock. This indicates the mass of theoretical calcite neutralised by the produced acid.
- Acid Neutralisation Potential (ANP) – this test determines the amount of acid that could potentially be consumed by the rock material. The test is performed by adding a known volume of sulphuric acid or hydrochloric acid to a sample and then adding a litre of sodium hydroxide to determine the amount of unreacted acid. ANP is also expressed as kg of $CaCO_3$ per ton of rock to represent the amount of theoretical $CaCO_3$ available in the rock material to neutralise acid.

The Net Acid Generation Potential (NAG) value is obtained by subtracting the AGP from the ANP. A positive value indicates potentially non-acid-forming rock whereas a negative value indicates potentially acid-forming rock.

7. CONCEPTUAL MODELS

Proper vertical and spatial material descriptions increase confidence in conceptual models through accounting for differing material properties (§6.1). Hydraulic data then are superimposed onto the conceptual model to deduce hydraulic behaviour. Variability of earth materials governs the hydrological behaviour. Examples of typical South African soil profiles from Limpopo, Gauteng and Mpumalanga Provinces shown in Box 28 (granite and gabbro-norite) and Box 29 (sedimentary and volcanic rocks), emphasising the variability in similar lithologies in similar climatic regimes.

7.1.1. Conceptual geological models

A conceptual geological model including detailed variation in earth materials both vertically and spatially should form a starting point prior to inferring hydrological data. The conceptual model should progressively be updated as data are added and the model is refined. Proper material descriptions form the obvious starting point from where a fence diagram or section can be deduced. Given the variability of earth materials, it should be ensured that data points sufficiently describe the vertical variation, preferably until at least encountering highly or lesser weathered bedrock. Spatially, all different landforms or geomorphological settings should be profiled in detail. Challenges and trends in geological modelling and visualisation – often forming the first input of the conceptual geological model – are addressed by Turner (2006).

The important role of water in engineering is notable in pivotal position of fluid mechanics in the triangle of geomechanics, as well as the inclusion of groundwater under "composition" in the triangle of engineering geology as depicted in Figure 7-1 (Bock 2006).

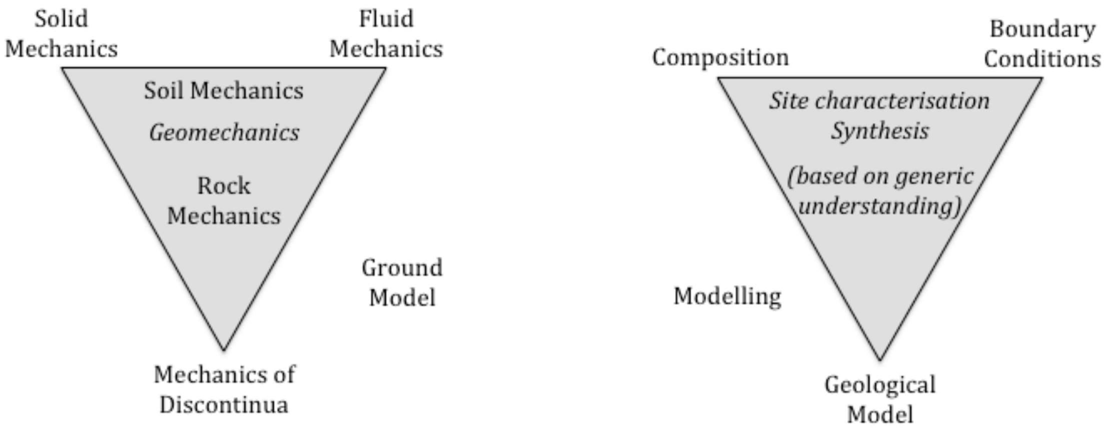
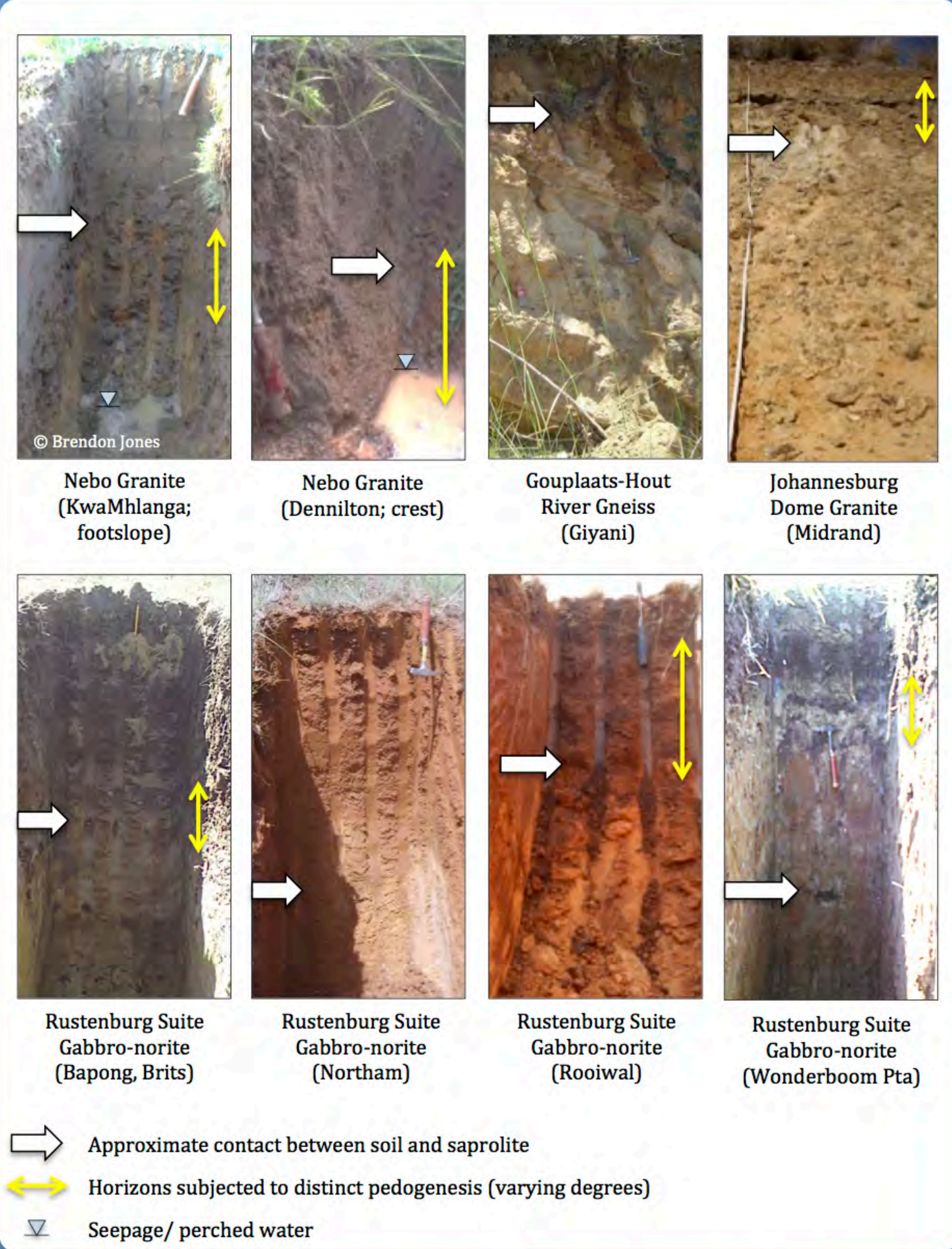


Figure 7-1. Triangle of engineering geology and geomechanics (not shown: geotechnical engineering) (after Bock 2006).

Box 28. Typical Intrusive Igneous Profiles from South Africa.

BOX 28: TYPICAL INTRUSIVE IGNEOUS PROFILES FROM SA



READ MORE & CITED FROM:

Geology of South Africa, edited by Johnson, Annhaeuser and Thomson
Series "Engineering Geology of South Africa" by A. B. A. Brink
Department of Agricultural Development 1991

Box 29. Typical Sedimentary and Extrusive Profiles from South Africa.

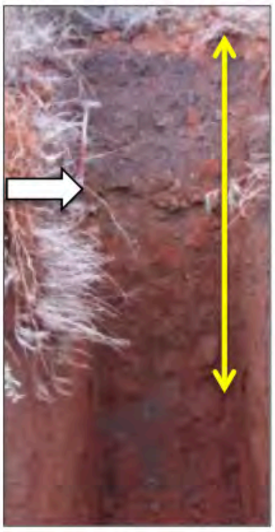
BOX 29: TYPICAL SEDIMENTARY AND EXTRUSIVE SOIL PROFILES FROM SA

Machadodorp Basalt (Machadodorp)

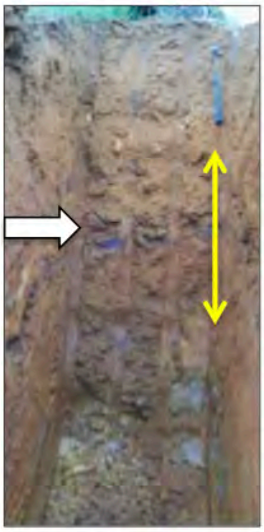
Ghaap Group Dolomite (Taung)

Chuniespoort Dolomite (Sabie)

Chuniespoort Dolomite (Vosloorus)



Silverton Shale (Proclamation Hill Pta)



Karoo Supergroup Shale (Middelburh Mpu)

Magaliesberg Sandstone (Mooinooi)

Hammanskraal Sandstone (Temba)

Approximate contact between soil and saprolite

Horizons subjected to distinct pedogenesis (varying degrees)

Seepage/ perched water

READ MORE & CITED FROM:

Geology of South Africa, edited by Johnson, Annhaeuser and Thomson
Series "Engineering Geology of South Africa" by A. B. A. Brink
Department of Agricultural Development 1991

The compilation of a geological model, based on this, includes all aspects relating to composition (lithology, distribution, water content, etc.) and boundary conditions (discontinuities, variations), accentuating the need for detailed conceptual geological models. This can be expanded to supersede geological models and to include all aspects of earth material models as will be detailed later.

7.1.2. Conceptual hydrostratigraphic models

Lithofacies types refer to sedimentary properties (particle size distribution, texture and fabric) which directly relates to hydraulic properties (e.g. hydraulic conductivity and porosity), resulting in the term hydrofacies which relate to homogeneous anisotropic units of hydrogeological similarity (Heinz and Aigner 2003). These combined compile the hydrostratigraphy of a given region with knowledge regarding the hydraulic behaviour of different stratigraphic units.

The importance of hydrostratigraphy and means of standardizing and simplifying classification of hydrostratigraphic units are addressed in a number of recent studies (e.g. Allen et al. 2007; Angelone et al. 2009; Heinz and Aigner 2003). Application is mostly in sedimentary and unconsolidated aquifers with some recent development in fractured and confined aquifers and vadose zone assessments.

Hydrostratigraphy is based around increasing scale of investigation as shown at the hand of sedimentary environments (Heinz and Aigner 2003):

- ***Hydrogeochemistry*** – basic transport processes at particle scale
- ***Hydrofacies*** – depositional dynamics at strata scale
- ***Hydraulic connectivity*** – geomorphological dynamics at depositional elements scale
- ***Aquifer compartments*** – environmental system dynamics at facies bodies scale
- ***Aquifer storeys*** – process dynamics at sequence scale
- ***Hydrostratigraphy*** – basin dynamics at basin fill scale.

Hydrostratigraphy will henceforth be slightly redefined to include regional variation of earth materials to include the complete phreatic and vadose zones, as well as all forms of aquitards, aquicludes and aguifuges. However, the focus will henceforth be solely on understanding the vadose zone component.

7.1.3. Conceptual vadose zone models

A detailed review of three basement granite terrains in South Africa (Johannesburg Dome Granite, Goudplaats-Hout River Gneiss and Nelspruit Suite Granite) collating available hydraulic, hydrogeological and geotechnical data from numerous discipline-specific investigations accentuates the importance of incorporation of large multidisciplinary datasets in refinement of the conceptual model for application to the vadose zone (Dippenaar and Van Rooy 2014). The review incorporates data from VZSA1 and deduces process-specific conceptual models for basement granite terrains in various climatic settings in South Africa (Figure 7-2). Similar conceptual models have been derived for VZSA1 and VZSA3, attached in Part 3 of this text.

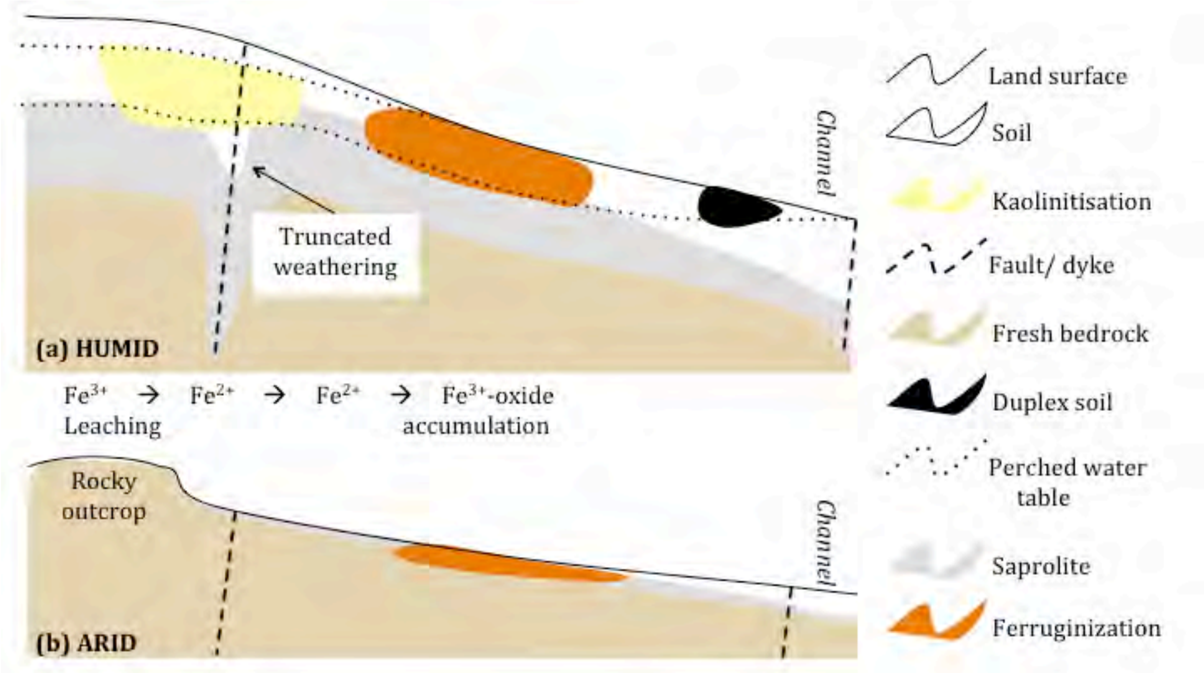


Figure 7-2. **Typical material successions and pedogenetic processes from a hillcrest (left) to drainage channel (right) underlain by basement granite in humid and arid settings (Dippenaar and Van Rooy 2014).**

Triangles of interaction in vadose zone hydrology and the compilation of the vadose zone model have been deduced based on the large datasets and is shown in Figure 7-3.

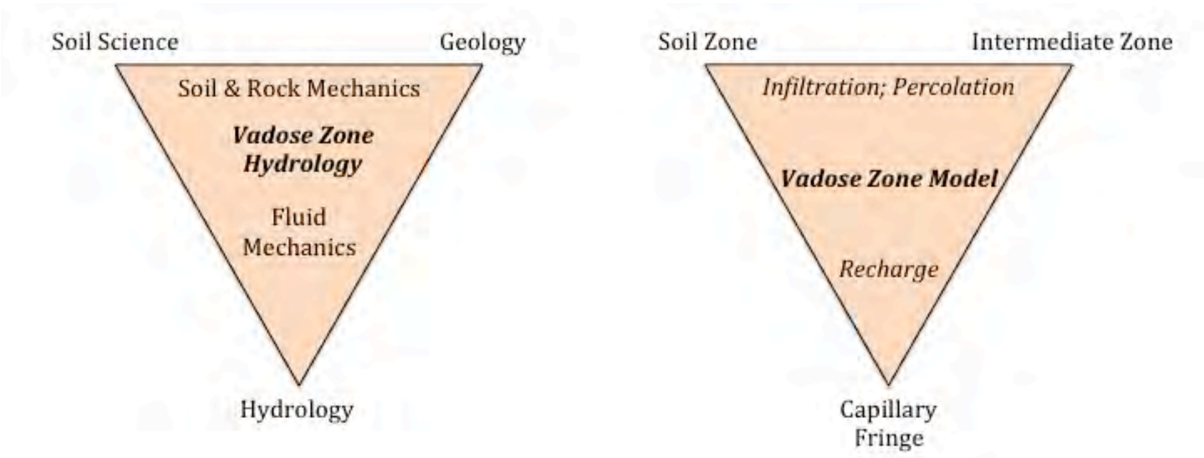


Figure 7-3. **Triangle of vadose zone hydrology (left) and the compilation of the vadose zone model (right) (Dippenaar and Van Rooy 2014).**

7.1.4. Provisional findings

VZSA1 and VSZA3 – both areas with wetland conditions – substantiate the importance of soil profiling in compilation of the conceptual model where the zone of shallow interflow can be identified through visual inspection. Increasing detail regarding vertical, spatial and temporal heterogeneities are, therefore, important in compiling correct conceptual models.

Influences of mineralogy and petrology, also evident from VZSA1, both govern and result from the movement of water. Moving water mobilises fines and ions that are then deposited elsewhere when energy becomes less or when conditions become reducing. This movement of fines and ions then result in further changes to the flow paths, and the system is therefore continuously changing in terms of hydraulic parameters, porosity, flow directions and the like. This is also important in instances where land use changes as both the water budget and the material properties may be altered over time.

Single data points – whether empirical, field or laboratory – also pose the risk of bias and samples or tests should be replicated and should be expanded to cover all anticipated geological or pedological heterogeneity.

Incorporation of large, multidisciplinary datasets – as explained at the hand of basement granite terrain – improves conceptual model confidence and results in improved understanding of the subsurface hydrology, subsequently, also resulting in better crossdisciplinary application of findings.

8. VADOSE ZONE HYDROLOGY APPLIED

A number of relevant case study scenarios were selected to evaluate the investigative techniques. In all instances, the case studies entail development within the vadose zone or on land surface, resulting in influence of the vadose zone on the relevant development.

8.1. Wetlands

8.1.1. Defining wetlands

Various definitions exist for wetlands. Some of these definitions, including the one used in South Africa according to the NWA (36, 1998), as well as the most common types of wetlands, are explained in Box 30.

Wetlands are characterised by a number of distinguishing features, most notably the presence of stationary water above the ground surface for a specific period of time, together with particular organisms (specifically vegetation) and unique soil conditions (Mitsch and Gosselink 2000). Due to the high variability in hydrological conditions, the occurrence along slope margins as well as deep-water systems, and due to their high variability in location, size and human influence, defining wetlands are not very straightforward (Brison 1993).

Mitsch and Gosselink (2000) suggest a three-tiered approach to defining wetlands based on hydrology, the physiochemical environment and biota as shown in Figure 8-1.

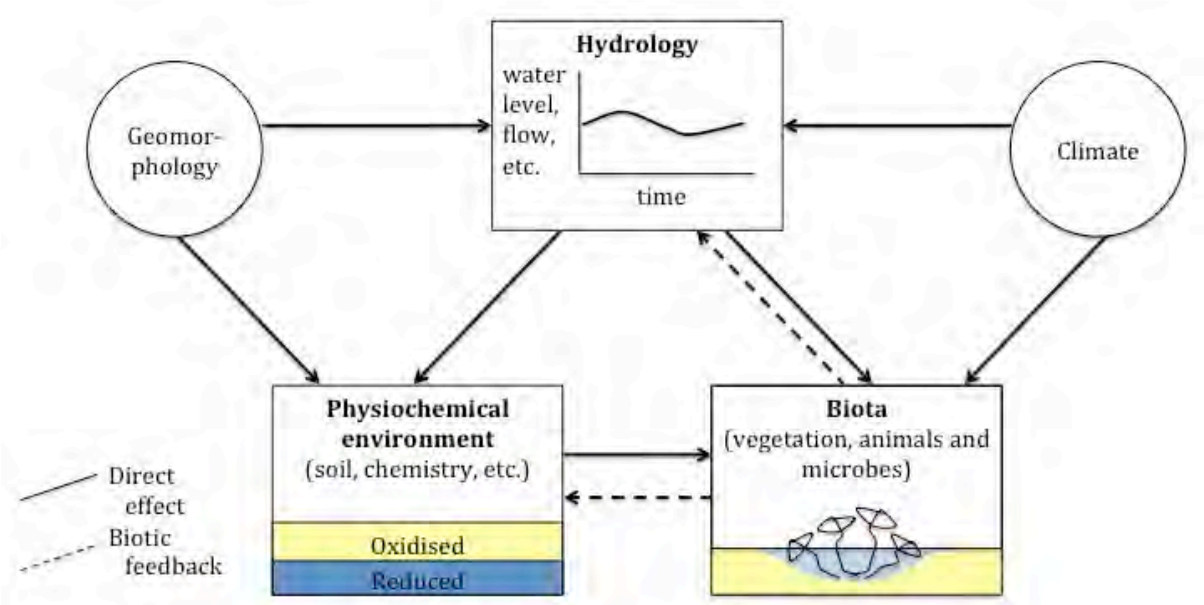


Figure 8-1. Defining wetlands based on hydrology, the physiochemical environment and biota (adapted from Mitsch and Gosselink 2000).

Box 30. Wetlands: Definitions and Types.

BOX 30: WETLANDS: DEFINITIONS AND TYPES

WETLANDS ARE:

"... areas of marsh, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed ten metres" (NWCS).

"... lakes and rivers, swamps and marshes, wet grasslands and peatlands, oases, estuaries, deltas and tidal flats, near-shore marine areas, mangroves and coral reeds, and human-made sites such as fish ponds, rice paddies, reservoirs, and salt pans. (SANBI).

"... land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which under normal circumstances supports or would support vegetation typically adapted to life in saturated soil" (NWA).

"... areas where water is the primary factor controlling the environment and the associated plant and animal life" (RAMSAR).

TYPES OF WETLANDS (Ewart-Smith et al.)

Seeps and springs (where rivers originate)	**Floodplains** (areas flooded when a river exceeds its banks)	**Marshes and swamps** (low-lying wetlands)
Lakes (permanent bodies of fresh water)	**Mangrove swamps** (tropical coastal swamps)	**Estuaries** (tidal mouths of rivers)

TYPES OF WETLANDS (Semeniuk and Semeniuk)

Land Form	Permanently inundated	Seasonally inundated	Intermittently inundated	Seasonally waterlogged
Basin	Lake	Sumpland	Playa	Dampland
Stream	River	Creek	Wadi	Trough
Flat	—	Floodplain	Barlkarra	Palusplain
Slope	—	—	—	Paluslope
Highland	—	—	—	Palusmont

READ MORE & CITED FROM: DWAF 2005; Ewart-Smith et al. 2006; NWA 1998; RAMSAR 2006; SANBI 2009; Semeniuk and Semeniuk 1995

8.1.2. Wetland classification and delineation

The primary goal of classifying wetlands, according to Cowardin et al. (1979 in Mitsch & Gosselink, 2000), is "… to impose boundaries on natural ecosystems for the purposes of inventory, evaluation, and management." From, this, four primary objectives of the classification system are defined:

- To describe ecological systems with certain homogeneous natural characteristics
- To arrange these systems in a unified framework for the characterization and description of wetlands, that will help resource management decisions
- To identify classification systems for inventory and mapping
- To provide evenness in concepts and nomenclature.

Some approaches to wetland delineation and classification are discussed in Box 31. Wetland classification is usually based on the environmental driving functions and most notably on hydrology and, as discussed by Ewart-Smith et al. (2006), is based on its biophysical characteristics and is labelled the hydrogeomorphic classification (HGM). Landforms and hydrology are two fundamental features that determine the existence of all wetlands, both of which are included in the HGM approach.

The structure of this classification system is hierarchical and progresses from Systems through Subsystems to Functional, Structural and Habitat Units where each level in the hierarchy focuses on the discriminators that distinguish between different types of wetlands. Based on this, distinction is recommended between three types of systems based on Level 1, viz. marine systems (along the coastline); estuarine systems (permanently or periodically connected to ocean, influenced by tidal action and of which the water is at least occasionally diluted by freshwater); and inland systems (permanently or periodically inundated or saturated and with no existing connection to the ocean).

Level 2 refers to the level of drainage and applies only to estuarine systems (permanently open or temporarily closed) and inland systems (non-isolated or isolated). Following this, Level 3 relates to the landform and tidal discriminators; Level 4 to the substratum, surface/ subsurface vegetation and/ or emergent vegetation, including non-vegetated areas; and Level 5 relating to specific habitats (e.g. dominant vegetation characteristics).

The four indicators (terrain, soil form, soil wetness and vegetation) are mostly applied in wetland delineation. The first – the terrain unit indicator – relates to those parts of landscapes where wetlands are more likely to occur, but should not be used as a sole indicator of a wetland. Typical terrain units likely for wetland occurrence are valley bottoms and valley bottoms connected crests, midlopes and footslopes as per Figure 8-2 (DWA 2005). Alternative landform descriptions proposed by Venter (1986) for notably the igneous terrain in the southern and central Kruger National Park are shown for correlation.

Box 31. Wetlands: Classification and Delineation.

BOX 31: WETLANDS: CLASSIFICATION AND DELINEATION

HYDROGEOMORPHIC (HGM) WETLAND CLASSIFICATION SYSTEM

	DISCRIMINATORS		*DESCRIPTORS*
Primary Discriminators	Connectivity to open ocean	LEVEL 1: SYSTEM	Hydrology
	Drainage	LEVEL 2: SUBSYSTEM	Water chemistry
	Landform and tidal regime	LEVEL 3: FUNCTIONAL UNIT	Position in landscape
Secondary discriminators	Dominant cover type	LEVEL 4: STRUCTURAL UNIT	Geology
Tertiary discriminators	Dominant life-form/ vegetation	LEVEL 5: HABITAT UNIT	Soils
			Natural and artificial influences

WETLAND DELINEATION ACCORDING TO THE FOUR INDICATORS

- ***Terrain Unit Indicator***: to outline probable portions of the landscape
- ***Soil Form Indicator***: to identify soils subjected to prolonged and frequents periods of saturation
- ***Soil Wetness Indicator***: relates to morphological signs developing in the soil profile due to prolonged and frequent periods of saturation
- ***Vegetation Indicator***: identifies the hydrophilic vegetation commonly associated with such frequently saturated soils.

ADDITIONAL INDICATORS

- Hydromorphic soils exhibiting characteristics due to prolonged saturation
- Hydrophytes (water-loving plants) should be present occasionally or more frequently
- A high water table, causing saturation of the surface or shallow subsurface and resulting in anaerobic conditions in the upper 0.50 m of the soil
- Shallow clay or impervious layer within 0.50 m of the surface
- Deep polygonal cracks on thick clayey substrata
- Thin curled polygons of inorganic fines on the surface
- Thin muck layers, often overlying sandy soil
- Sediment deposits on plants, rocks and other objects
- Biotic crusts or algal markers
- Water marks on rocks or any other fixed structures
- Shells, exoskeletons and bodies of aquatic vertebrates.

READ MORE & CITED FROM: Day et al. 2010; DWAF 2005; Ewart-Smith et al. 2006; NWA 1998; RAMSAR 2006; SANBI 2009

The second – the soil form indicator – identifies soil forms specifically associated with prolonged and/ or frequent saturation. This prolonged and repeated saturation leads to microorganisms gradually consuming the oxygen present in pore spaces, resulting in anaerobic conditions in these so-called hydromorphic soils. These anaerobic conditions are also associated with the leaching of iron and manganese, resulting in a typical change from reddish and brownish colour due to iron to greyish, greenish or bluish. This is called gleying and is interpreted as a zone which is temporarily or seasonally saturated (Tiner 1999).

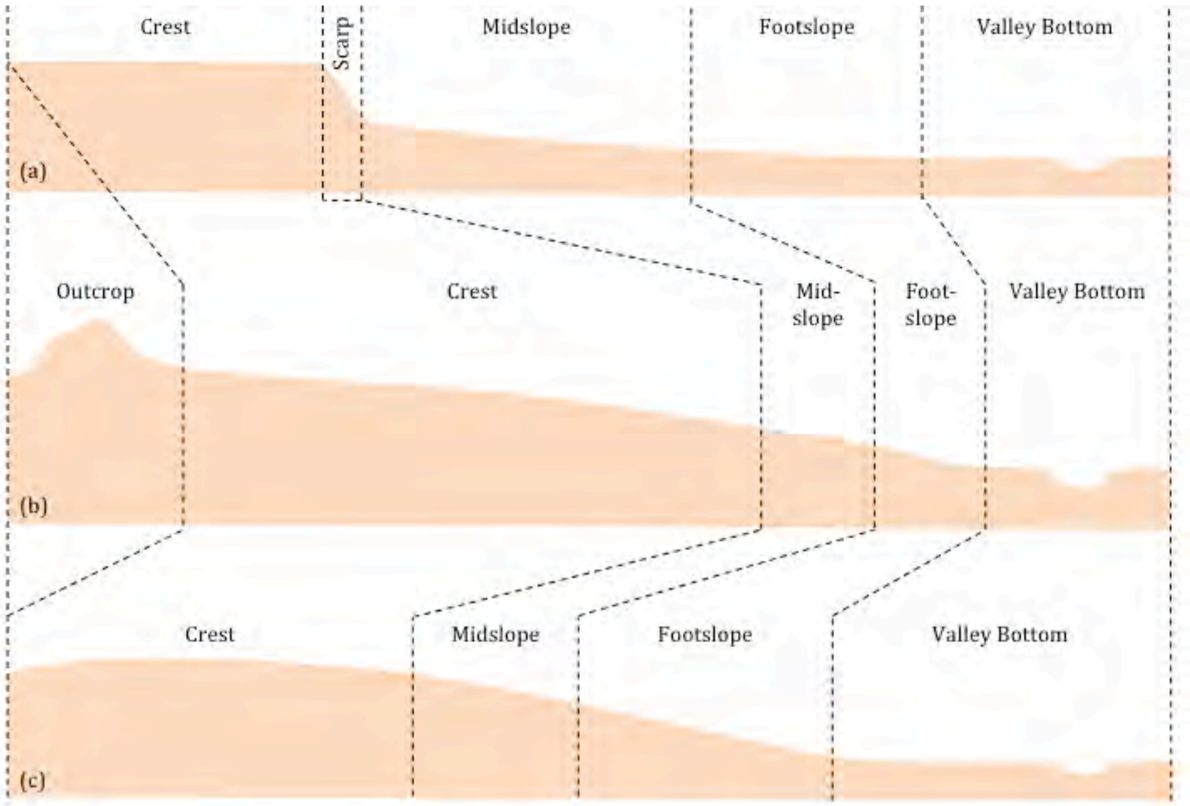


Figure 8-2. (a) Typical terrain units of wetlands (after DWA 2005) correlated to typical alternative landform units used in South Africa and based on the (b) southern and (c) central Kruger National Park (Venter 1986).

Water table lowering subsequently leads to aerobic conditions once again and dissolved iron becomes insoluble again. Precipitation is typically in the form of patches or mottles, also a typical indicator of wetlands. This soil wetness indicator identifies morphology signatures developed throughout the soil profile due to prolonged and frequent saturation. This is one of the most practical indicators with the increasing length and regularity of periods of saturation in a profile, the more distinctly grey the colours become. A grey soil matrix and/ or mottles must be present to support the soil being wet in the temporary, seasonal and permanent zones (DWA 2005). This accentuates the importance of proper description of colour during soil profiling and the inclusion of this in soil profile description.

Finally a vegetation indicator is applied to identify hydrophilic vegetation requiring frequently saturated soil. Vegetation in an untransformed state is a beneficial field guide in identifying the wetland boundaries as the plant species change from the centre of the wetland towards its edges. Due to the saturated conditions, plant roots cannot behave in its normal metabolic function and certain nutrients become unavailable to the plants, leading to certain elements being in elevated concentrations in the soil. Due to extensive morphological, physiological and/ or reproductive adaptation, these plant species are able to persist in these anaerobic soil conditions (DWA 2005).

Whether a particular area is classified as a wetland is subject to the number of identified wetland indicators. The edges of a wetland are established at the point where these indicators are no longer present. The presence of all indicators provide a logical, defensible and technical basis for identifying an area as a wetland, but an area should display a minimum of either soil wetness or vegetation indicators in order to be classified as a wetland. Verification of the terrain unit and soil form indicators increases the level of confidence in deciding the boundary and therefore, the more indicators present, the higher the confidence in the delineation (Tiner 1999).

8.1.3. Provisional findings

Two notable wetland areas were investigated:

- Randjesfontein, en ephemeral hillslope wetland, as detailed in VZSA1, and which has been excavated for development (§11)
- Temba, a seasonal wetland linked to a primary drainage channel, as detailed in VZSA3, and which has been developed as a cemetery (§13)

The selection of these sites is not arbitrary. Although all the study areas can be incorporated in other sections of this manual, the wetland behaviour has been evaluated at the hand of its hydrological characteristics.

Present guidelines identified the Randjesfontein wetland through being zones as marshy land in the geotechnical reports. This wetness was, however, absent during subsequent investigations in the winter months when the site was burnt down, resulting in absence of significant wetland indicators. In the instance of Temba, the need for a cemetery exceeded the environmental risk and the development predated the NWA as the first true enforcement particularly mentioning wetlands.

8.2. Cemeteries

8.2.1. Risk associated with cemeteries

According to the DWA (2010), the risk of pollution to water resources posed by cemeteries is acceptable and mostly negligible due to the following reasons:

- The decay of human bodies is a slow process and mostly bacteria will not survive for long periods outside of a living human body. These bacteria also will very probably also not survive in surface water or groundwater and the risk involved is much lower than other forms of waste.

- Other municipal sources of pollution are considered more likely to have an adverse effect on water resources than cemeteries, for example waste disposal sites, sewage, etc.
- Water is supplied to residential areas through reticulation systems to account for water quality degradation to all potential pollution sources, including cemeteries.
- Poorer quality groundwater can be used for other practices such as irrigation with a very low risk compared to other environmental factors.

According to the Section 21 of the Environmental Conservation Act (DEAT 1989), the "… change of land use to that of a cemetery is subject to a mandatory Environmental Impact Assessment (EIA)". Poorly sited cemeteries can pose a pollution threat to the environment, including short-term impacts such as noise, flies and air pollution, as well as long-term impact such as pollution to the water regime. Decomposition of buried human corpses results in groundwater contamination due to, for instance, residues and pathogens that are generated during the decomposition process (Fisher and Croucamp 1993).

Vulnerability is accentuated in areas with high rainfall, shallow water tables, fractured rocks and any other high permeability area. The risk of water contamination is, furthermore, increased where burial is near the water table or next to groundwater abstraction points as this reduces the time needed for mobile waste production to degrade completely and for the geological subsurface material to purify the potential pathogens. Additionally contamination can be increased where corpses are buried in direct contact with the groundwater, causing reduction in the time taken for mobile degradation to reach the subsurface, or with an increase in number of burials (Engelbrecht 2000).

The influence of infiltrating water is explained through Figure 8-3. Backfill material in graves may be less compacted than the in-situ material and may, therefore, act as preferential pathways. This may result in the graves being near water saturation, leading to anaerobic conditions for the breakdown of the organic matter. Interaction and interflow are possible between proximate graves, and/ or contaminated water may enter the vadose zone below the grave bottom if the water table is sufficiently deep. Natural attenuation of contaminants can occur through aerobic conditions in the aerated vadose zone. Shallower groundwater should be more vulnerable to contamination due to (1) the thinner vadose zone where natural attenuation can occur and (2) possible mounding of the water table, which can even result in a periodical contact between the grave bottom and the groundwater table.

Risk is also exacerbated by possible groundwater – surface water interaction. The proximity of surface water drainage features and, notably, streams in direct interaction with the regional groundwater (Figure 8-4a) are more vulnerable to contamination of both surface water and groundwater, whereas losing streams (Figure 8-4b) are possibly more protected as the groundwater flow may be in an opposite direction at a local scale. Deep groundwater systems (Figure 8-4c) are the most protected due to the thick vadose zone enhancing natural attenuation through aerobic decomposition.

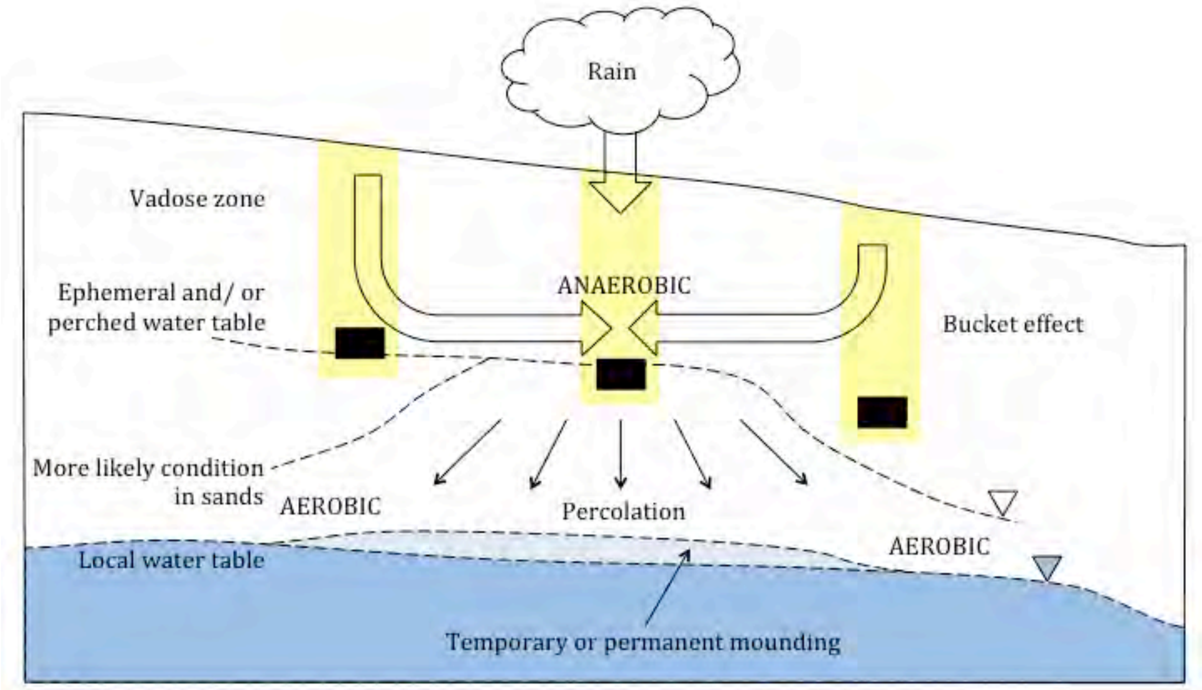


Figure 8-3. **Interaction between graves and the subsurface hydrology (adapted from Dent and Knight 1998).**

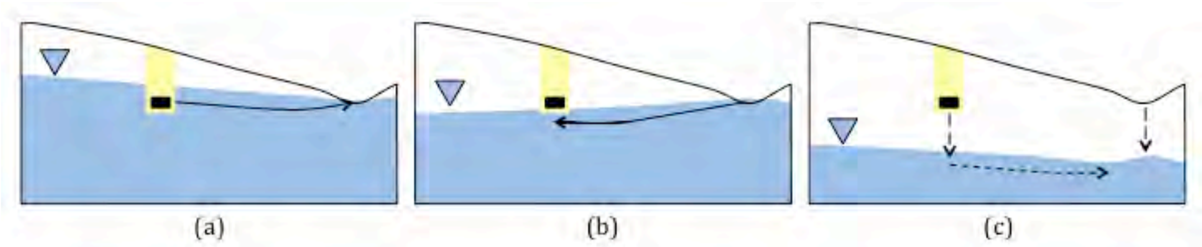


Figure 8-4. **Hypothetical interactions between graves sites and (a) a gaining stream at risk from contamination from gravesites, (b) losing stream possibly more protected and (c) deep groundwater table with possible contamination (arrows indicate likely flow directions).**

Dent and Knight (1998) summarise risk from decaying bodies (cited partially from Forbes 1987) where a lean 70 kg adult male human body is composed of approximately 16 000 g C, 1 800 g N, 1 100 g Ca, 500 g P, 140 g S, 140 g K, 100 g Na, 95 g Cl, 19 g Mg, 4.2 g Fe and 70-74% water by weight. Females are generally two thirds to three quarters of this and other elements occur in millimole and micromole amounts.

8.2.2. Site investigation for cemeteries

There is a potential for pollution from cemeteries, and the Department of Water Affairs acknowledges this by certain guidelines and the requirement for registration as a water use for cemeteries implemented after 1998, including the following:

- Cemeteries constitutes a water use according to s21(g) of the National Water Act (NWA 36, DWA 1998) and new cemeteries following the implementation of this act needs to be authorised.
- Local authorities manage the implementation and legislation and land use planning fall within these authorities and govern the location according to the NWA that cemeteries should not be located:
    - Within the 1 in 50 year floodline of a river
    - Near water bodies such as wetlands, pans, vleis, estuaries and floodplains
    - Near unstable areas such as fault zones and karst areas
    - Near ecologically sensitive areas
    - In areas with shallow gradients or shallow or emergent groundwater
    - In areas with steep gradients, shallow bedrock or areas prone to slope failure
    - In areas of groundwater recharge due to topography or soil permeability
    - Overlying or adjacent to (potentially) important water supply aquifers.
- Poor siting of cemeteries leading to increased risk is due to poor land use planning from the local government and detection of pollution due to cemeteries will be enforced according to the NWA.

Fisher (1992) recommends investigation of geological factors influencing soil conditions, underlying rock, groundwater conditions and surface water:

- Soil conditions include soil type, structure, density, permeability and moisture content
- Underlying rock comprise bedrock, pedogenic material, joint and discontinuity frequency, joint condition, joint fill material and degree of weathering
- Groundwater conditions relate to depth of the permanent water table, frequency of perched water tables, prevailing hydraulic gradient, as well as the relationship between topography and groundwater table
- Surface water occurring in drainage features refer to perennial or non-perennial streams, as well as frequency of flow of the latter, stream order, storage dams, topographical and climatic influences, slope shape and gradient, and the incised nature of the landscape.

Following on the abovementioned, Fisher (1994) also recommends the following requirements for a site to serve as a cemetery:

- The surface gradient should be between 2° and 6° (up to 9° in extreme cases) to ensure adequate drainage of the site, to minimise erosion and to promote mobility on site.
- The soil profile depth should be at least 1.80 m for ease of excavation.
- The soil consistency should be such that it ensures the stability of the grave walls for a few days.
- The underlying site soils should have a low permeability (10^{-5} to 10^{-6} cm/s) to prevent groundwater contamination.
- The site should be located at least 100 m from the 50-year flood line.
- The groundwater depth should exceed 4 m.

- A buffer zone of at least 2.5 metres should be present between the bottom of the grave and the top of the groundwater table.
- No drainage channels should intersect the proposed cemetery area.
- The site should not be underlain by dolomitic material.
- No borehole drinking water should be located closer than 500 m of the proposed cemetery.
- The cemetery should be large enough for future expansions at an estimated 3 000 graves per hectare.

Croucamp and Richards (2002) recommend ten selection criteria based on engineering and hydrological conditions:

- Soil excavatability, pertaining to the ease of grave excavation without any mechanical aid, to a minimum depth of 1.80 m, is addressed according to soil consistency. Very loose to loose (very soft to soft) material is readily excavated by means of a spade and will be suitable, provided that grave stability is not a problem. Medium dense (or firm) material requires picks and spades and is considered ideal. Exceeding this will require back actors, jack hammers or blasting which may not always be affordable and the shallow bedrock leading to harder excavation conditions may not be suitable for grave sites.
- Soil permeability relates to the rate of fluid movement through the soil and must be between 1×10^{-7} cm/s and 5×10^{-5} cm/s. Where the cemeteries are located further from water sources than recommended, the upper limit can be extended to 1×10^{-4} cm/s.
- The position with respect to domestic water sources depends on the soil permeability range and the maximum survival times of several bacteria and viruses.
- The position with respect to drainage features (including lakes, dams, rivers, streams and gully heads) is important to ensure that these features are not affected in any way by pollutants from the cemetery sites.
- Site drainage should ensure minimal ingress of surface water into the graves and storm water run-off should be implemented to ensure this.
- Site topography should ideally have a gradient between 2 and 6 with a maximum gradient of 9 being considered acceptable.
- The basal buffer zone refers to the vertical soil succession between the base of the deepest grave and the water table, forming a barrier between the source of pollution (the grave) and the groundwater.
- Grave stability is required to ensure competency in the excavated graves.
- Soil workability entails the ease of manipulation of soil from and into the grave.
- Cemetery size, finally, is often limited by the lack of suitable conditions due to, for instance, dense drainage networks and the required capacity for the intended community. Based on all such factors, a cemetery can be considered suitable or unsuitable.

A rating system, based on physical and sanitary aspects, was proposed by Hall and Hanbury (1990). The system is summarised in Box 32, resulting in final ratings of unacceptable, poor, satisfactory or very good.

Box 32. Cemetery Site Investigation (Physical and Sanitary).

BOX 32: CEMETERY SITE INVESTIGATION (PHYSICAL AND SANITARY)

EXCAVATABILITY	Assessment		Rating Score
Easy spade	Geological pick pushed in 50 mm with ease		15
Pick and spade	Geological pick causes slight indentation		10
Machine	Firm blows with pick cause 1 – 3 mm indentations		5
Blasting	Backactor refusal		0
STABILITY	**Assessment**		**Rating Score**
Stable	Little overbreak with safe excavation profiling		20
Overbreak	Overbreak between 1.3 and 1.8 m		15
Slightly unstable	Minor falls of material		8
Unstable	Collapse of excavation likely		1
WORKABILITY	**Unified**	**MOD AASHTO**	**Rating Score**
Excellent to good	GW. SW, GP	> 1 800 kg/m^3	10
Fair	SP, SM	< 1 800 kg/m^3	5
Poor	OL, CL, NL	< 1 700 kg/m^3	2
Very poor	OH. CH, MH	< 1 500 kg/m^3	0
WATER TABLE	**Water Table Depth (m)**		**Rating Score**
Deep water table	> 8		25
Intermediate water table	4 – 8		5
Possible perched water	0 – 4		5
Waterlogged soil	0 – 4		Fail
SUBSOIL PERMEABILITY	**Percolation Rate**	**Approx. Permeability**	**Rating Score**
Impermeable	Not measurable	< 10^{-7} m/s	15
Relatively impermeable	10 – 15 mm/h	10^{-6} – 10^{-7} m/s	20
Relatively permeable	15 – 50 mm/h	10^{-5} – 10^{-6} m/s	10
Permeable	50 – 1 000 mm/h	< 10^{-5} m/s	0
BACKFILL PERMEABILITY	**Unified Class**		**Rating Score**
Impermeable	OH, CL, CH		5
Relatively impermeable	GC, SC, MH		10
Relatively permeable	GP, SP, GW		7
Very permeable	SW, SP		0
FINAL RANKING	**Suitability**		
> 90	Very good		
75 – 90	Satisfactory		
60 – 75	Poor – precautions required		
< 60	Unacceptable		

READ MORE & CITED FROM: Hall and Hanbury 1990

8.2.3. Provisional findings

Slow decay and slow contaminant release coupled with the possible changes in saturation and redox conditions in grave sites make cemeteries lower risk than other major potential contamination sources such as landfills. However, the inability (due to ethical constraints) of removing the contaminant source when contamination is detected make cemeteries, notably the poorly sited ones, a long-term concern where, if contamination is detected, mitigation methods exclude relocaiton of graves or treatment of the contaminant source.

Flow in the vadose zone should be assessed in significantly more detail to account for impacts of (1) intense rainfall events, (2) possible interflow or shallow throughflow, (3) possible perched water tables, (4) variable saturation and alternating oxidizing and reducing conditions and (5) backfill permeability when of differing compaction or permeability than the in-situ materials.

Changes in the water budget (due to, for instance, reduced or increased infiltration resulting from surface sealing or disturbance of surface materials, increased or reduced groundwater abstraction and variable backfill properties) will furthermore alter redox conditions which control the natural attenuation of the contaminants and their ability to be transported to groundwater or surface water bodies. Land use planning with respect to cemeteries should exceed consideration of the cemetery alone, and should include some estimation of the impact of changing the proximate land use such as through increased development.

8.3. Construction and Engineering

8.3.1. The role of water in engineering geology

The influence of moisture becomes increasingly important in engineering geological and geotechnical investigations. Water – being practically incompressible in its liquid state – keeps soil structure intact and only with reduction in moisture content, often associated with simultaneous loading of the soil, can the soil undergo vertical shortening. Although not the purpose of this study, its inclusion as part of a multi-disciplinary investigative approach is fundamental.

The new draft South African National Standard (SANS 634:2009b) suggests the inclusion of seepage in the delineation of sites for development in terms of:

- Most favourable, being a permanent or perched water table more than 1.5 m below ground surface
- Intermediate, being a permanent or perched water table less than 1.5 m below ground surface
- Least favourable, being swamps and marshes.

Additionally, inclusion of regional geohydrological data and local data in the instance of dolomite land are required. It is also required to comment on the prominent water courses, preferred drainage routes and should properly interpret groundwater seepage conditions (SANS 2009b).

Water is important in construction in that surface water causes erosion and flooding, and groundwater controls effective stress and frictional strength. Changes in groundwater conditions induced by engineering (e.g. dewatering, tunnelling or groundwater lowering) induce movement of water and possibly also internal erosion, increasing effective stress and self-weight compaction of earth materials. Rising water levels may furthermore weaken the ground supporting structure due to, for instance, dissolution of cementing materials (Hencher 2007).

Water is noted as one of the factors with the highest incidence that affects the geotechnical behaviour of materials and result in (González De Vallejo and Ferrer 2011):

- Dissolution resulting in loss of material in soluble rocks and karstification, causing cavities, subsidence and/ or collapse
- Erosion or piping resulting in loss of material, sheetwash, internal erosion and gully erosion, causing subsidence, collapse, settlement, piping and/ or silting
- Chemical reactions resulting in changes in chemical composition, attacking cement, aggregates, metals and rocks
- Weathering resulting in changes in the chemical and physical properties of the materials, causing decrease in strength and increasing deformability and permeability.

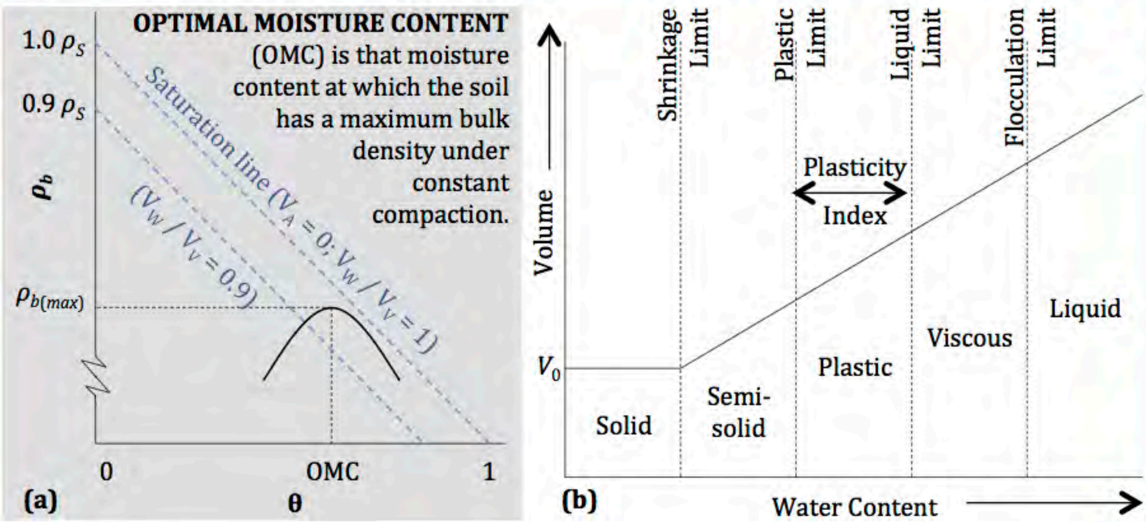
The influence of variable saturation in engineering is explained at the hand of the optimal moisture content, the Atterberg limits (relating soil consistency to moisture content in cohesive soils) and stress distribution in Box 33.

The optimal moisture content (OMC) refers to that moisture content at which the soil exhibits a maximum bulk density ($\rho_{b(\max)}$) under constant compaction and is especially important in defining the compactive effort required in road construction (Rose 2006). At lower moisture contents, soil tends to be difficult to compact due to its consistency and structure. With increasing moisture content, the soil becomes more workable until the OMC is reached. Beyond the OMC, the dry density decreases as more water is added and an increasing proportion of the soil becomes occupied with water. The relationship between these parameters is shown in Box 33.

$$\rho_b = \frac{m_S}{V} = \frac{\rho_S V_S}{V} = \rho_S - \rho_S \cdot \theta = \rho_S(1-\theta)$$ **Equation 60**

Box 33. Geotechnical Engineering and Engineering Geology.

BOX 33: GEOTECHNICAL ENGINEERING AND ENGINEERING GEOLOGY



ATTERBERG LIMITS

Geotechnical engineers relate soil moisture content to soil consistency (b). The liquid limit is the lower moisture content above which soil behaves as a viscous fluid. Between the plastic and liquid limits, the soil behaves as a plastic solid, and below the plastic limit as a semi-solid and eventually a solid. The plasticity index is calculated as the percentage difference between the liquid and plastic limits. Granular (coarse-grained non-cohesive) soils generally have very low values and are often considered non-plastic due to the lack of cohesion between non-clay minerals. Atterberg Limits are mostly applied to cohesive (clayey and silty) soils.

EFFECTIVE STRESS

Transmission of load from above are mainly through sub-vertical "chains" (c) and is due to the weight of the overlying soil and grain-to-grain contact. Terzaghi stated that "... stress at any point ... can be calculated from the total principal stress, σ_1, σ_2, σ_3, acting on that point..." and that if "... the soil pores are full of water under pressure *u*, the total principal stress will be composed of two parts... (of which) one part, *u*, called neutral pressure or pore pressure, acts on water and solid particles in all directions and with equal intensity."

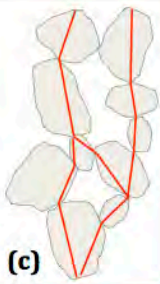
Excess pore water pressure (***u**$_e$*) will induce
- Drainage (without becoming unsaturated)
- Consolidation (vertical direction only due to lateral confinement)

Then, effective stress = total stress – pore pressure:

$$\sigma_1' = \sigma_1 - u; \quad \sigma_2' = \sigma_2 - u; \quad \sigma_3' = \sigma_3 - u;$$

$$\sigma_{\text{initial}}' = \sigma_{\text{initial}} - u_{\text{initial}} \text{ (if no volume change)}$$

Fully saturated soils comprise three stresses:
- Total normal stress (***σ***) – force per unit area transmitted in a normal direction across the plane, imagining the soil to be a solid (single-phase) material)
- Pore water pressure (***u***) – pressure of water filling void space between solid particles
- Effective normal stress (***σ'***) – stress transmitted through the soil skeleton only (inter-particle forces)



(c)

READ MORE & CITED FROM: Craig 2002; Das 2008; González de Vallejo & Ferrer 2011; Knappett and Craig 2012

8.3.2. Problem soils

Construction may involve problem soils (Box 23) where the soil may undergo volume change on changing load and/ or moisture content. Soil consistency, notably in cohesive soils, is linked to moisture content according to fixed Atterberg Limits. The plastic index is calculated as the difference between the liquid and plastic limits and is commonly used in estimations on the likelihood of expansive behaviour in soils.

8.3.3. Constructed fills and made ground

A problem soil of major concern and subject to movement in any direction addressed above (based on composition and compaction) is constructed or manmade fills. The heterogeneity of these materials poses significant problems, notably when wetted or loaded. Examples of these are mine tailings, cut-and-fill operations for construction, development over decommissioned landfills, building rubble and so forth. It is imperative that the origin of such materials are noted as such when describing the soil profile to ensure early cognisance of the likelihood of variably compacted and heterogeneous and anisotropic material. Compaction prior to construction is usually at or near optimal moisture content to ensure bulk dry density.

8.3.4. Drainage for infrastructure and excavations

Drainage and dewatering are important in construction to minimise damage and to prevent failure of slopes and are discussed in detail by numerous authors, for instance Cashman and Preene (2013). In terms unsaturated flow, variable saturation may result in intermittent seepage from, for instance, road cuttings, retaining structures and/ or into basements and foundations.

Water adversely influences the integrity of many manmade materials and should therefore be considered. The Randjesfontein study are (VZSA1 §11), for instance, details the significant influence of water (perched and not linked to the phreatic zone) in construction, as well as the cost implications of being misinterpreted.

8.3.5. Construction impacts on the water budget

Development inevitably changes the hydrological budget. Most aspects have been covered elsewhere, and include for instance (Box 34):

- Compaction of in-situ materials resulting in reduced porosity and permeability
- Sealing of surface materials with foundations, pavements and roads

Box 34. Construction Impacts on the Vadose Zone.

BOX 34: CONSTRUCTION IMPACTS ON THE VADOSE ZONE

INCREASED WATER SUPPLY DUE TO GOLF COURSE IRRIGATION

Golf Course underlain by Johannesburg Dome Granite

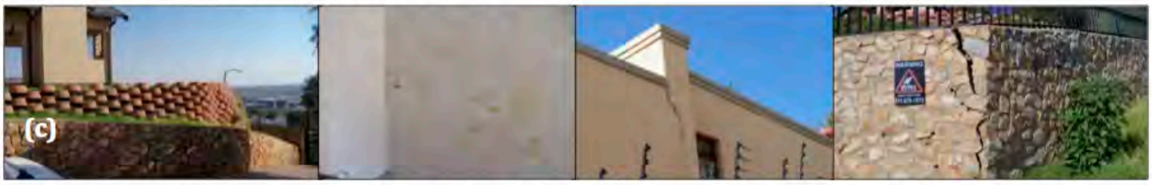
- Soils clayey-silty with distinct mottling in upper 10 cm
- Water damage to buildings resulted from increased golf course irrigation not accounted for in water budget
- Perched water table formed
- Subsequent damage to mortar and plaster and erosion of soils under foundations.

SURFACE SEALING AND IMPORTED FILL

Proposed Shopping Center underlain by Johannesburg Dome Granite:

- Developed on demolished buildings and site underlain by pavements and 1.0 m of uncompacted fill and building rubble
- Infiltration localised to unpaved areas
- Increased porosity of uncompocated materials may result in changes to the water budget in the shallow vadose zone

CUT-AND-FILL AND LEAKING PIPELINES



Residential dwelling in Johannesburg, during high-intensity rainfall period, underlain by Witwatersrand Supergroup sediments

- Cut-and-fill construction resulted in poorly compacted, highly porous made ground under down-gradient extension on an already steep gradient
- Recorded leaking underground infrastructure upslope of erf and/ or excessive 2010 rainfall may have contributed to the settlement of the fill and water seepage was noted in the retaining walls
- Resulted in extensive cracking of retaining structures and walls, as well as water damage to paint and mortar in basement.

CONFINED AQUIFER LEAKING AFTER DRILLING

Residential dwelling underlain by Johannesburg Dome granite

- Drilling and poor borehole construction resulted in water rise in borehole and gravel pack
- Water pushing up in borehole and from borehole exerting pressure into pavement area.

SWIMMING POOL EXCAVATION IN SHALLOW GROUNDWATER

- Residential dwelling underlain by Silverton Formation Shale, Pretoria Group
- Excavation of pool in flat valley intersected groundwater table.

READ MORE & CITED FROM:

- Removal of precipitation through stormwater systems or to induce focused recharge elsewhere on the site
- Additional water input through increased irrigation, notably in, for instance, urban golf courses
- Variable properties of imported fill material for cut-and-fill operations or underground pipelines
- Properties of made construction materials such as geotextiles, concrete and steel
- Leaking underground services such as pipelines and sewerage
- Possible presence of contaminated land or water where development is taking place and the associated influences on construction materials
- Artificial drainage, filtering and dewatering systems such as sumps.

8.4. Aquifer Susceptibility

8.4.1. Aquifer vulnerability

The vadose zone in groundwater-related studies serve fundamental purposes in protecting groundwater against potential contamination (as addressed in ***aquifer vulnerability studies***) and in transmitting surface water and precipitation downwards to add to the groundwater reservoir (as labelled ***groundwater recharge***), both summarised in Box 35 and discussed below.

Aquifer susceptibility is used in the broad sense. Aquifer vulnerability assessment entails one such a method (comprising numerous different approaches) to qualify the likelihood of contamination reaching the groundwater table. The main mechanism of entry of this contaminated water into the aquifer is through the process of recharge.

Aquifer vulnerability applied to the vadose zone of fractured basement granite areas in South Africa is documented by Makonto and Dippenaar (2014) and in urban areas by Sililo et al. (2001). Quantitative parameters developed in the prior as the RDSS-method during this study focussed around four parameters: Recharge, Depth to Water Table, Soil Type (conductivity) and Slope. The principles of aquifer vulnerability are well documented (e.g. Foster et al. 2002; Sililo et al. 2001) and generally include at least some incorporation of:

- Travel rates and distances through properties and/ or thickness of the vadose zone
- Precipitation, infiltration and/ or groundwater recharge to address the load and the likelihood of contaminants entering the subsurface
- Aquifer protection through confining layers.

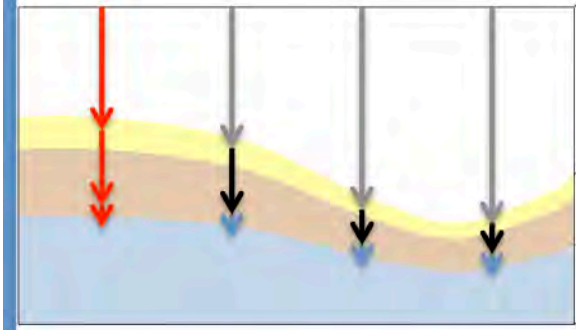
Box 35. Recharge and Aquifer Vulnerability.

BOX 35: RECHARGE AND AQUIFER VULNERABILITY

SPECIFIC VULNERABILITY

Risk exacerbated by specific contaminant:

- Contaminant properties/ toxicity
- Manner of contaminant disposition
- Persistence, bioaccumulation



INTRINSIC VULNERABILITY

ATMOSPHERE AND LAND SURFACE

Likelihood of infiltration:

- Precipitation (intensity/ duration)
- Topography/ slope
- Land use/ land cover

VADOSE ZONE

Likelihood of recharge:

- Distance (depth to water)
- Flow rate (K_{unsat})
- Confining layers

PHREATIC ZONE

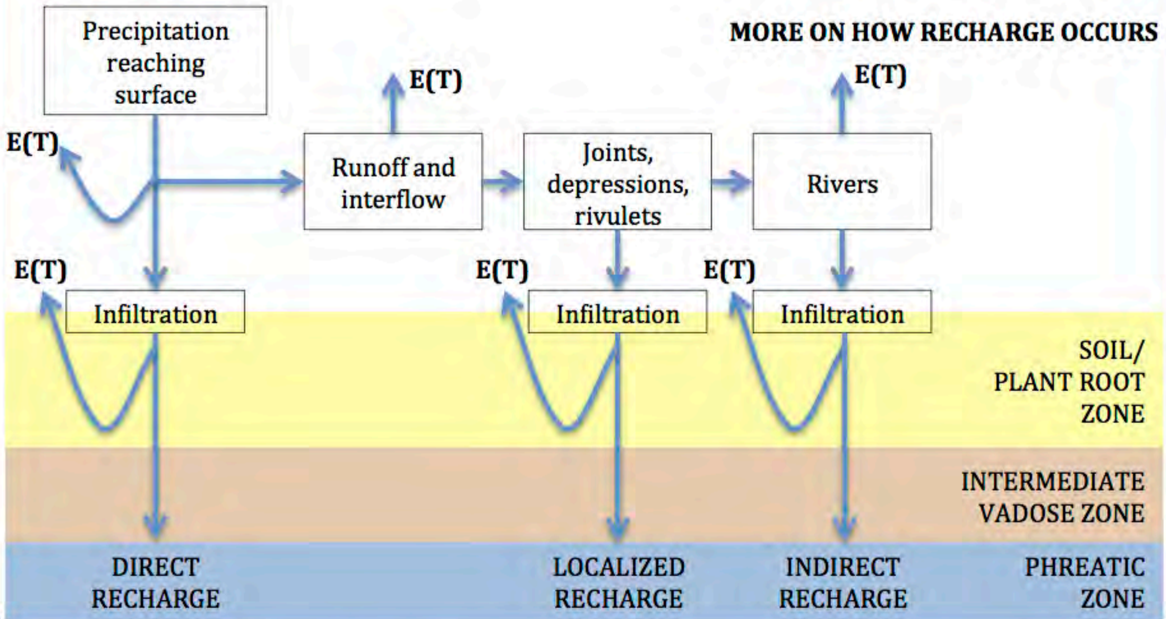
Impact on aquifer:

- Recharge rate
- Aquifer media

Contaminants enter the groundwater through the process of recharge, which forms a fundamental input parameter in most aquifer vulnerability assessments. Recharge is typically coupled with the input from precipitation, depth to groundwater (travel distance or vadose zone thickness) and the ability of the vadose zone materials to protect the groundwater (confining layers, conductivity, etc.)

Groundwater is also typically more vulnerable in areas where recharge is direct, provided that the source of contamination is located where direct recharge occurs. The potentially increased contamination of losing surface streams may, however, result in conditions where localised or indirect recharge carry more contaminants.

MORE ON HOW RECHARGE OCCURS



READ MORE & CITED FROM:

Vulnerability: Foster 2002; Saayman et al. 2007; Sililo et al. 2001

Recharge: Lerner 1997 in De Vries and Simmers 2002

The above parameters define the intrinsic vulnerability. Specific vulnerability can be included to accommodate for the specific contaminant and its disposition.

Recharge can be direct, localized or indirect. In arid countries and/ or areas where groundwater is not in direct contact with the land surface or with surface water bodies, the vadose zone forms a fundamental component of the recharge process. This thicker vadose zone and possible low-permeability horizons occurring in it can serve as additional protection to the aquifer

8.4.2. Provisional findings

Although aquifer vulnerability approaches aim to rank different portions of an area in terms of its vulnerability, the methods are generally not quantitative and represent broad index approaches. The methods are also generally very subjective and depend on the rankings and weights assigned, as well as on the interpretation of the findings.

As a useful baseline approach, more quantitative data are required for adequate interpretation of aquifer susceptibility. A high profile example of the importance of quantitative assessment of vulnerability and recharge is evident from, for instance, tailings storage facilities (VZSA2 §12) with the importance of some means of proper assessment also evident in urban land use planning, the siting of contaminant point sources such as cemeteries (VZSA3 §13.2.1) and ground-based sanitation systems.

8.5. Ground-based Sanitation

Ground-based sanitation options are numerous and generally fall within two broad types, viz. (1) pit latrines (such as the ventilated improved pit latrine or VIP) which are dry systems, and (2) on-site soakaway systems (such as septic tanks and french drains) where conditions are generally anaerobic. Investigation for the latter is well documented and prescribed in the field percolation test by SANS as per Box 27. The main considerations for such on-site groundbased sanitation systems are, however, similar to that off cemeteries, and should for sanitation specifically focus around:

- Prevention of direct recharge through the contamination source, which is why french drains are installed in septic systems, to ensure dissipation of the contaminant load
- Cognisance of whether conditions are predominantly aerobic or anaerobic
- Safe siting distance from surface water bodies and water abstraction points
- Easy excavation for installation and proper construction
- Proper monitoring of all proximate water sources, notably sources of potable water.

8.6. Riparian Interaction and Groundwater Dependent Ecosystems

The role of the vadose zone in riparian systems is that of a special type of fluvial wetland system where the stream banks and flood plains may be permanently, seasonally or intermittently indundated, saturated or waterlogged. Where the investigation of wetlands in study areas VZSA1 (Randjesfontein, Midrand) and VZSA3 (Temba, City of Tshwane) are all seasonally to intermittently wet, riparian systems have the likelihood of longer periods of waterlogging and of surface water-groundwater interaction as per Figure 8-4. Conditions governing these systems are, however, more likely the influence of the direct interaction with a stream channel and the associated surface water, and not necessarily the function of intricate hillslope processes.

The same applies to groundwater dependent ecosystems (GDEs) where the groundwater is known to source water to inland wetlands for the development of associated habitats.

8.7. Agriculture

The importance of the vadose zone in agriculture is notable in water and nutrient cycling and the suitability of the site soils for root penetration. Additionally, optimising irrigation practices is becoming increasingly important as a means of preservation of scarce water resources.

The assessment of soil conditions and on the management of water resources during irrigation have been addressed in significant detail by Stevens and Laker (2012) and Stevens and Buys (2012). Additional considerations to these, however, include the changes induced in soil hydrological properties through, for instance, removal of natural vegetation, grazing and changing soil structure through plowing.

8.8. Urban Hydrology

Impacts of urban development on hydrology incorporate bulk of the other applications as addressed in §8 as well as in the case studies presented in Part 3. The main reason for being noted separately is the highly variable and frequent change in land use which continuously affects the hydrological cycle, alters the vadose zone and changes the subsurface processes governing natural water movement.

Some distinct considerations, apart from land use change and the impacts on water availability and quality, include the following:

- Increased surface sealing results in decreased infiltration as bulk of stormwater from sealed or paved surfaces are generally discharged in stormwater systems. The exception to this is where runoff is localised an directed to unsealed surfaces, resulting in forced preferential infiltration.

- Some anticipated changes in soil properties due to changing land use include ploughing (loosening), compaction (densification), imported material or made ground (variable properties), cut-and-fill (interuption of flow paths), drying of wetlands (due to removal of source of water), creation of manmade wetlands (due to accidental or planned redistribution of water) and changes in the interflow processes and the associated movement of ions and fines.
- Connectivity between stream channels and wetlands may be lost due to interruption of the continuous water supply or through canalisation of such channels. Downstream ecosystems are inevitably influenced, and groundwater recharge may be significantly decreased due to increased evaporation from sealed surfaces and removal of water through stormwater systems.
- Aquifer vulnerability becomes increasingly important given the high density of potential sources of contamination in urban areas. Allocation of groundwater polluters are difficult, as for instance in the example of organic contamination in areas where numerous petroleum storage facilities are present. Cognisance of the vadose zone may aid in understanding the subsurface flow paths and subsequently in addresseing deteriorating urban water quality.

9. STANDARD GUIDELINES FOR VADOSE ZONE ASSESSMENT

In order to assess the vadose zone regardless of application, a unified approach borrowing from a number of disciplines is required. A multi-faceted Vadose Zone Assessment Protocol (VZAP) has been developed based on the high sensitivity of the case studies detailed in the subsequent section. It is hoped that such a methodology will increase the sensible placement of data points, relevance of data acquired, proper interpretation of results and ease of application of findings. This section documents the development of the VZAP. Appraisal of the existing methodologies and guidelines are documented in the relevant subsections.

Four means are defined in characterising vadose zone hydrological conditions. These are based on distinctly different considerations and both can be applied simultaneously.

9.1. Development-dependent Investigation

Rather than employing standard guidelines, the norm is to develop a methodology or scope per individual project. Albeit effective, this does not enforce some certain minimum requirement and often result in discrepancies. Although investigations should be focussed around the proposed development, incorporation of the effectiveness of the method relevant to the cost and ease will aid in ensuring that the most effective methods are employed within given budget, timeframe and risk. Additionally, proper superposition of determined parameters over characterised vertical and lateral heterogeneity will aid to better address uncertainty and site-specific variability. The type of development can then be superimposed at the final stage to address the findings with particular reference to the problem at hand.

9.2. Cost-Ease-Benefit Screening

Relative cost and effort are shown in relation to increasing data accuracy in Figure 9-1. This indiscrete approach is to be configured for each study, incorporating the bulk of the sampling and analyses (where and how required) as one cost, one estimate of the ease of the approach followed, and yielding one result of data certainty. This will aid in selecting the best methods based on available accuracy data and is probably most effective in smaller investigations.

Based on this, the tiered approach (§9.4) can be applied depending on data requirements with increasing effort and cost associated with higher accuracy data., and with cognisance of the identification of competent persons for relevant tiers, and with decision-making incorporated into the process.

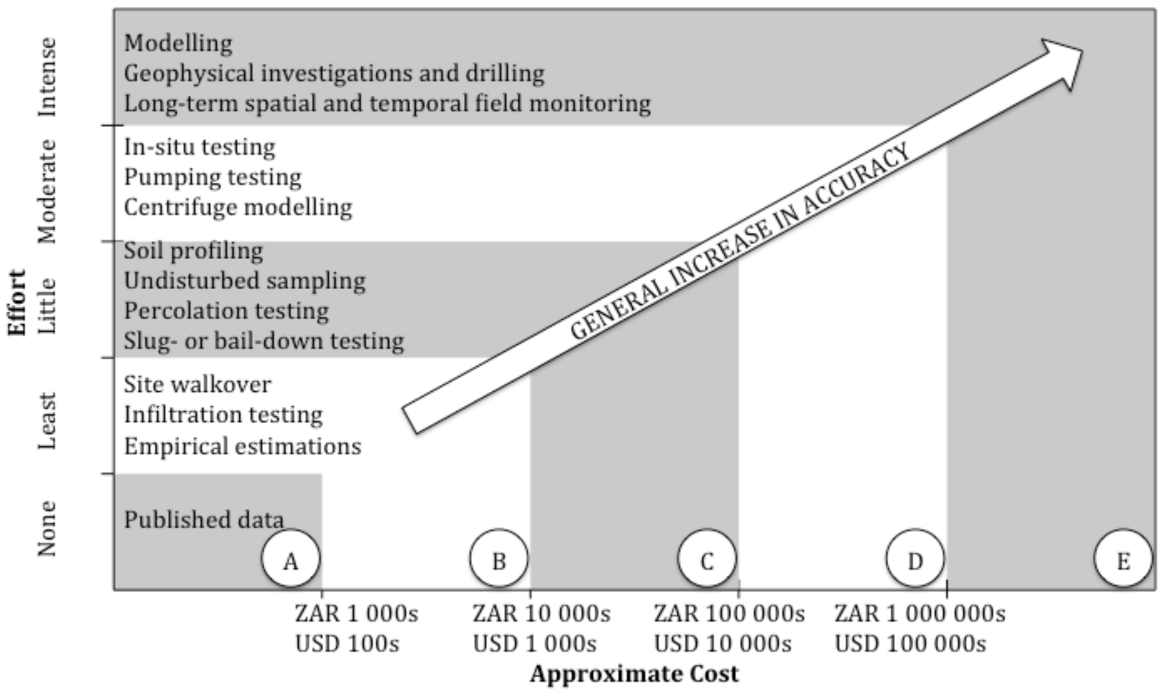


Figure 9-1. Relative cost-effort screen related to tiers of investigation.

9.3. Deducing the Comprehensive Earth System Model

The aim of proper investigation is to compile a comprehensive, trustworthy earth system model or hydrostratigraphic model comprising attributes of geology, pedology and hydrology. In generating the conceptual earth system model of the site, certain questions have to be addressed. This is clearly dependent on the purpose of the investigation, for instance, whether shallow groundwater is a positive or a negative scenario attribute may depend on the purpose of investigation, e.g. whether for the preservation of a groundwater dependent ecosystem or whether for the development of a burial site. This method is described in more detail in Dippenaar et al. (2009 and 2010) and is being refined and evaluated based on a number of case studies. The process is outlined below, documenting the approach to ensure trustworthy, detailed conceptual models are generated.

9.3.1. Stage 1: Define the settings

The surface of the area under consideration can be subdivided into zones of similar infiltration behaviour. Parameters to consider include relief and slope length, land cover and land use, available water through precipitation and anthropogenic activities such as irrigation, topsoil structure in the plant root zone, distinct macropores and any other definable influence.

9.3.2. Stage 2: Superimpose the scenarios

Scenario-superposition on the different setting zones aim to generalise vertical behaviour for with similar infiltration properties. This assumes initially, for instance, that zones at similar positions on the landscape, with similar soil structure and constant water addition should result in similar vadose zone conditions. Where this is not the case, scenarios can be used to further subdivide setting based on different behaviour of similar settings. Properties incorporated here typically include soil hydraulic conductivity under both saturated and unsaturated conditions, vadose zone thickness or depth to permanent groundwater table, vertical variation in material properties, presence or influence of perched water tables and so forth.

9.3.3. Stage 3: Define the conceptual models

The conceptual model is eventually compiled by quantifying hydraulic properties based on relevant test methodologies (which combined yield the different scenarios) for each setting. Based on this, a conceptual, quantitative three-dimensional block model can be generated for proper hydrological understanding. The interpretation of these models is then still the prerogative of the interpreter and will depend on the purpose of the assessment.

9.4. Multi-faceted Vadose Zone Assessment Protocol

Three parameters are selected to evaluate the efficacy of selected methods in quantifying hydraulic parameters. These are:

- Accuracy of the method to determine consistent and representative hydraulic conductivity of the sampled material with adequate representation of behaviour under unsaturated conditions and applicability to the relevant study
- Cost benefit of the estimation technique, whether entailing field visits, field equipment, laboratory equipment, computer software or excessive man hours
- Ease with which the parameters are determined, including for instance to accessibility and duration of field tests, sampled material required and setting-up of laboratory experiments.

Increasing effort and cost generally result in an increase in accuracy and validity of results obtained. Straightforward as this may seem, certain analyses or tests at certain stages of investigation will ensure adequate data input for the requirements. A recommended outline of a 5-tiered approach to increasing detail is shown in Box 36.

The purpose of a Multi-faceted Vadose Zone Assessment Protocol (VZAP) is (i) to ensure adequate data input (ii) in order to compile a hydrostratigraphical and geological model (iii) which includes the mechanical and hydraulic properties of earth materials (iv) for a wide range of applications (v) but based on minimum requirements to address the level of risk posed by the proposed development in the proposed area and (vi) to ensure reusability of data and findings for distinctly different future work.

In order to do this, it is proposed that a fixed sequence of activities is employed correlating roughly to the five tiers outlined in the minimum requirements. Progressing towards the higher tiers, investigation become more focused for a specific purpose with the benefit of being able to apply lower-tier input to different applications. This can be summarised as per Box 37 with elaboration in Table 9-1. It is recommended to start at A1 and move downwards until the required level of detail is reached based on the risk posed by the required development. Omissions of certain stages or requirements are at the prerogative of the competent person conducting the investigation.

Decision-making, definition of competent persons and justification for inclusion or exclusion of selected studies are discussed in the following section.

9.5. Decision-making and Competent Persons

Each tier should be followed by decision-making regarding the hydrological regime and the impacts of the proposed conditions, whether natural or anthropogenic. The decision-making process should include:

- Clear minimum requirements for follow-up work through specification of specific tier levels (e.g. C2 and C3 excluding C1 for a given proposed development), as well as identification of the relevant competent persons
- Refining of the conceptual model to increase confidence and accuracy
- Reassessment of Tier A to ensure that the impacts of the proposed development (if any) and the hydrological pathways of importance remain unchanged.

The tiered approach considers only water-related impacts, and should not be viewed as a justification for exclusion of other studies such as Phase 2 Detailed Geotechnical Investigations, Contamination Assessments, Ecological Studies and so forth.

Competent persons should be defined based on academic qualification, professional registration and vocational experience within the specific water-related field required for the relevant tier. More experience should also be required for the higher tiers where a certain level of expertise is required, notably with respect to, for instance, hydrogeological modelling.

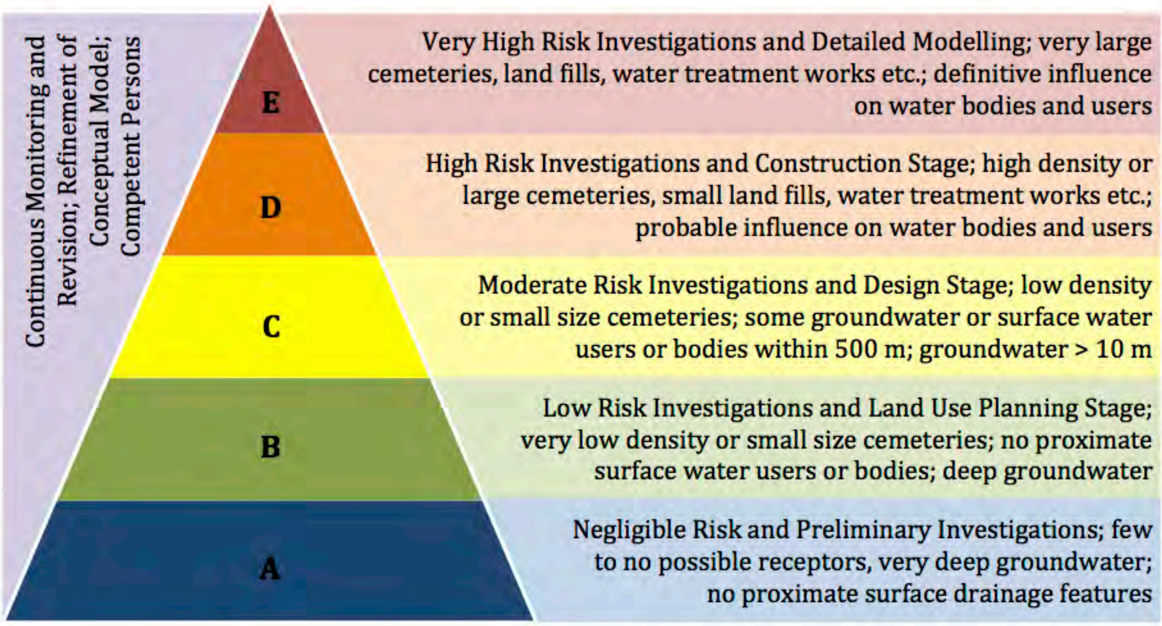
Competent persons should be confirmed after each tier to ensure compliance with such minimum requirements.

Box 36. Minimum Requirements for Vadose Zone Assessment (VZA).

BOX 36: MINIMUM REQUIREMENTS FOR VADOSE ZONE ASSESSMENT (VZA)

A 5-TIERED APPROACH BASED ON AN ACCURACY–COST–EASE MATRIX

- **Tier A** is at low cost and effort, coupled with poor confidence data and application to preliminary investigations at desk study level based on published data; not adequate for decision-making.
- **Tier B** entails a preliminary site walkover and limited field data and suffices for land use planning. Empirical estimations and non-intrusive or easily conducted field tests form the main data.
- **Tier C** is adequate for low-risk developments or small-scale influences on the hydrological cycle. Intrusive testing, borehole testing and extensive disturbed and undisturbed sampling commence.
- **Tier D** is equivalent to a detailed investigation and is adequate for proper planning, construction and operational phases. In-situ testing and extensive laboratory testing are required.
- **Tier E** is applied to high profile, high risk applications, require numerical modelling and entails most cost and effort resulting from geophysical investigations, long-term monitoring and extensive modelling.



MINIMUM REQUIREMENTS BASED ON THE 5-TIERED APPROACH

The 5-tiered approach is incorporated into the Multi-faceted Vadose Zone Assessment Protocol and supplies minimum requirements, deliverables and contents for each stage of each tier. Examples of the applications include the following:

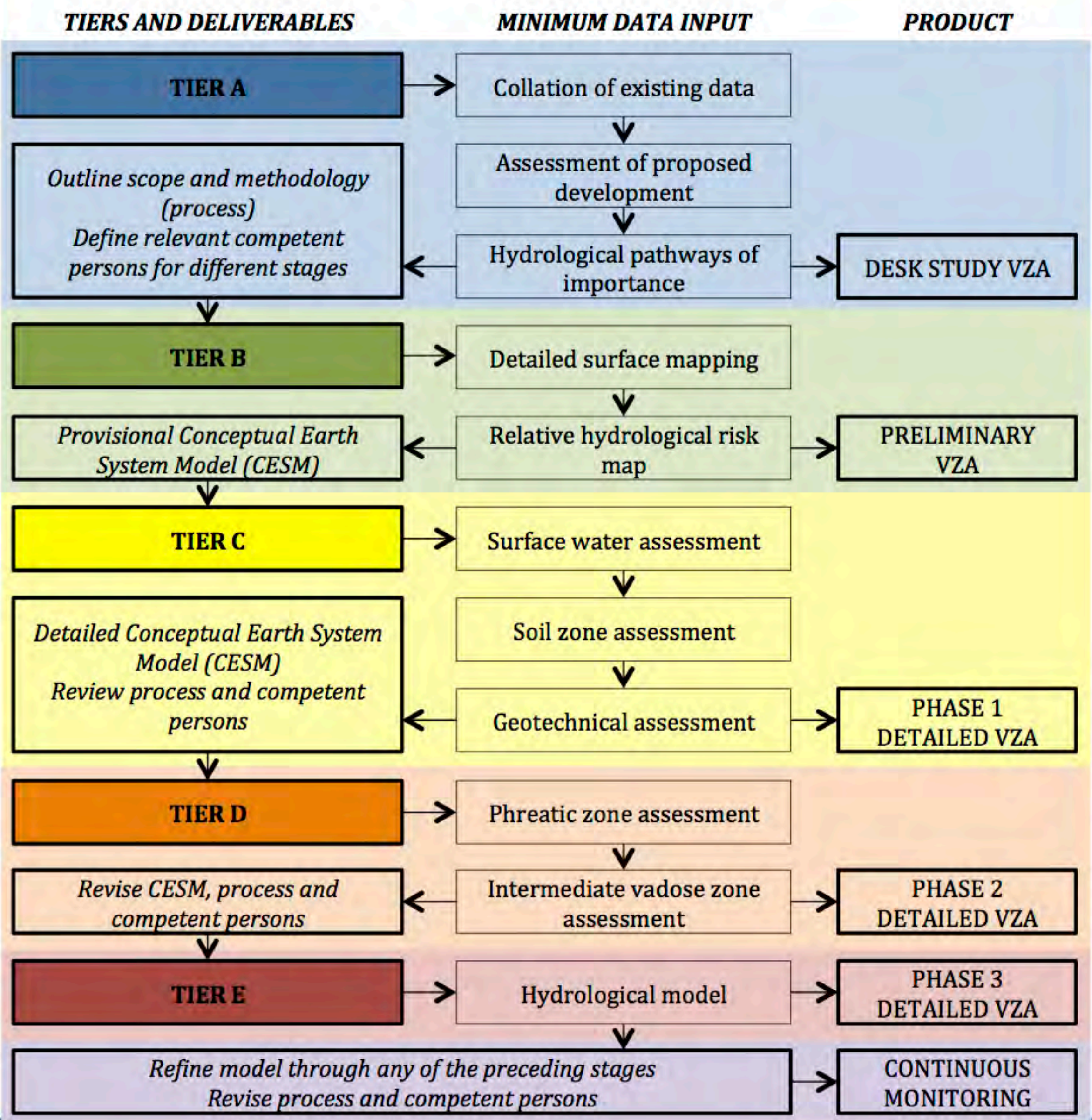
- Basic assessments, initial assessments, planning phase: Level A or B will suffice where an initial estimate of hydraulic conductivity is enough, where limited funding and effort are involved and based on which subsequent planning will happen.
- Pollution sources such as french drains and burial sites: Level C or D should supply adequate information in the characterisation of risk based on fairly cheap and easy field or laboratory tests.
- Mines, waste disposal sites, urban development: Level D and E will be required to adequately describe the system for high risk developments having significant potential impact on ecosystems, surface water and groundwater.

READ MORE & CITED FROM:

Box 37. Multi-faceted Vadose Zone Assessment Protocol (VZAP).

BOX 37: MULTI-FACETED VADOSE ZONE ASSESSMENT PROTOCOL (VZAP)

The proposed VZAP recommends five tiers of investigation, each requiring different levels of data input with increasing data certainty and effort with each subsequent tier. Stages of investigation are recommended as minimum data input with products in the form of investigation reports. Each product will suffice for a certain level of detail required. Deliverables are noted and should be addressed in the relevant Tier Report to ensure that issues can be addressed, should investigation at a higher tier be required. These deliverables generally include (i) continuous updating of the conceptual earth system model (CESM, including geology, pedology and hydrology),(ii) reevaluation of the competent persons suitably qualified and experienced to conduct further work, and(iii) revisiting the scope and objectives for the investigation at the hand of the proposed development.



READ MORE & CITED FROM:

Table 9-1. Minimum input requirements (where applicable) for a tiered Vadose Zone Protocol.

TIER	LEVEL OF DETAIL	MINIMUM INPUT REQUIREMENTS
A1	Collation of Existing Data	Maps: geological, soils, hydrology, topography
		Climatic data
		Existing water quality data
		Historical reports
A2	Assessment of Proposed Development	Details on proposed development
		Details on anticipated risks
		Details on anticipated environmental vulnerability
A3	Hydrological Pathways of Importance	Plant water availability and ecosystems
		Groundwater recharge
		Aquifer vulnerability
		Water influencing infrastructure
B1	Detailed Surface Mapping	Outcrop mapping
		Surface soils
		Land cover and vegetation
		Prevailing land use
		Drainage and topography
B2	Relative Hydrological Risk Mapping	Contaminant sources
		Hydrocensus and water table map
		Water abstraction points
		Surface drainage
C1	Surface Water Assessment	Detailed drainage
		Surface water quality
C2	Soil Zone Assessment	Detailed soil profiling
		Infiltration and/ or percolation testing
		Indicator tests (e.g. grading; hydrometer)
		Visual evidence of mobilisation and seepage
		In-situ moisture characterisation
C3	Geotechnical Assessment	Excavatability
		Stability of excavations
		Geological hazards
D1	Phreatic Zone Assessment	Drilling and aquifer testing
		Groundwater quality
D2	Intermediate Vadose Zone Assessment	Detailed hydrostratigraphy
		Deep soil and unsaturated bedrock conditions
		Drilling, augering and/ or push probe
		Penetration testing
E1	Hydrological Model	Collation of above
		Validation by field measurements

9.6. Best Practice Guidelines and Learned Societies

More information on best practice guidelines, minimum requirements and professional expectations can be found through most professional bodies and learned societies. Although vadose zone hydrology transects many specialist fields, some learned societies include (listed alphabetically):

- Ground Water Division of the Geological Society of South Africa (www.gwd.org.za)
- South African National Chapter of the International Association of Hydrogeologists (www.iah.org)
- Water Institute of South Africa (www.wisa.org.za)
- Soil Science Society of South Africa (www.soils.org.za)
- Geotechnical Division of the South African Institution of Civil Engineers (www.geotechnicaldivision.co.za)
- South African Institute for Engineering and Environmental Geologists (www.saieg.coza)
- South African Wetland Society (www.society.wetlands.za.net/)

National standards, codes of practice and legislation should also be consulted to ensure compliance with such best practice guidelines.

Part 3: Case Studies

Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, S. and Mulders, J. A.

10. INTRODUCTION TO SUPPORTING CASE STUDIES

The following section depicts case study descriptions, sampling, analysis, interpretation and results. The final conclusions have been collated and incorporated into the first sections of this document, typically under headings labelled *Provisional Findings*. The intention is not to use these case studies as discreet investigation aiming to clarify important concepts, but to use the collective dataset to understand the implications of improper investigation, lack of guidelines and oversimplification in vadose zone and, notably, intermediate vadose zone hydrology.

Laboratory credits are as follows:

- Bulk of the foundation indicator analyses were done at Soillab (Pty) Ltd in Pretoria.
- CEC analyses were conducted and partly funded by the Soil Science Laboratory (University of Pretoria).
- Bulk of the XRD analyses were conducted and partly funded by the Analytical Facility of the Geology Department (University of Pretoria).
- Bulk of the TCLP and ICP-MS analyses were conducted and partly funded by the UIS Analytical Facility in Pretoria.
- ABA tests are being conducted by Waterlab (Pty) Ltd in Pretoria.

11. VZSA 1: Ephemeral Inland Wetlands (Midrand, Gauteng)

11.1. Rationale for Study Area

Apart from being excavated and having created an environmental controversy, the site is being considered due to the exposure of an ephemeral inland perched water wetland system which is presently not considered in classical wetland classification systems. Classification generally requires a shallow groundwater table or influence from surface water, and subsequently this system that forms in the vadose zone is presently not considered a wetland (s. s.). However, the vital role played by this hydrological system needs consideration in water quality of the proximate stream and biodiversity, as well as consequences that will need to be addressed when developing the land as water will inevitably influence foundations. The inclusion is based on earth material variability typical to basement granite terrain and temporary hillslope wetlands, both resulting in selected but not definitive conclusions regarding the vadose zone and unsaturated flow.

11.2. Study Area

11.2.1. Locality and background of study area

Development has commenced in the form of excavation on Part of the Remainder of Portion 442 of the Farm Randjesfontein 405-JR, Midrand, Gauteng Province (Figure 11-1). The investigated area is bounded to the east by the N1 Highway, Olifantsfontein Road to the south, Lever Road to the west and the Development Bank of South Africa to the north (open land indicated on Figure 11-2; note the excavation in the northern portion and the visible evidence of gullies or seep areas indicated by dashed lines). This site has since been classified as a wetland, following evidence of wetland soils, waterlogged conditions and fauna and flora associated with wetlands. The wetland is temporary, seasonal to intermittent, situated on a hillslope underlain by tonalitic gneiss and occurs perched in ferricrete. The area around the site ranges from commercial to light industrial land use in the north, east and south, to residential land use in the west and southwest.

The following technical reports were available for inclusion in the study:

- Van Rooy, J. L. (2006). Report on a Phase 1 Geotechnical Site Investigation for Headway Hill Extension 1 on Part of Re/Portion 442 of the Farm Randjesfontein 405-JR, Midrand, Gauteng Province. Report Number 671. Prepared for Zoning Solutions.
- Van Rooy, J. L. (2008). Report on a Phase 1 Geotechnical Site Investigation for Headway Hill Extension 2 on Part of the Remainder of Portion 442 of the Farm Randjesfontein 405-JR, Midrand, Gauteng Province. Report Number 858. Prepared for Zoning Solutions.

- ARQ (Pty) Ltd. (2009). Geotechnical Investigation Report: Development Bank of southern Africa – Access Road. Report Number 5260/10947. Prepared for Wedge Projects.

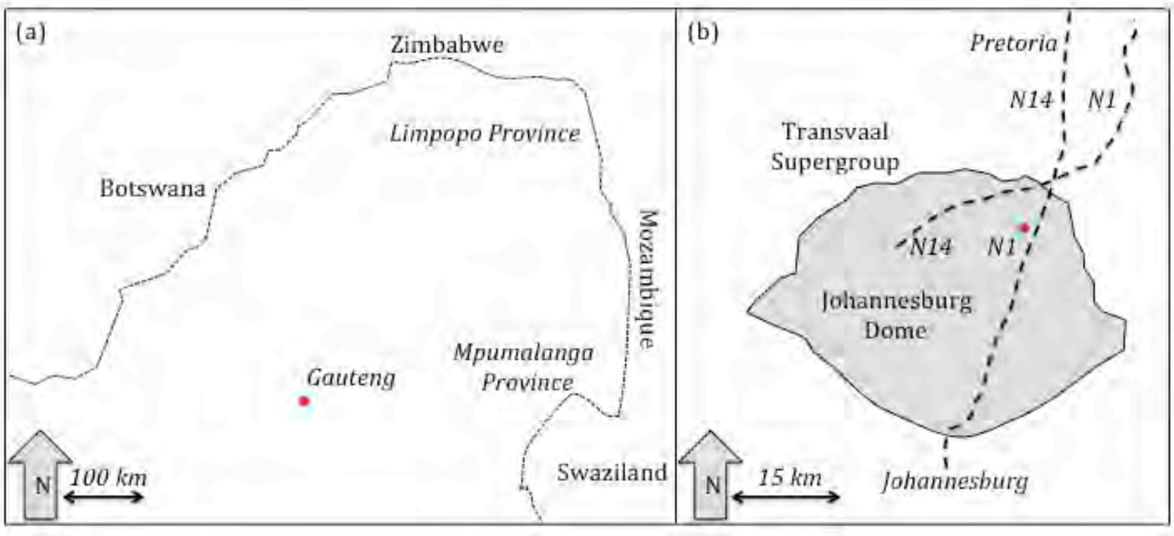


Figure 11-1. **(a) Locality of the study site in South Africa, (b) locality and extent of Johannesburg Dome Granite in Gauteng.**

Figure 11-2. **(a) Satellite imagery before excavation and (b) satellite imagery after excavation with the proximate stream and wet areas indicated (Google Earth imagery).**

11.2.2. Geology

The study area is underlain by Swazian granite-gneiss, granite in places and occasional gneiss and amphibolite (1:250 000-scale 2528 Geological Sheet) of the Johannesburg Dome Granite which was previously referred to as the Halfway House Suite (Figure 11-3, denoted by dark grey shade Z). The Johannesburg Dome Granite comprises various stratigraphic units of near-granitic composition. The area of interest is situated in the northern portion of the dome and underlain by trondjemitic and tonalitic gneiss and migmatite with mafic and ultramafic xenoliths. The granite composition becomes more granodioritic to the south (Linden Gneiss, Bryanston Granodiorite, Honeydew Granodiorite and Victory Park Granodiorite) and the outcrop is occasionally obscured by younger sediments or volcanics of the Karoo, Transvaal, Witwatersrand and Ventersdorp Supergroups, or Quaternary unconsolidated sediments (Robb et al. 2009).

Figure 11-3. Regional geology of the study area (1:250 000-scale 2528 Geological Sheet represented on Google Earth imagery, 2012).

Tonalite has sodium plagioclase as major feldspar as opposed to potassium feldspar in senso stricto granites (Figure 11-4). This change in mineralogy has certain influences on the behaviour of the residual soils and weathering products, most notably being potential dispersive behaviour resulting in piping, donga formation and significant erosion.

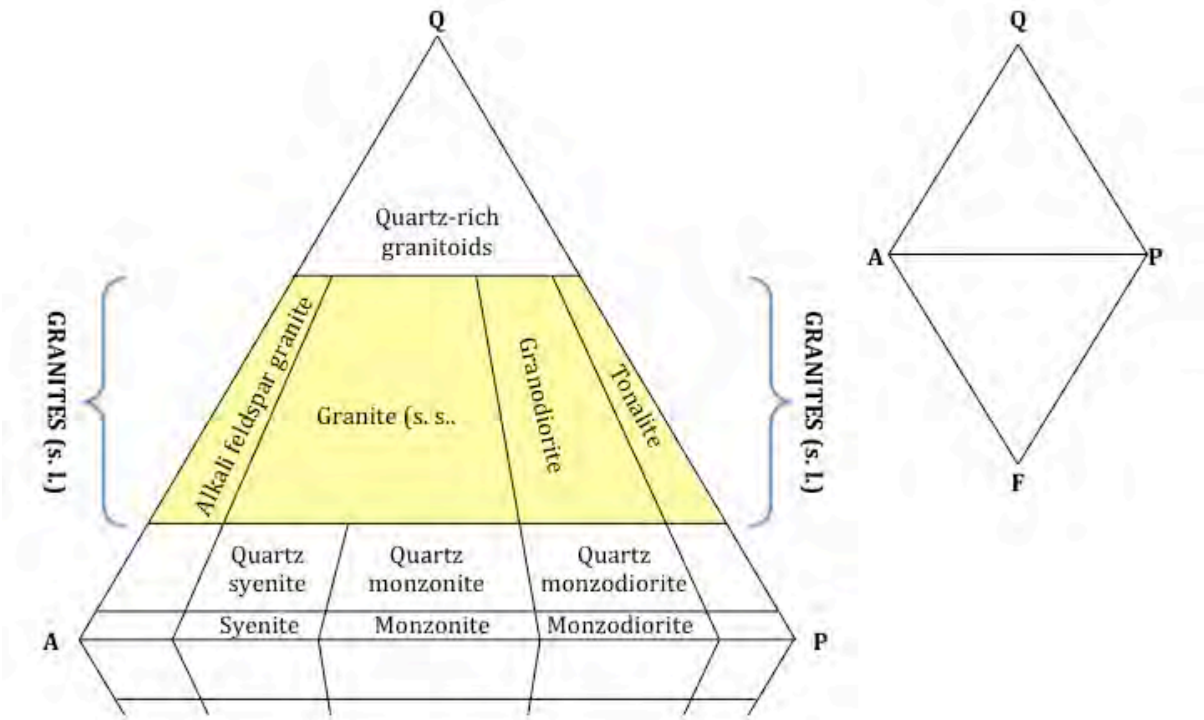


Figure 11-4. **Upper part of Quartz (Q) – Alkali feldspar (A) – Plagioclase (P) – Foid (F) diagram (excluding foids) depicting plutonic igneous rock composition (after Blatt and Tracy 1997).**

11.2.3. Local geology and geological processes

The site is underlain by yellowish-white to white, coarse-grained granite (s. s.) to tonalite with distinct bands of essentially only well-crystallised quartz, microcline or albite, or darker bands of foliated muscovitic melanogneiss. The distinct well-crystallised acid phase and foliated mafic phase forms a migmatite with alternating bands of light coloured leucogranite (granite to tonalite, coarse-grained, well-crystallised) and dark coloured melanogneiss (micaceous, foliated, medium-grained) at a large scale of 10s to 100s of metres. Bedrock is intricately fractured at shallow depth and is expected to become more intact with depth.

Quartz is weathering resistant and is expected to break down to finer fragments of SiO_2. Quartz sand is present over bulk of the site, sourced from the underlying granite. The feldspars (both albite and microcline) are fairly resistant to chemical decomposition, but will – over long periods of exposure – eventually change to clay minerals. Limited expansive clays are expected from the leucogranite phase of the migmatite and bulk of the clay minerals is typically inert kaolinite.

Iron and manganese are sourced from the melanogneiss phases and may precipitate – under changing redox conditions – as ferricrete.

11.2.4. Climate and drainage

Midrand is situated in an area of subtropical climate with summer rainfall, and receives an average of 537 mm of rainfall per year. The peak of the rainy season is reached during January (on average 101 mm), after which rainfall decreases, to the peak of the dry season in June (0 mm). Midday temperatures range on average between 17.2°C in June to 26.8°C in January. The lowest temperatures are reached in July with an average night temperature of 1.1°C (SAExplorer 2011). The study site falls within the A21C Quaternary Drainage Region of the Crocodile (West) and Marico Water Management Area, WMA 3, near the water divide with the A21B Quaternary Drainage Region to the northeast. Local drainage is to the southwest until confluence of the smaller tributaries with the Hennops River.

The site is located on a hillslope with elevations ranging from 1 560 mamsl in the northeastern corner to 1 495 mamsl in the southwest (Figure 11-5). The vegetation is classified as Bakenveld (DEAT 2000), and the area is thus grassland. Being a wetland, the connection with the permanent water table is not confirmed and water probably flows as interflow, daylighting to form the wetland and flowing as sheet flow to the stream in the southern portion of the site.

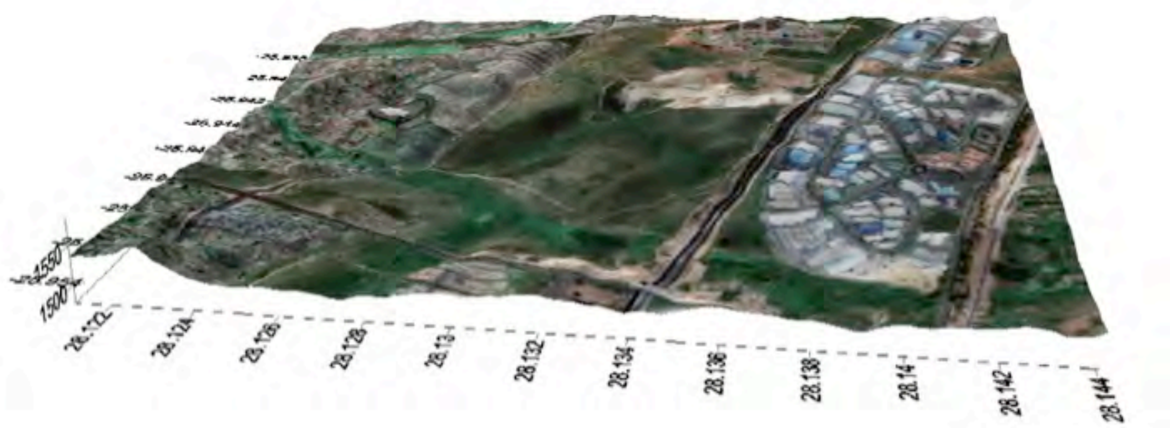


Figure 11-5. Topography of the study area.

The classification of the site as a wetland contradicts many conventions, notably due to the distinct absence of shallow groundwater or surface water. The perched water table does not satisfy majority of the international classification systems; however, the site has since been identified as such and is treated as a special type of ephemeral inland wetland sourced from perched water.

11.2.5. Prevailing conditions

The site is shown in Figure 11-6 prior to excavation. Images (a) and (d) represent the wet season in 2005 and 2009 respectively, whereas (b) and (c) were during the drier winter months of 2007 and 2008 respectively. Note the colouring on the satellite images indicating –

irrespective of seasons – possible wetter areas as outlined on Figure 11-1. The site has since been excavated for the proposed footprint, although the development has since moved to another locality (Figure 11-7). Note the wet conditions prevailing despite the dry winter months and how a new wetland appears to be forming despite the vast area excavated.

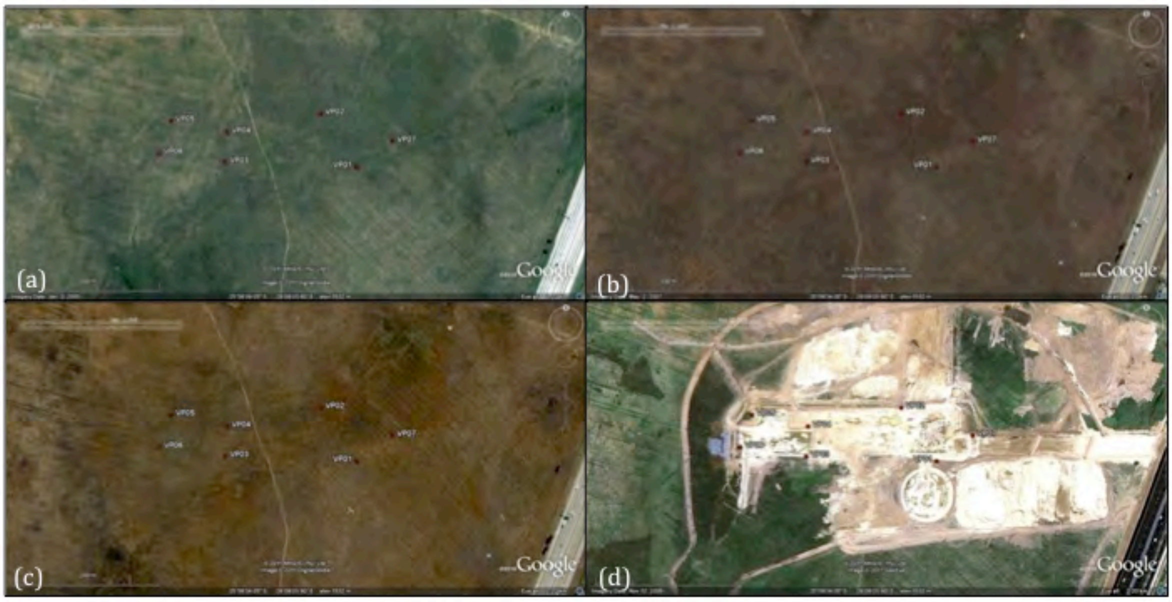


Figure 11-6. **Historical imagery of the site: (a) January 2005, (b) May 2007, (c) August 2008 and (d) November 2009 (© Google Earth imagery, 2011)**

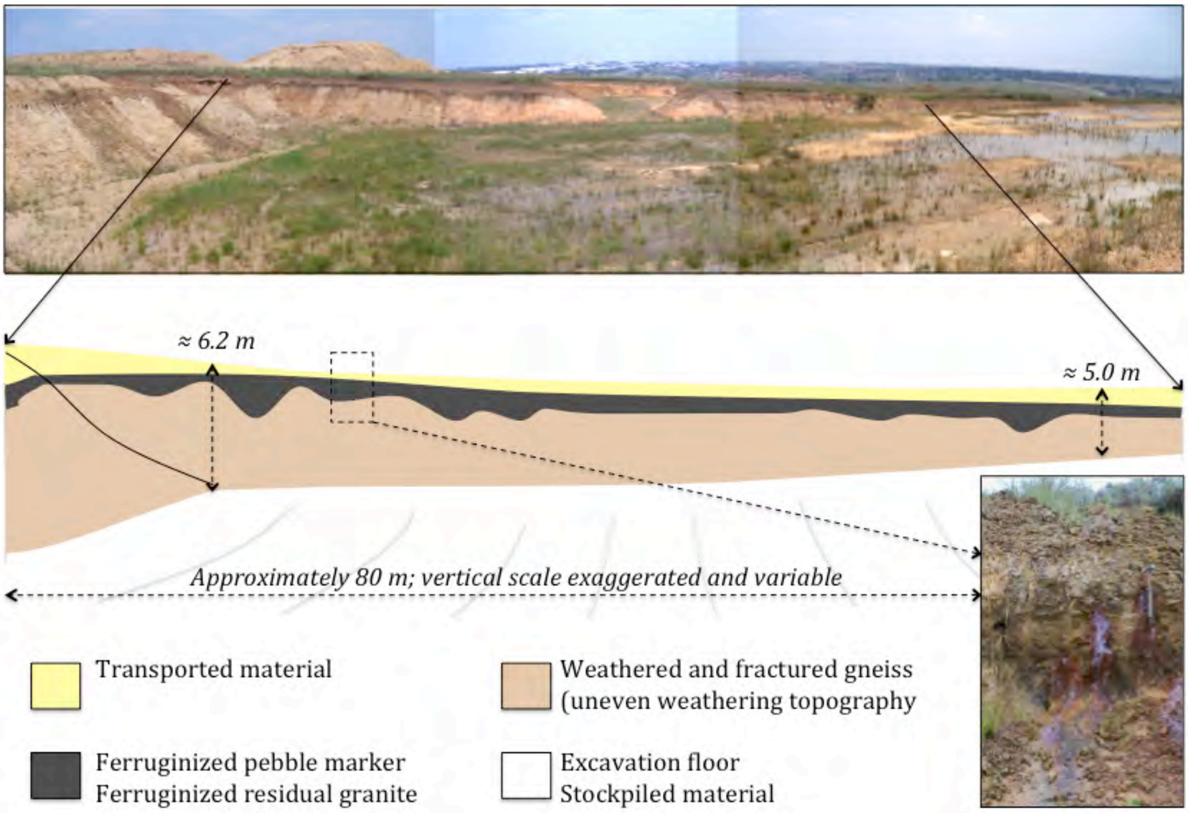


Figure 11-7. **View towards the south showing the excavation and wet conditions, as well as seepage from the ferricrete horizon.**

11.3. Materials and Methods

Field work was conducted on several occasions during 2011 and 2012. The field work followed collation of historical reports and included soil profile descriptions and a number of laboratory tests on retrieved samples to evaluate the physical, chemical, mineralogical and hydraulic properties of the site materials. For the sake of simplification, the study areas was subdivided based on land form as follows (Figure 11-8):

- Upper slope higher than 1 550 mamsl
- Upper to midslope 1 540-1 550 mamsl
- Midslope 1 525-1 540 mamsl
- Middle to lower slope 1 500-1 525 mamsl
- Lower slope < 1 500 mamsl
- Drainage features.

Figure 11-8. Land forms: northernmost shaded yellow – upper slope; central shaded yellow – midslope; southern shaded yellow – lower slope; drainage feature and wet areas indicated.

11.3.1. Profile description and physical properties

At present, the following data points relating to material descriptions are available (Figure 11-9):

- Seven test pits TP01-TP07 described for the geotechnical investigation for the DBSA access road
- Seven test pits HH01-HH07 and three auger profiles AH11-AH13 described during the geotechnical investigation for the PAP site
- 16 open profiles VP01-VP16 described during 2011 and 2012.

Figure 11-9. **Distribution of historical and new profile description positions overlain by slopes as defined (Google Earth imagery 2012).**

11.3.2. Chemical properties

A total of 39 samples were retrieved from VP01 to VP07 to characterise the vertical variation of the seven profiles down the hillslope in the excavated wetland. Analyses included soil grading and geotechnical properties, XRF, XRD, CEC, SEM and TCLP on selected samples.

11.3.3. Hydraulic properties

Field percolation tests were conducted in accordance with SANS for french drains to relate field values to empirical and laboratory results. Fourteen such tests were conducted and tests were repeated until consistent percolation rates were achieved. The positions of these test sites are shown on Figure 11-10.

Empirical approaches were also applied to evaluate the applicability of these methods to estimating hydraulic conductivity.

Figure 11-10. Positions of fourteen percolation tests depicted on surface contours inferred from Google Earth (© 2013); north-eastern contour 1 550 mamsl, decreasing by 5 m intervals to 1 500 mamsl in the southwest.

11.4. Results

11.4.1. Physical properties

The soil profiles from existing reports (numbered AH, HH and TP) and as described in the excavation (numbered VP) are summarised in Table 11-1. The soil textures for each horizon in the new profiles VP01-VP07 are shown in Figure 11-11. Note the distinct textural changes, notably over the depth of the pebble markers and ferruginized horizons, where materials become notably more gravelly. Weathered granite bedrock horizons are furthermore also characteristically more coarse-grained than surface horizons. As discussed in the subsequent section, this relates to the soil mineralogy.

Table 11-1. Generalised soil profile descriptions and depths to different horizons (m).

Profile	Colluvium	Pebble Marker	Ferricrete	Residual Granite	Completely Weathered	End of Profile
AH11	0.80	1.20	—	3.50	> 6.80	6.80
AH12	0.31	0.41	—	2.40	> 5.91	5.91
AH13	0.50	0.70	1.45	(1.45) 2.40	X	2.40
HH01	0.60	1.45	—	2.15	> 2.50	2.50
HH02	0.50	0.65	—	1.35	> 2.00	2.00
HH03	0.60	0.70	—	1.40	> 2.20	2.20
HH04	0.50	0.70	> 1.10	(1.10)	X	1.10
HH05	0.50	0.70	—	1.00	> 1.30	1.30
HH06	0.30	0.45	—	—	> 0.90	0.90
HH07	0.40	0.50	—	0.70	> 1.30	1.30
TP01	> 1.20	—	—	—	—	1.20
TP02	0.70	—	—	> 1.00	—	1.00
TP03	0.70	—	—	(1.10) > 1.10	—	1.10
TP04	0.80	—	—	(1.20) > 1.20	—	1.20
TP05	0.20	—	—	(1.20) > 1.20	—	1.20
TP06	> 1.20	—	—	—	—	1.20
TP07	0.60	—	—	(1.10) > 1.10	—	1.10
VP01	0.46	0.75	1.90	(1.90)	3.20	6.20
VP02	1.47	—	2.94	(2.94) 4.20	5.50	6.74
VP03	1.27	—	—	2.20	> 3.40	3.40
VP04	Stripped	Stripped	1.14	(1.14)	1.99	4.69
VP05	1.07	—	2.63	(2.630	> 4.26	4.26
VP06	1.14	—	2.49	(2.49)	3.83	4.97
VP07	0.85	—	2.48	(2.48)	> 3.26	3.26

— horizon not identified
X end of excavation prior to possible occurrence of horizon
( ) depth of extensive ferruginization of indicated horizon

11.4.2. Chemical properties

The XRD results for seven profiles in the excavation are shown in Figure 11-12. Of notable interest is the distinct absence of goethite in VP03 and VP07, which represents positions along the midslope and upper slope respectively. Note the distinct variation in goethite and kaolinite, depending on position on the slope and depth, where clay translocation and ion leaching processes altered the soil profiles. Regardless, quartz still dominates throughout all horizons with goethite and kaolinite being the major variable minerals relating to soil forming processes. This may relate to distinctly varying porosities as well as void sizes and connectivity in the different soil horizons, potentially explaining the occurrence of the perched water table system.

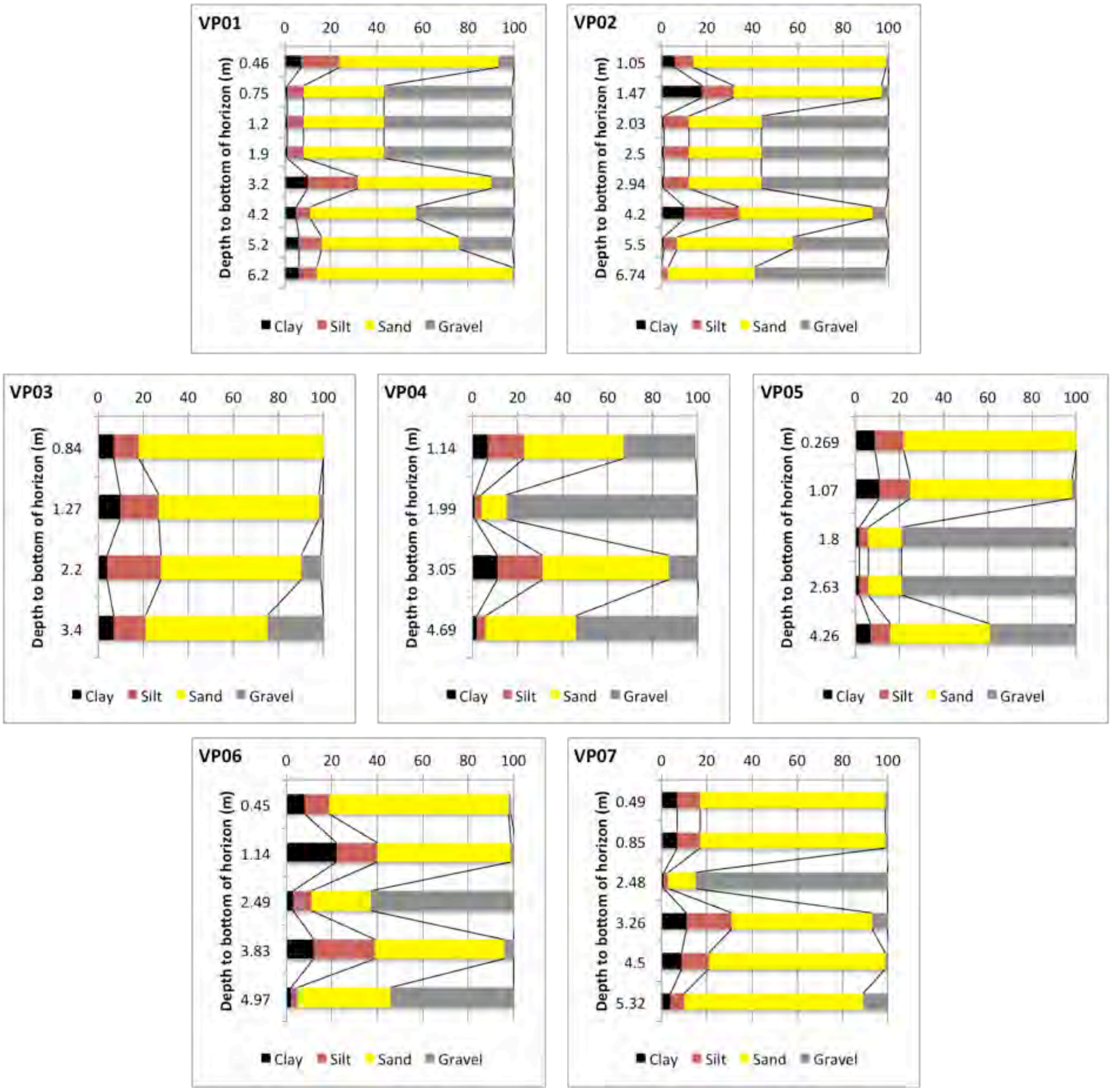


Figure 11-11. Soil textures for each horizon in profiles VP01-VP07.

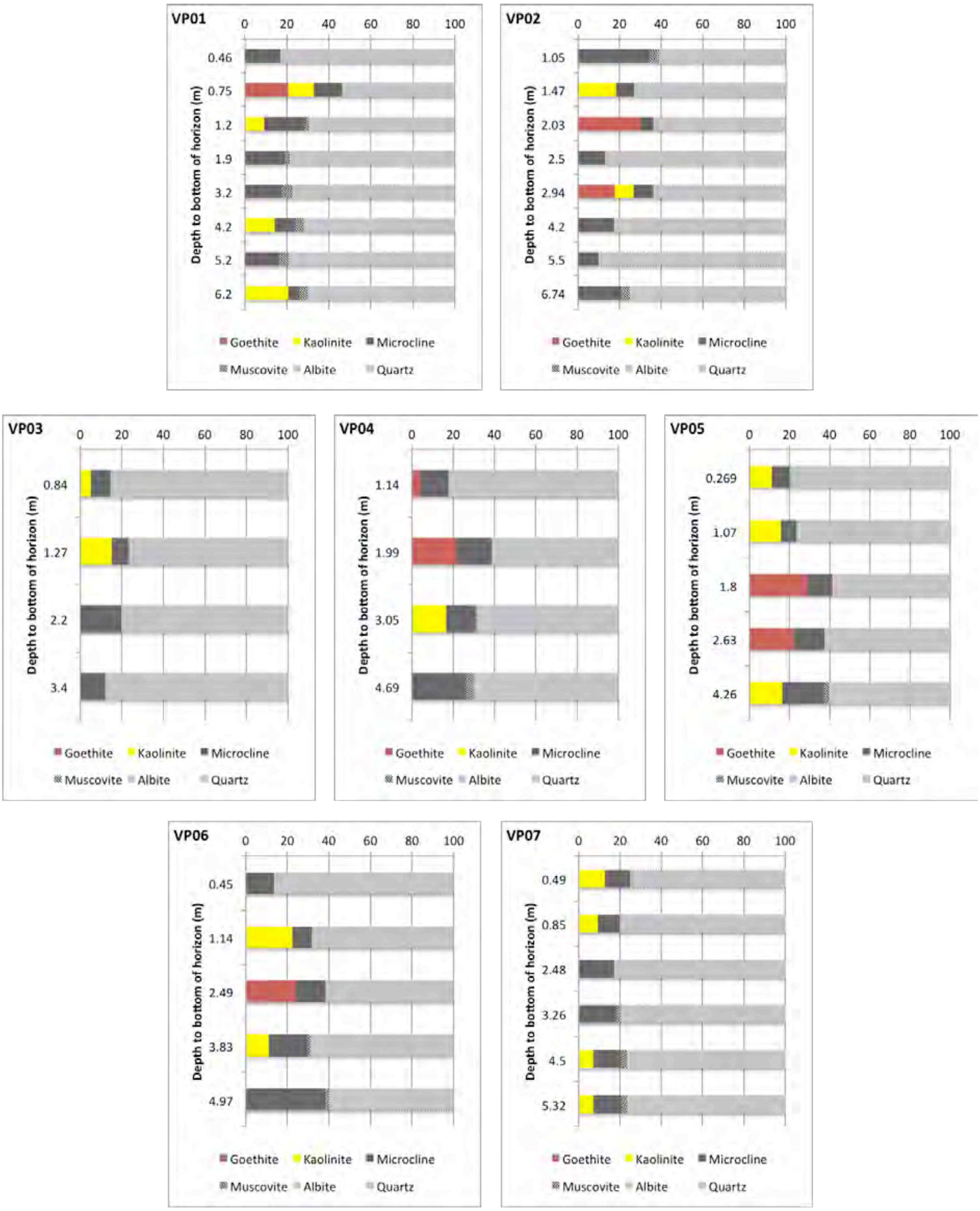


Figure 11-12. Mineral compositions (XRD) for each horizon in profiles VP01-VP07.

11.4.3. *Hydraulic properties*

Fourteen field percolation tests were conducted over the site to estimate saturated vertical hydraulic conductivity (Table 11-2). Tests were grouped into two major groups based on the landform in which the test was conducted. The upper to middle reaches of the hillslope (in the vicinity of the excavation) has an average vertical saturated hydraulic conductivity of the colluvial materials in the order of 6.9 x 10^{-5} m/s. This increases to 1.8 x 10^{-4} m/s on the middle to lower slope below the excavation.

Table 11-2. Field percolation test results.

Landform	Test	K (m/s)	Mean	St. Dev	n
Upper-Mid	Perc01	1.55E-05	6.94E-05	6.54E-05	8
	Perc07	2.13E-04			
	Perc09	3.07E-05			
	Perc10	6.21E-05			
	Perc11	9.52E-05			
	Perc12	8.77E-05			
	Perc13	1.96E-05			
	Perc14	3.15E-05			
Mid-Lower	Perc02	1.14E-04	1.81E-04	5.93E-05	6
	Perc03	1.96E-04			
	Perc04	2.38E-04			
	Perc05	1.25E-04			
	Perc06	2.56E-04			
	Perc08	1.54E-04			

11.5. Discussion and Findings

11.5.1. *Efficacy of methods*

The methods employed are discussed under the relevant methodology headings (§6.4). Empirical approaches tend to be more variable and limited to fairly small ranges of applicability. Correlation does exist with the field percolation test, notably with respect to the empirical approaches of Kozeny-Carman, Shababi et al. and Slichter. However, the following should be diligently noted when using either these empirical or field methods:

- Field percolation tests assume saturated conditions and solely vertical flow. This is not the case and saturated conditions cannot be confirmed, nor can the depth of the wetting front. Similarly, lateral dispersion of water from the test hole is inevitable and will influence final results.
- Empirical methods apply to very distinct ranges of materials, typically requiring uniform sands. Once again, these conditions rarely exist in nature, notably in old terrains and residual materials where the particle size distribution can be highly

variable due to long periods of in-situ weathering, transport and later pedogenic processes. Most materials, and notably these used in this case study, do not adhere to these narrow ranges and the intention of evaluation was solely to gain knowledge on the extent of possible misrepresentation.

Chemical methods such as XRD contribute significantly to the understanding of the chemical processes with the notable emphasis on pedogenesis and clay movement. This, evaluated together with anticipated weathering processes, contribute to the understanding of the geological model and also to the hillslope hydrology. XRD, furthermore, contributed to the increased understanding of the porosity of the various materials, supplying significantly more realistic values for further use. These porosity values also increased the reliability of the empirical hydraulic conductivity estimates. Although Istomina's approximation and density-relationship porosities had minor influence on empirical hydraulic conductivity estimates, the improved data from the latter significantly improves the understanding of the system through more accurate and representative porosity values.

11.5.2. Conceptual model of hillslope hydrology

Figure 11-13 depicts a conceptual model of the site from the upper to midslope. Inferred flow directions are indicated with zones where infiltrating or perched water are allowed to percolate deeper expected in the areas where ferricrete is absent. The section commences in the profiles without ferricrete labelled TP, HH and HH on the upper reaches of the slope, showing some ferruginization and ferricrete in the lower portions. VP07 is the first profile in the excavation and is also characterised by the absence of ferricrete. VP03 at the midslope also shows no ferricrete, with this horizon being distinctly present between the upper slope and midslope and below the midslope. Possible deeper percolation zones are, therefore, indicated on the higher slopes and in the vicinity of VP07 and VP03.

11.5.3. Micro- and mesoscale porosity

High porosity, together with small pore size and low connectivity in the upper transported soil horizons, result in water retained by adhesion with excess water gradually draining under gravity. The underlying ferricrete is less porous but with larger pores and better connectivity, resulting in cohesion between water molecules and subsequently drainage under gravity. However, as the saprolite underlying the ferricrete is once again porous but with much smaller pores and more clogging due to clay minerals such as kaolinite and mica, adhesion retains moisture with interflow in the overlying ferricrete being easier than percolation into the saprolite. This results in surface infiltration, interflow in the perched water table in the ferricrete, and limited deeper percolation in ferruginized portions (Figure 6-2).

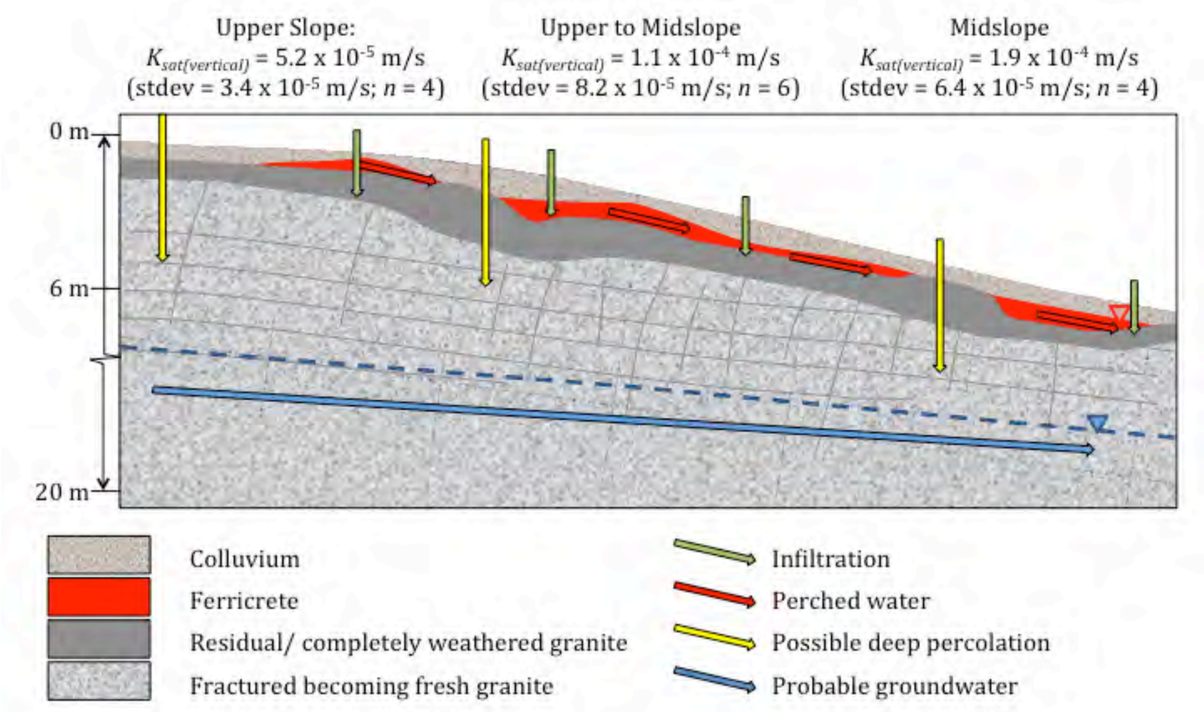


Figure 11-13. Conceptual model depicting colluvial conductivities, vertical and downslope succession of materials and main inferred possible flow directions.

The soil structure of some of the well-leached surface horizons and, to a lesser extent, granitic saprolite is open with voids created as the granular fraction (quartz and some feldspar) is being held by clay minerals. On simultaneous wetting and loading, these clays may wash out and the soil may consolidate instantaneously into denser packing. This mechanism of soil collapse is typical in these old granites and result in a permanent decrease of the void ration or porosity, and subsequently permanently alters the soil hydraulic properties (Box 24).

11.6. Advances in the Understanding of Ephemeral Inland Wetlands

Although terminology is absent for systems not linked to surface water or groundwater, these systems affect biodiversity, influences groundwater-surface water interaction and may result in seepage problems when developed. Inclusion of perched water wetlands (ephemeral, palustrine and often isolated) in wetland terminology is important, notably in more arid climates such as South Africa where wetlands (senso stricto) are scarce and scattered.

Investigation should be detailed. Focus should be on distinct indicators of these special systems, which may be present in the absence of the four classical indicators. Although the land form may be indicative, the wetness indicators may be present in surface soils, the soil form may be difficult to identify and the vegetation may be absent during dry periods or at disturbed sites which are common in South Africa. An additional indicator is recommended, relating to intermittent waterlogging of deeper soils. The term Intermediate Vadose Zone Indicator is recommended to accentuate the possible lateral or vertical upward water logging, sourcing moisture from beyond the plant root zone.

The hillslope hydrology model which can be simplified as a catena or a seep face may be more complex and may include – as in the case at hand – multiple zones of water seeps. Whether pedocretes or clays form these zones, they cannot always be simplified into one single position along a slope and should be investigated as temporally and spatially variable systems.

11.7. Contributions to the VZAP

Main issues of importance outlined during investigation of VZSA 1 include:

- The need for incorporation of temporary hillslope wetlands in wetland delineation practice despite the likely absence of majority of wetland indicators
- The importance of detailed soil profile description to be able to deduce soil hydrology from logs of geologists, soil scientists or any other discipline
- The inefficiency of many quick and easy methods such as empirical approaches in quantifying hydrological parameters
- The importance of geochemical characterisation together with physical characterisation.

12. VZSA 2: Platinum Tailings Storage Facility (Bushveld Complex)

12.1. Rationale for Study Area

The link between tailings storage facilities and the phreatic surface is not generally well discussed. The geochemical processes governing contaminant mobilisation or attenuation can be modelled, but the influence of a potentially thick and fractured vadose zone underlying such TSFs may be important in addressing aquifer vulnerability. Furthermore, tailings may not be permanently waterlogged and may behave as anthropogenic vadose zone which is periodically or intermittently waterlogged or saturated, and overlying the natural vadose zone. In context of the proposed guidelines for vadose zone assessment, the consideration of the tailings material and the underlying bedrock as likely being periodically unsaturated require specialist input.

12.2. Study Area

12.2.1. Locality

The study area is situated on a mine between Steelpoort and Mashishing in Mpumalanga Province. The exact locality is confidential and, therefore, not disclosed. The full study and all associated data are available in Huisamen (2013) and, given confidentiality agreements, no exact locality can be specified.

12.2.2. Local geology

The TSF under investigation is located on Critical Zone lithologies of the Bushveld Igneous Complex. According to Cawthorn et al. (2006), the Critical Zone consists of layered chromitite, pyroxenite, norite and anorthosite on scales of millimetres to tens of meters. The Critical Zone consists of 3 sub-zones as discussed below, from lower to upper.

The Lower Critical Zone consists of an 800 m thick sequence of pyroxenite cumulates with chromite disseminated throughout, almost ambiguously (Cawthorn et al. 2006). This sequence also contains an olivine interval as well as seven, distinct chromite seems of varying thickness.

The Middle Critical Zone marks the boundary between the Upper Critical Zone and Lower Critical Zone in the form of the MG2 chromitite layer where noritic-anorthositic cumulates first occur. The base of this zone is marked by harzburgite-pyroxenite assemblages, while the upper part represents a different magmatic cyclic unit and includes anorthosite, subsequently changing the lithology (McCandless et al. 1999).

The Upper Critical Zone marks the transition to the famous Merensky Reef in the Main Zone of the Bushveld Igneous Complex. Here, cumulus anorthite is abundantly present along with the UG1 and UG2, as well as UG3 in the case of the eastern limb chromitite seams (Cawthorn et al. 2006).

The TSF under investigation is bounded by the Dwarsriver- and Steelpoort thrust faults to the west and east respectively. The Dwarsriver fault is illustrated in Figure 12-1 to the north of the study area. The Steelpoort fault, southeast of the study area, was probably active from Transvaal (2060 Ma) to post-Bushveld (2050 Ma) times (Hartzer 1995). This fault is characterised by medium to high-grade metamorphic assemblages, specifically andalusite and cordierite, indicating its compressive, thrust nature, as well as medium to high emplacement temperatures of the Lebowa Granite Suite (Hartzer 1995). These faults are also preferred pathways for groundwater movement as the aquifer underlying the TSF is of secondary, fractured porosity. Therefore any contamination reaching the aquifer will potentially move by advection, along these secondary structures.

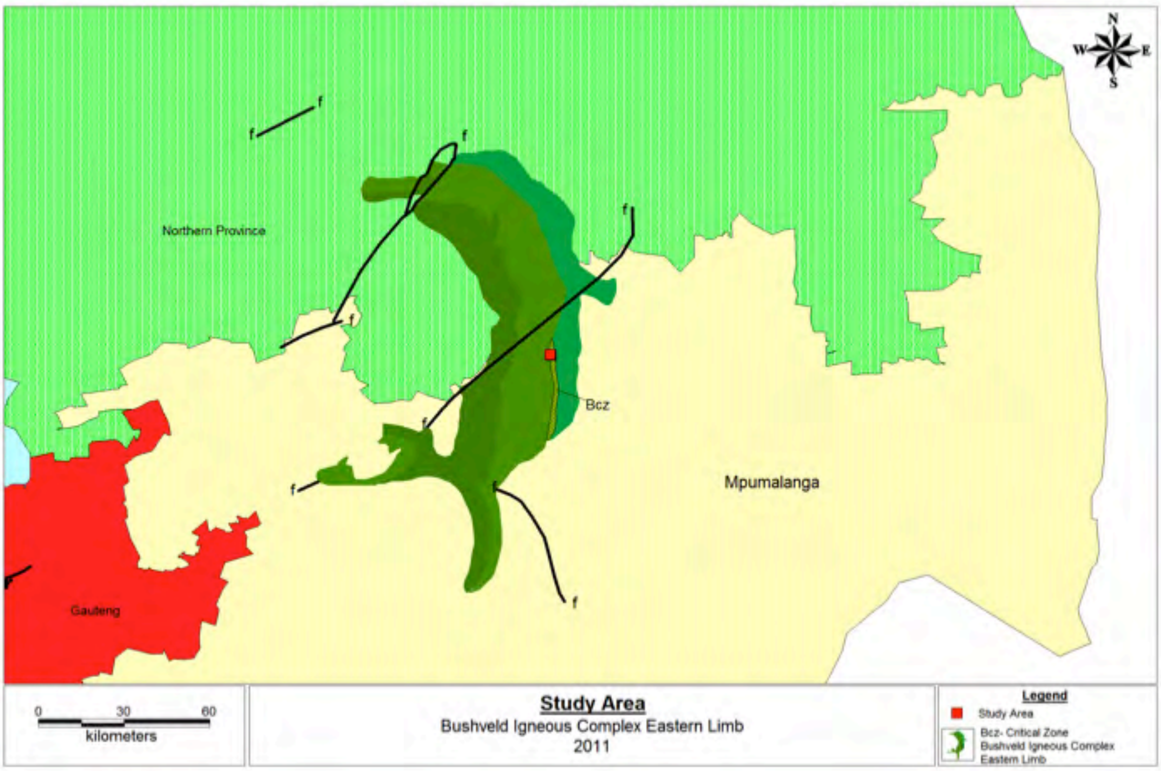


Figure 12-1. Locality of the tailings storage facility in the eastern limb of the Bushveld Igneous Complex.

12.2.3. Climate and drainage

Rainfall in the Steelpoort basin occurs predominantly in the summer months between October and March with January generally having the highest rainfall. Average annual rainfall in the area is between 630 mm and 1 000 mm, which is generally superseded by evapotranspiration figures. Thunderstorms are common in the Steelpoort basin with a low infiltration rate of soil in mountainous areas. Rainfall data obtained from the South African Weather Service representing rainfall from the last decade are generally lower with highest rainfall of the period being 643.2 mm and 663.6 mm in 2001 and 2010 respectively (Figure 12-2).

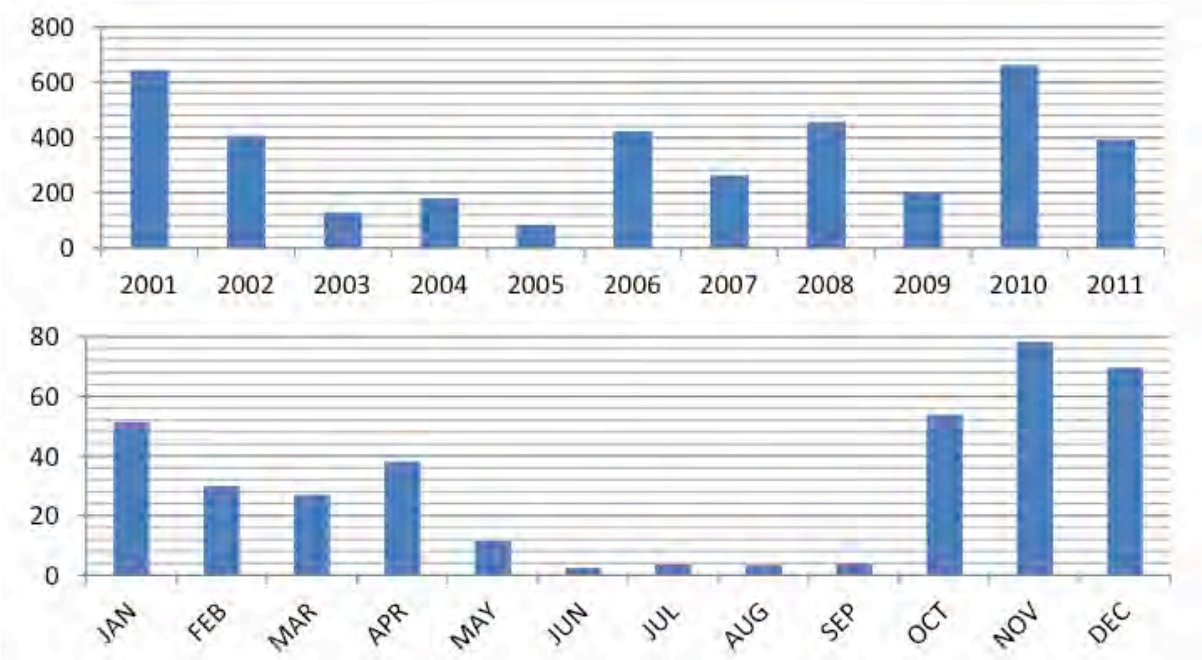


Figure 12-2. Average annual and monthly precipitation (mm) for the Steelpoort Catchment (data SAWS Mashishing station).

Surface drainage on site is generally to the west into the adjacent Steelpoort River. No streams or smaller tributaries were identified in the area, which contributes to the Steelpoort River. Lower amounts of recharge is expected on site as expansive clay-rich soils underlie the TSF which may possibly slow infiltration, even though the average annual rainfall in the area is between 630 and 1 000 mm per year.

12.2.4. Prevailing conditions

The site is presently developed as an active mine with large tailings storage facilities. Bulk of the surface is disturbed and the TSF is continuously being increased as new material is being added.

12.3. Materials and Methods

The data were collected during a number of field visits between 2011 and 2013. The tailings storage facility comprises material graded at -86 µm and of mafic to ultramafic nature. The mine where the investigated TSF is situated commenced full operation in 2008, three years after initiation of the project phase. Currently, only the UG2 reef is being mined, producing the mafic minerals in the TSF.

Based on the literature review performed and data obtained from the mine, a conceptual site model was developed to provide a conceptual understanding of the hydrogeological, geochemical and geological characteristics of the tailings-aquifer system (Figure 12-3).

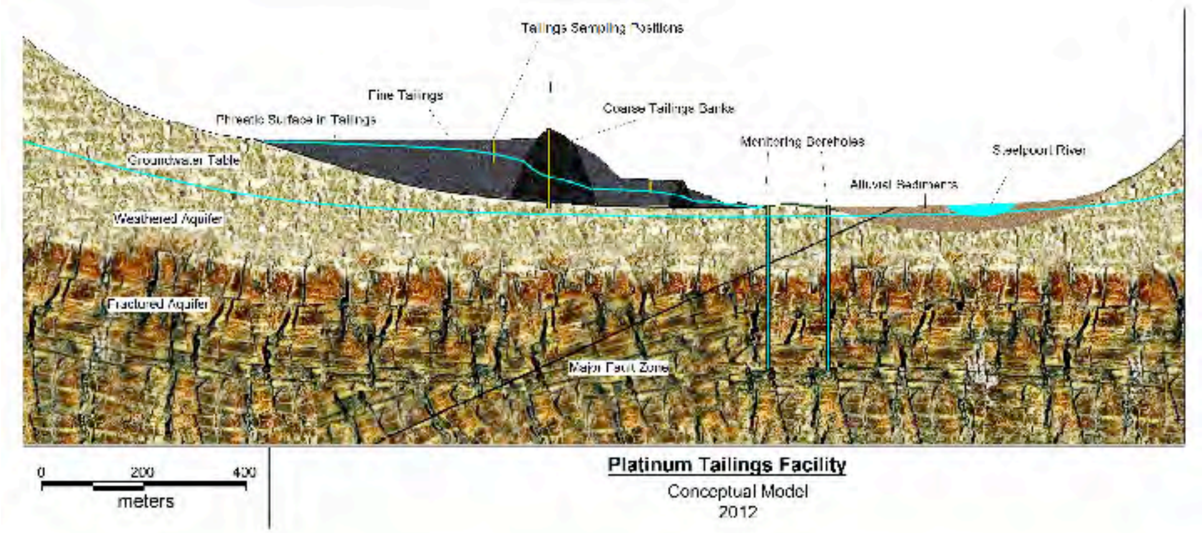


Figure 12-3. Conceptual model of the platinum tailings storage facility

The deposition of the tailings takes place using a jet method where finer tailings are deposited in the tailings dam with coarser tailings being deposited on the bank where the jet is located. Utilising this method, tailings banks are gradually generated over time from the coarser material. This method was used to generate three consecutive tailings terraces for stability of the pile. Keeping this in mind, sampling of the material was equally spaced between the three terraces to intercept the finer material. Samples of the coarser material were collected across the entire profile of the highest tailings bank to obtain representative samples of the entire tailings profile to soil level. This would also give a good indication of the moisture content distribution in the tailings to obtain data for the flow gradient and phreatic surface in the tailings.

Data on the groundwater monitoring system implemented by the mine was also provided. From this data, a generalised hydrogeological profile could be developed and was classified into two aquifer systems viz. a shallow, weathered aquifer system and a deeper, fractured rock aquifer system. The data also provided water levels in the monitoring boreholes, which were generally measured at depths within the weathered aquifer.

From the geological maps, it was evident that the Dwarsrivier fault was present in a northeast- southwest orientation adjacent to the tailings and was therefore included as an important part of the conceptual model. The geological map also indicated the presence of alluvial sediments adjacent to the Steelpoort River and this was noted as a possible third aquifer system, but less relevant to the study in terms of the localised flow under the tailings facility.

The development of the conceptual model provided a clear conceptual understanding of possible redox conditions and flow directions in the system and aided in the planning of sample and data collection for the development of the geochemical and unsaturated flow models.

12.3.1. Profile description and physical properties

Four profiles were described and sampled for laboratory analyses. The tailings material was sampled by means of hand auger drilling at the positions on the TSF. Bulk samples were retrieved for each 0.2 m from surface at three locations to depths of 3.8 m (TAH01), 3.4 m (TAH02) and 1.2 m (TAH03). The shallow sampling in TAH03 resulted from shallow hand auger refusal below the tailings material. Excavation was stopped in TAH01 and TAH02 due to collapse of the auger holes with influx of water from the tailings. Wet conditions were encountered at 3.2 m in TAH01, 0.3 m in TAH02 and 0.1 m in TAH03.

This was followed by direct push probe sampling. This drilling method produces Perspex tubes filled with an undisturbed, slightly compressed sample, preserving the mineralogical profile and moisture content in the tailings almost perfectly. This method was used to obtain a complete profile through the TSF down to natural soil level. Profile TPH was sampled at 1.2 m frequency until a final depth of 10.0 m.

12.3.2. Mineralogy and chemical composition

XRD analysis, XRF analysis and Acid Leach Tests were performed on the tailings material sampled from the Tailings Storage Facility in 2011. Additional samples obtained from the direct push probe tubes were also submitted for XRD, XRF, SEM, NAG and ABA analyses as well as three water samples for ICP scans in 2012. These analyses were performed to determine the mineralogical composition and the possible chemistry of permeating fluids at different depths in the TSF as well as present groundwater chemistry.

24 samples of the tailings material have been submitted for XRD analysis. Data obtained from these analyses were in a geochemical model to characterise mineral-fluid interaction (Huisamen 2013).

24 samples of the tailings material have been submitted for XRF analysis. The data obtained from these analyses may be used to characterise the temporal abundance of specific metals in the solid state in the tailings material as well as the characterisation of the different contaminants that may be liberated at different depths in the TSF.

18 samples of the tailings material have been submitted for TCLP Acid Leach Tests. The data obtained from these analyses will be used to calibrate the refined geochemical model as well as to assess the leachability and contaminant liberation from the tailings material.

One bulk sample of the tailings material has been submitted for ABA and NAG analyses. The data obtained from these analyses will be used to assess the acid generating potential of the tailings and in what form the acid rock drainage will occur in the TSF as well as the underlying aquifer.

12.3.3. Hydraulic properties

A falling head permeameter test was conducted on the tailings material on the 18th of October 2011. The test was conducted for 8 hours as steady state flow was already established after 2 hours. The permeameter is illustrated in Figure 12-4. It was constructed using a calibrated rain gauge; flexible PVC tubing with 10 mm diameter; 5 mm thick Perspex lids which were grooved; a 500 mm Perspex column of 5 mm thickness and an internal diameter of 150 mm; 8 marine grade turnbuckles; 2 mm thick steel cables; 2 valves to control flow and finally sealed with silicon to prevent any leakage. The Perspex column was filled with the tailings material, which was premixed with water, after which additional water was added to ensure that the maximum degree of saturation possible was obtained. Tailings material and water were added continuously as the material consolidated to ensure adequate hydrodynamic compaction. The column was sealed after insertion of the tailings and wall mounted to run the test.

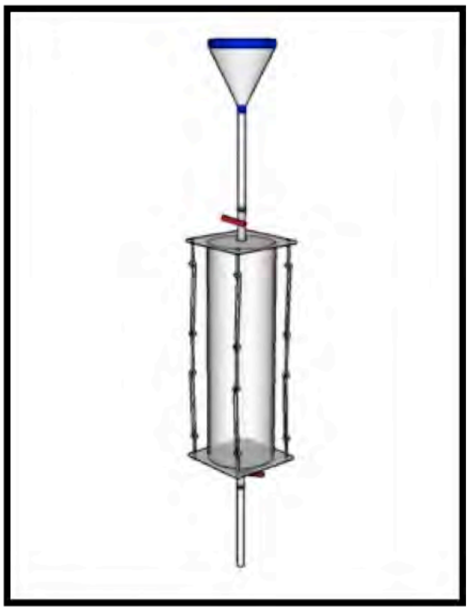


Figure 12-4. Schematic depiction of permeameter constructed for falling head and constant head tests.

A second permeameter test using the same apparatus is envisaged to be completed by the end of April 2012 to verify the results obtained in 2011 as well as for use in a column tracer test. The envisaged tracer test will make use of an uranine dye tracer, which will be detected using a spectro-fluorimeter. This test will provide a breakthrough curve, which will be used to calculate the contaminant transport properties of the tailings material, aiding in the calculation of the rate of contaminant input into the aquifer underlying the TSF.

Two pumping tests were conducted around the tailings storage facility between 14 and 16 March 2012 on existing monitoring wells to determine the hydraulic properties of the underlying aquifer. The tests were performed on two wells located between the tailings and the

Steelpoort River, which is considered to be a possible receptor of contamination. A pump was inserted to a depth where a known water strike was encountered during drilling as indicated by information received from the mine. The wells were pumped at a low discharge rate equal to the observed blow yield obtained during drilling, with water level readings being noted at differing intervals to obtain high-resolution data. This was performed using a TLC dipmeter. The low yielding wells were each pumped for a limited time period as steady state conditions were reached within 2 to 3 hours of pumping, and left to recover to a level as close as possible to the original datum water level.

The data obtained from these tests were then interpreted using AQTESOLV software to determine the hydraulic parameters of the aquifer such as hydraulic conductivity, transmissivity, fracture depths, no flow boundary conditions as well as aquifer storativity. AQTESOLV is a software package used to analyse pumping tests, slug tests and constant-head tests.

12.3.4. Modelling

The data collected from the field work, testing and analyses, were used to construct and calibrate geochemical and unsaturated flow models. The models were used to predict the future flow and chemical behaviour of the tailings, as well as to attempt to explain the processes that are currently taking place in the material.

12.4. Results

12.4.1. Profile description and physical properties

The four profiles are physically fairly homogenous, representing material crushed to fixed particle size diameter.

12.4.2. Mineralogy and chemical composition

12.4.2.1. XRD and XRF

Chlorite, muscovite and anthophyllite phases can all be observed to be minor phases in the tailings profile with biotite and diopside phases increasing with depth. Talc and lizardite can also be found throughout the tailings profile, approximately inversely proportional to the abundance of the enstatite phase, which may indicate talc formation as a secondary mineral after enstatite breakdown by subsurface hydrothermal alteration. Chromite in the profiles showed little to no variation, indicating its stability under a wide range of redox conditions as well as temperature and pressure conditions during the formation of the reef.

The mineral phases found in the natural vadose zone on site predominantly consisted of anorthite, chlorite and kaolinite. Chlorite can be directly linked to the weathering of orthopyroxene minerals such as enstatite while kaolinite is a product of anorthite breakdown in the soil environment. Chromite was found as a minor phase in the soil profile which may indicate mixing from tailings material, although its low abundance may also indicate natural mixing from the underlying bedrock and its high resistance to weathering in the natural soil environment and redox conditions.

Correlation of specific trace elements with specific major elements from the XRD data is shown in Figure 12-5. Table 12-1 shows the main deductions. Further poor to unacceptable correlations existed between Cu and S (R^2 = 0.065) and Cu and Fe (R^2 = 0.15), possibly from chalcopyrite. The good correlation of Fe to Si is negative, confirming that the sulphide phase, chalcopyrite, is probably the main source of this metal in the system.

Table 12-1. Summary of correlated trace elements and major elements from XRD.

Elements	Correlation	Deduced Phases
Ca:Si	Linear trendline; R^2 = 0.76	Anorthite, diopside; Ca:Si mole ratio 1:2
Al:Si	Linear trendline; R^2 = 0.96	Anorthite, biotite, chlorite, muscovite, magnesiohornblende Al:Si Mole ratio 2:2
Mg:Si	Linear trendline; R^2 = 0.91	Enstatite; Mg:Si mole ratio 2:2
Na:Si	Linear trendline; R^2 = 0.67	Possibly magnesiohornblende; precipitated Na-salts and amorphous phases; Na:Si mole ratio uncertain
K:Si	Linear trendline; R^2 = 0.80	Possibly biotite; K:Si mole ratio 1:3
Fe:Si	Linear trendline; R^2 = 0.98	?
V:Cr	Linear trendline; R^2 = 0.95	Chromite; trace abundance
Co:Cr	Linear trendline; R^2 = 0.95	Chromite; trace abundance
Ni:Cr	Linear trendline; R^2 = 0.95	Chromite; trace abundance

Precipitation of salts is evident and is possibly ascribed to the reaction of metals with water moving through the tailings material (Figure 12-6).

12.4.2.2. Reflected light microscopy

Reflected light microscopy was performed on four polished sections using an Olympus Petrographic Microscope with 5x, 10x and 50x magnification. TPH1.2T (depth 0.01 m) shows two grains of chalcopyrite – the only identified from the thin section. Some alteration is evident possibly due to weathering (Figure 12-7a).

TPH2.2.4B (depth 2.4 m) contains some pyrite (left, Figure 12-7b) and chalcopyrite in the silica phase (right, Figure 12-7b). Sulphides appear somewhat more abundant and less altered, indicating shorter exposure to oxidizing environments. TPH6.7.2T (depth 6.01 m) contained limited sulphides, showing only one almost unaltered crystal of chalcopyrite in the entire thin section (Figure 12-7c). TPH8.4.9B (depth 9.6 m) also contained a single occurrence of pyrite and chalcopyrite, but appearing completely unaltered indicating highly anoxic conditions at the base of the TSF. The abundances of sulphide phases in the tailings can be concluded to be low based on the reflected light microscopy.

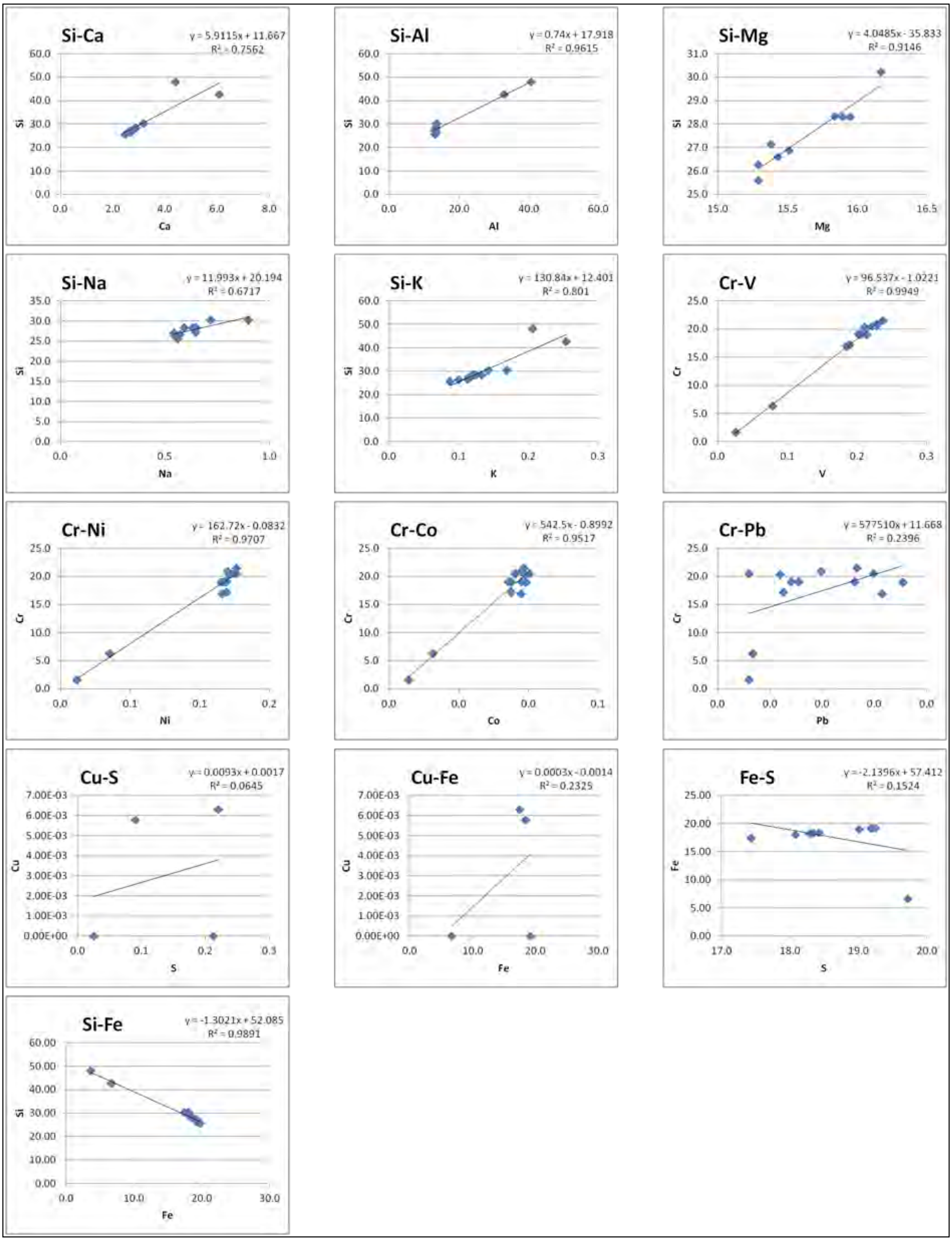


Figure 12-5. **Correlation of major and trace element abundances from XRD.**

Figure 12-6. Precipitation of salts due to metals reacting with acidic seepage through the tailings.

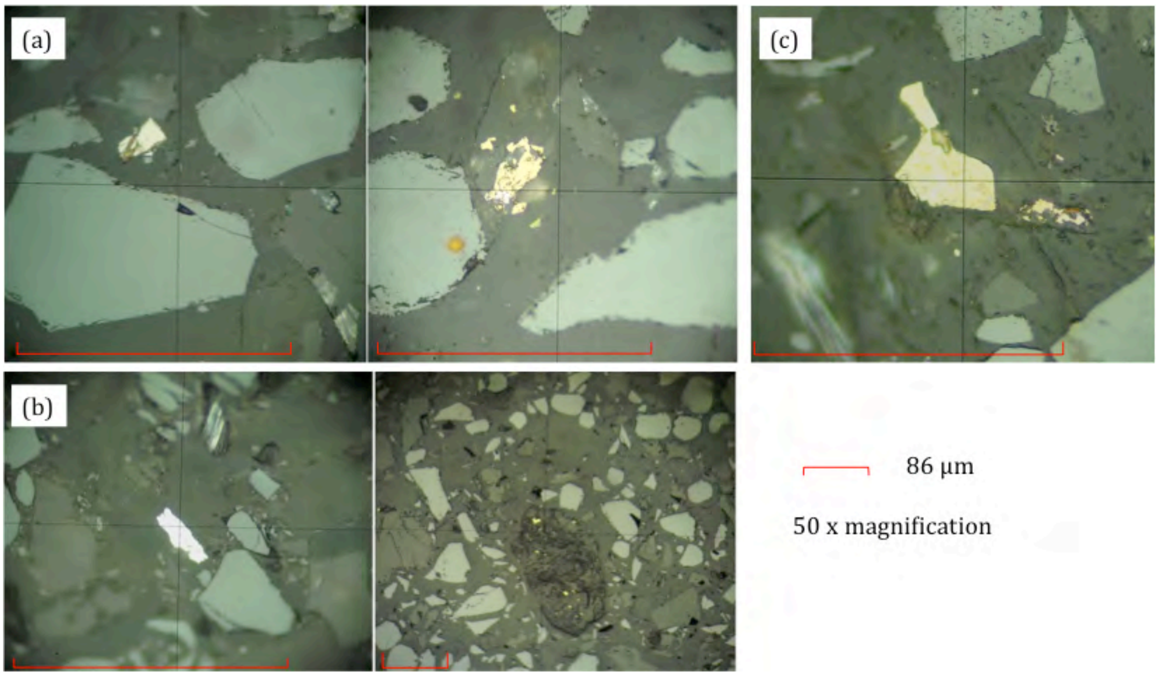


Figure 12-7. Reflected light microscopy for (a) TPH1.2T, (b) TPH2.2.4B and (c) TPH6.7.2T.

12.4.2.3. Acid-base accounting and net acid generation potential

Results of Acid-Base Accounting on sample TRPTS1 are shown in Table 12-2. A duplicate sample was submitted to ensure reproducible results.

Table 12-2. Acid-Base Accounting Results.

Acid-Base Accounting	TRPTS1 (lab nr 4114)	TRPTS1 (lab nr 4114D)
Paste pH	6.1	6.1
Total Sulphur (%) (LECO)	0.02	0.02
Acid Potential (AP) (kg/t)	0.62	0.62
Neutralisation Potential (NP)	8.50	9.50
Nett Neutralization Potential (NNP)	7.88	8.88
Neutralising Potential Ratio (NPR) (NP : AP)	13.73	15.34

The pH of the past (6.1) indicates the sample was mixed with distilled water to form a paste that has a liquid to solid ratio of 1:1. However, due to the nature of the test being performed over one hour, the paste pH value may be slightly skewed due to the time dependant reaction rates of sulphides and sulphates in the material, possibly generating acid in this time frame.

The total sulphur percentage of the sample was found to be 0.02% and the acid generation potential was calculated to be 0.062 kg of acid per ton of rock (calculated by multiplying the total percentage of sulphur by a factor of 31.25). The neutralisation potential was calculated, after treatment of the sample with a known volume of HCl and back-titrating it with a known volume of NaOH, to determine the amount of unconsumed acid and the neutralisation potential of the rock can then be expressed as kg $CaCO_3$/ton of rock and represents the theoretically available amount of calcite available in the rock, to neutralise acids.

The nett neutralisation potential was calculated by subtracting the acid generation potential from the neutralisation potential and amounted to 7.88 kg $CaCO_3$/ton of rock in excess. The neutralisation potential ratio was found to be positive in the sample as well as in the duplicate sample at an average of 14, indicating an unlikely ability of the rock material to generate acid. Tailings material is considered not potentially acid generating unless significant preferential exposure of sulphides exists, or extremely reactive sulphides in combination with insufficient reactive acid neutralisation potential are present (Price 1997).

12.4.2.4. Water quality

Water samples were collected from the toedrain of the tailings facility, two adjacent monitoring wells and the Steelpoort River during March and April of 2012. These samples were submitted for inductively coupled plasma- optical emissions spectroscopy analyses (Table 12-3).

Sample TOEDRAIN was collected from a toedrain of the TSF to give a direct indication of the composition of fluids permeating the tailings and is especially useful in the validation of geochemical models. Samples TRPMW6S and TRPMW9S were collected from shallow monitoring wells between the TSF and the Steelpoort River and sample STP RIV was collected from the Steelpoort River to the west of the TSF. The chemical data obtained from this sample would give an indication if any contamination reached the river by groundwater flow and if the river is impacted by this contamination, making it a receptor.

Table 12-3. ICP-OES results for water samples.

	Ag	Al	As	B	Ba	Be
LoD	<0.025	<0.100	<0.010	<0.025	<0.025	<0.025
TRPMW6S	<0.025	0.177	<0.010	<0.025	<0.025	<0.025
TOEDRAIN	<0.025	0.156	<0.010	<0.025	<0.025	<0.025
TRPMW9S	<0.025	7.28	<0.010	0.029	0.030	<0.025
STP RIV	<0.025	0.228	<0.010	<0.025	<0.025	<0.025
	Bi	Ca	Cd	Co	Cr	Cu
LoD	<0.025	<2	<0.005	<0.025	<0.025	<0.025
TRPMW6S	<0.025	179	<0.005	<0.025	<0.025	<0.025
TOEDRAIN	<0.025	66	<0.005	<0.025	<0.025	<0.025
TRPMW9S	<0.025	99	<0.005	<0.025	0.044	<0.025
STP RIV	<0.025	29	<0.005	<0.025	<0.025	<0.025
	Fe	K	Li	Mg	Mn	Mo
LoD	<0.025	<1.0	<0.025	<2	<0.025	<0.025
TRPMW6S	0.225	<1.0	<0.025	102	0.026	<0.025
TOEDRAIN	<0.025	1.7	<0.025	96	<0.025	<0.025
TRPMW9S	37	2.4	<0.025	113	0.377	<0.025
STP RIV	0.133	<1.0	<0.025	23	<0.025	<0.025
	Na	Ni	P	Pb	Sb	Se
LoD	<2	<0.025	<0.025	<0.020	<0.010	<0.020
TRPMW6S	40	<0.025	0.107	<0.020	<0.010	<0.020
TOEDRAIN	54	<0.025	0.149	<0.020	<0.010	<0.020
TRPMW9S	145	<0.025	0.063	<0.020	0.010	<0.020
STP RIV	8	<0.025	<0.025	<0.020	<0.010	<0.020
	Si	Sn	Sr	Ti	V	W
LoD	<0.2	<0.025	<0.025	<0.025	<0.025	<0.025
TRPMW6S	14.6	<0.025	1.1	<0.025	<0.025	<0.025
TOEDRAIN	9.5	0.030	0.430	<0.025	0.037	<0.025
TRPMW9S	17.2	0.026	0.640	0.060	<0.025	<0.025
STP RIV	7.5	0.084	0.103	<0.025	<0.025	<0.025
	Zn	Zr				
LoD	<0.025	<0.025				
TRPMW6S	<0.025	<0.025				
TOEDRAIN	<0.025	<0.025				
TRPMW9S	0.122	<0.025				
STP RIV	<0.025	<0.025				

Figure 12-8 shows Stiff diagrams constructed using the major cation and anion concentrations in the water samples. It can be seen that Ca and Mg are the most abundant cations in solution but show an abrupt decrease in the STP RIV sample. Abundant anions in each sample are CO_3 and HCO_3, which increase with distance from the tailings. Cl decreases steadily with distance from the tailings and abruptly decreases in the STP RIV sample with the same trend evident for SO_4. The Stiff diagrams appear to show a link between groundwater and surface water in the study area with a large dilution factor present in the river as a logical chemical evolution of the major ions takes place with distance.

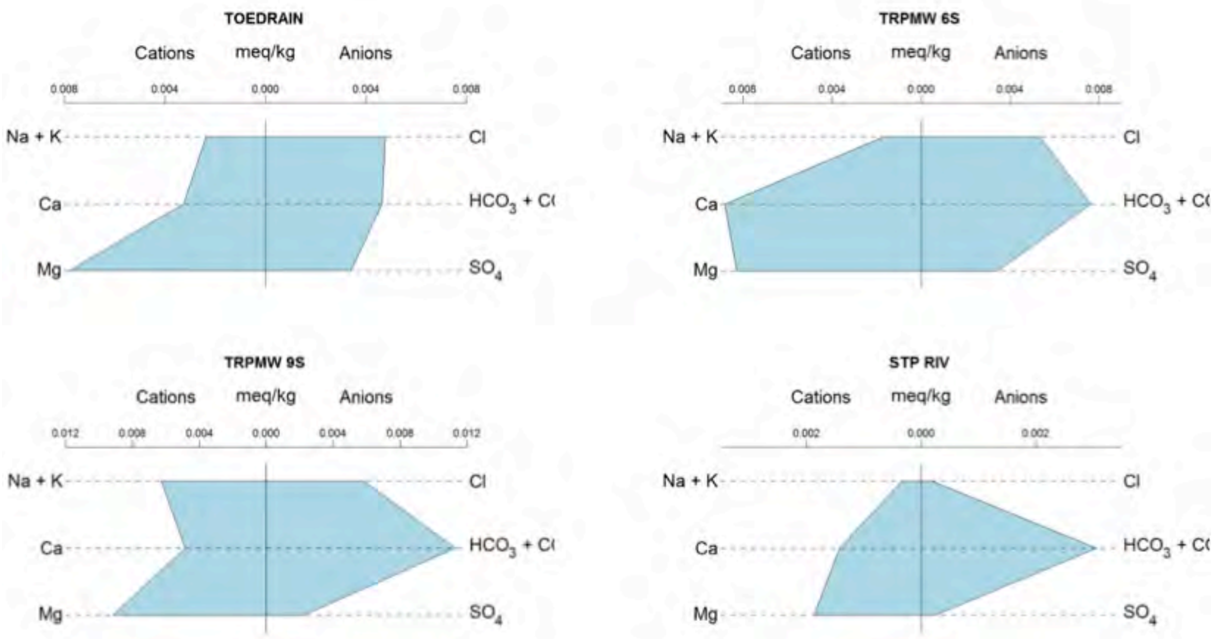


Figure 12-8. Stiff diagrams of major cations and anions in groundwater and surface water samples.

Figure 12-9 also illustrates this possible link with a Piper diagram. Samples TOEDRAIN and TRPGWM6S plot in the quadrant representing Ca-SO_4 waters and reflects gypsum groundwater and mine drainage. Samples TRPGWM9S and STP RIV plot in the quadrant representing Ca-HCO_3 waters and relate to shallow, fresh groundwater. TOEDRAIN and TRPGWM6S also plot very close to the border of the Ca-HCO_3 quadrant, indicating slight influence by mine drainage. The same chemical fingerprint may link these samples and contamination released from the tailings may reach the river. However, higher concentrations of major cations and anions were found in the groundwater as opposed to the river, possibly due to the dilution factor in the river. Groundwater is, therefore, considered to be the pathway in the system and groundwater users may be at risk.

12.4.3. Hydraulic properties

Falling head permeameter test data are shown in Table 12-4. The data were interpreted to determine the saturated hydraulic conductivity of the tailings material. Hydrodynamic compaction of tailings material is assumed and, as the tailings represent anthropogenic, homogenous and isotropic material, sample disturbance is not considered a concern. An average hydraulic conductivity of almost 4×10^{-9} m/s was calculated and is in accordance with data published by Jorgensen et al. (1998) and Malmstrom et al. (2006). This slow rate of water movement through the tailings corresponds to 3.44×10^{-4} m/d under unity hydraulic gradient and a possible fluid discharge of 0.34 litres per day per square meter cross-sectional area. However, saturation may not be encountered under natural conditions and the hydraulic gradient may be below one, and subsequently fluid discharge may be significantly less.

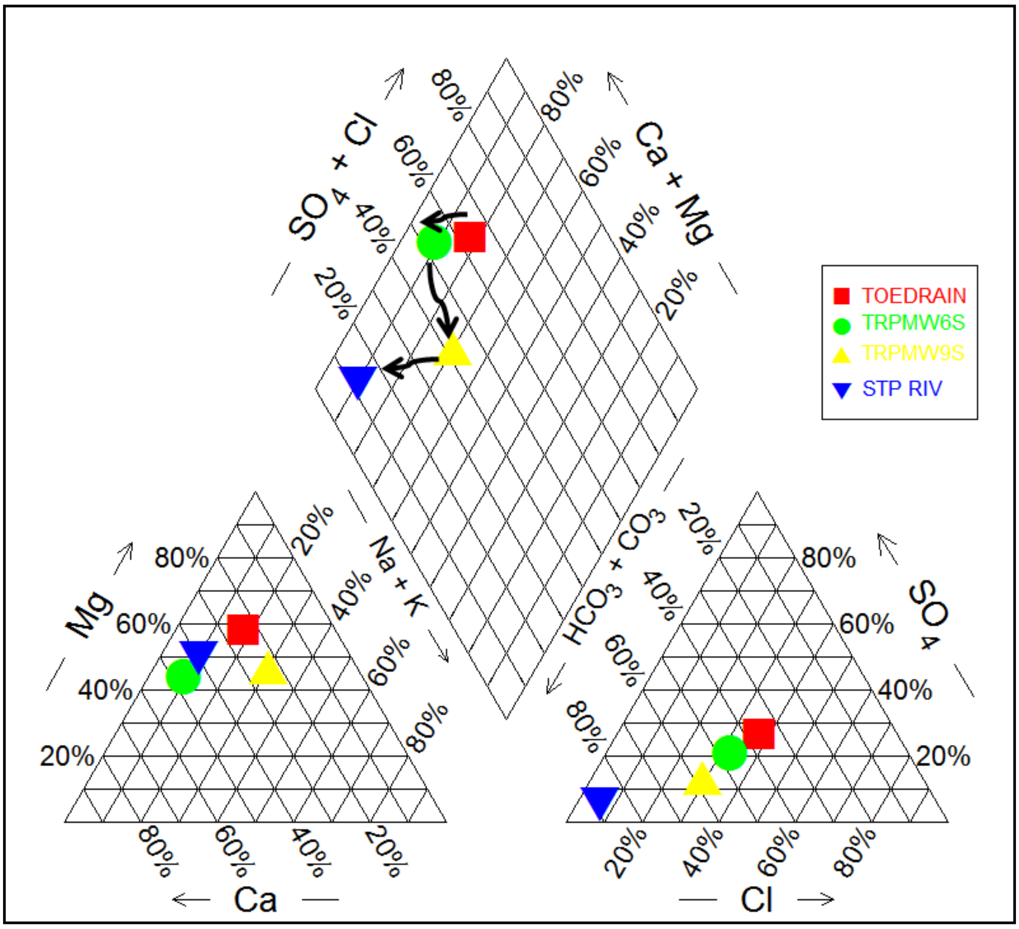


Figure 12-9. **Piper diagram of groundwater samples.**

Table 12-4. **Falling head permeameter test data.**

Time	Cumulative Minutes	Head (mm)	Drop (mm)
09:25	0.00	1530	0
10:30	65.00	1514	16
11:00	95.00	1507	23
11:30	125.00	1502	28
12:00	155.00	1495	35
12:30	185.00	1488	42
13:00	215.00	1482	48
13:30	245.00	1477	53
14:00	275.00	1471	59
14:30	305.00	1466	64
15:00	335.00	1461	69
15:30	365.00	1456	74
16:00	395.00	1451	79
16:30	425.00	1448	82
17:00	455.00	1444	86
17:30	485.00	1438	92

Pumping tests were conducted on two monitoring wells adjacent to the TSF between 14 and 16 March 2012. The pumping test data was analysed using AQTESOLV software to obtain hydraulic conductivity values for the underlying fractured aquifer.

The data obtained for TRPGWM06S was fitted with the Gringarten-Witherspoon curve assuming a single vertical fracture at depth (Figure 12-10). This method was selected based on its provision of a hydraulic conductivity value for a fractured aquifer and provided a better fit than the Moench method, and because the underlying aquifer is known to be fractured as it is composed of igneous rock. The late-time hydraulic conductivity is in the order of 0.46 m/day for the underlying fracture network, assuming an anisotropy ratio of 0.5 between the horizontal and vertical axes, and the linear flow velocity 0.015 m/d assuming 0.20 porosity and a hydraulic gradient of 0.0066 based on surface topography. Groundwater has a slow flow rate in this portion of the aquifer and accompanying contaminants are expected to flow at the same rate or at a slower rate.

The flattening of the derivative plot around 10 000 seconds and the subsequent abrupt dip in values indicates a dual porosity aquifer (Figure 12-11). Both components of a fractured and a weathered aquifer are present and the linear flow velocity may change significantly based on the medium through which water flows at a particular point.

A different situation is observed in TRPGWM09S (Figure 12-12), which is situated closer to the Steelpoort River and further from the TSF. The data were also fitted with the Gringarten-Witherspoon and provided (at late time) an order of magnitude lower hydraulic conductivity of 0.026 m/d. An anisotropy factor of 0.1 was assumed as it improved the fit of the curve considerably. A linear flow velocity under the same assumptions as TRPGWM06S of 8.6×10^{-4} m/d was calculated, which is significantly slower than in TRPGWM06S. A low-flow to no-flow boundary is indicated by the doubling of the slope between 1 000 and 2 000 seconds. The first slope increase may be due to the Dwarsriver Fault situated approximately 550 m east of the monitoring well, and the second slope increase to the Steelpoort River. The levelling of the data around 10 000 s corresponds to a water level of 10.26 m below ground surface which closely resembles the head in the Steelpoort River, and may represent a hydraulic connection between the aquifer and the river.

The derivative plot indicates a fracture or fault structure between 1 000 and 3 000 s. The dip between 300 and 1 000 seconds also indicate a dual porosity system and the same deductions apply as for TRPGWM06S.

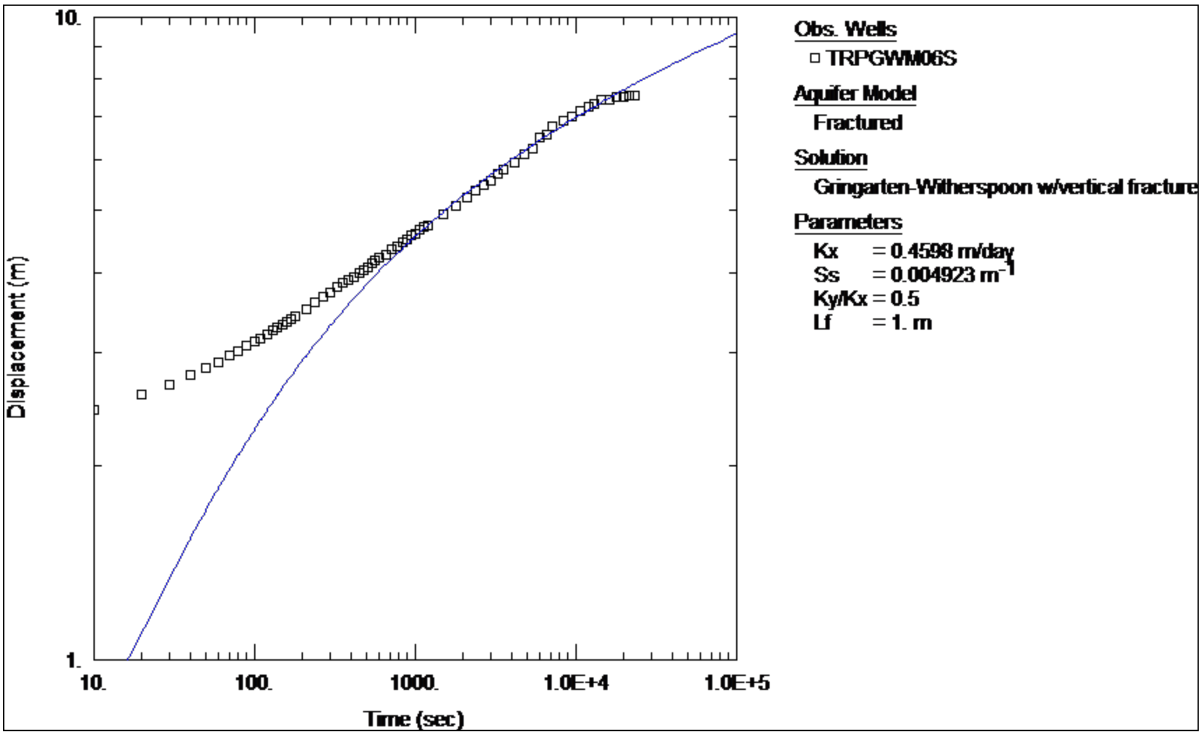


Figure 12-10. **Pumping test data for TRPGWM06S fitted with Gringarten-Witherspoon.**

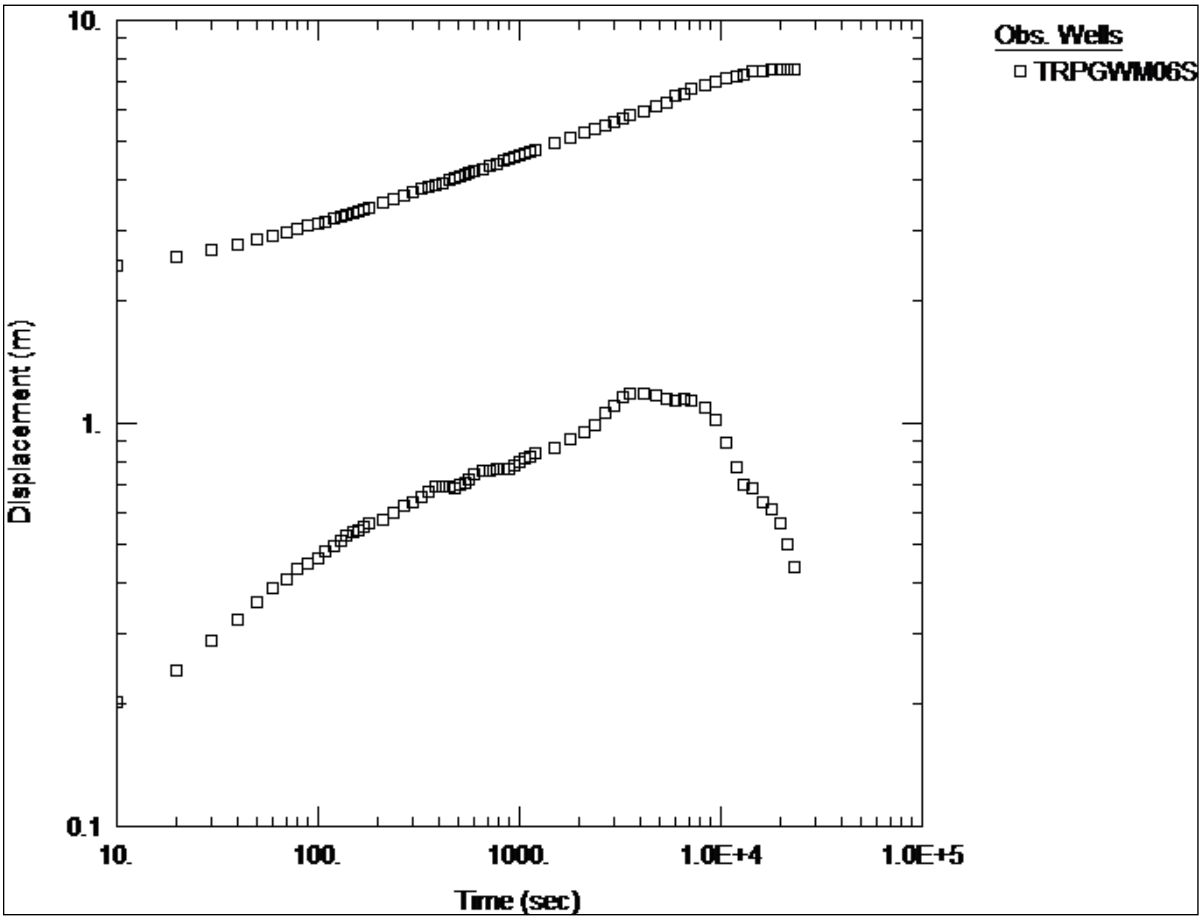


Figure 12-11. **Derivative plot for TRPGWM06S.**

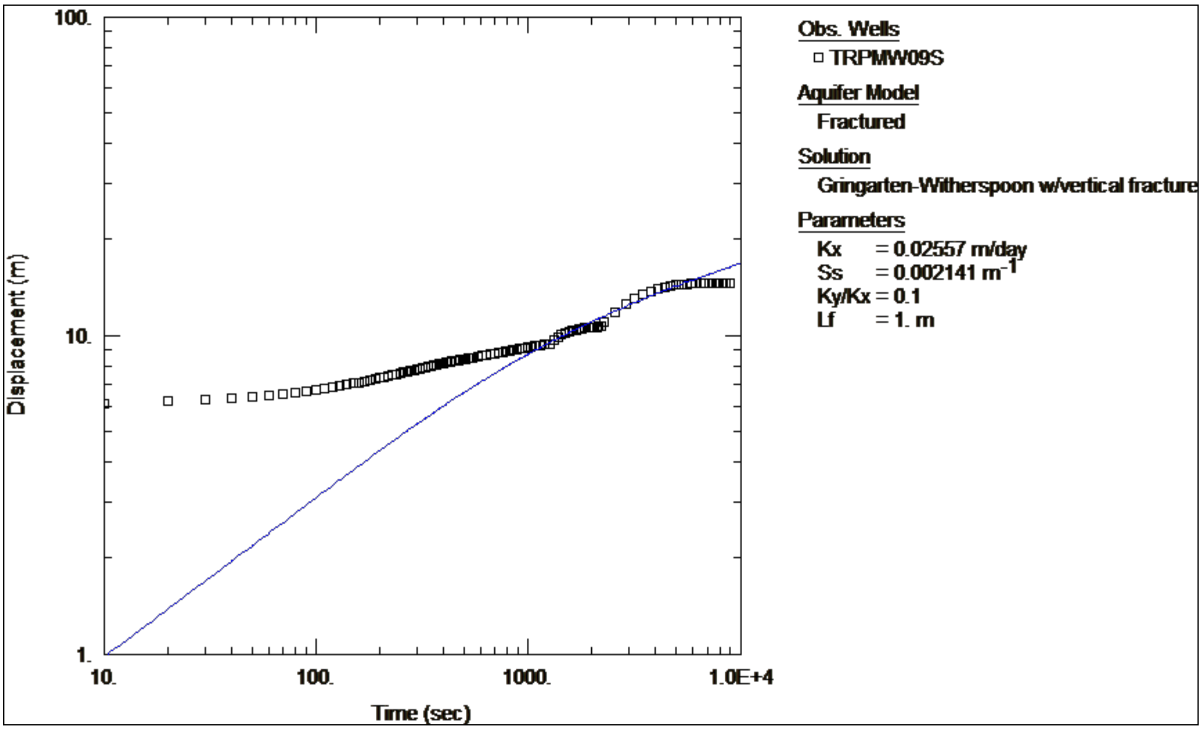


Figure 12-12. Pumping test data for TRPGWM09S fitted with Gringarten-Witherspoon.

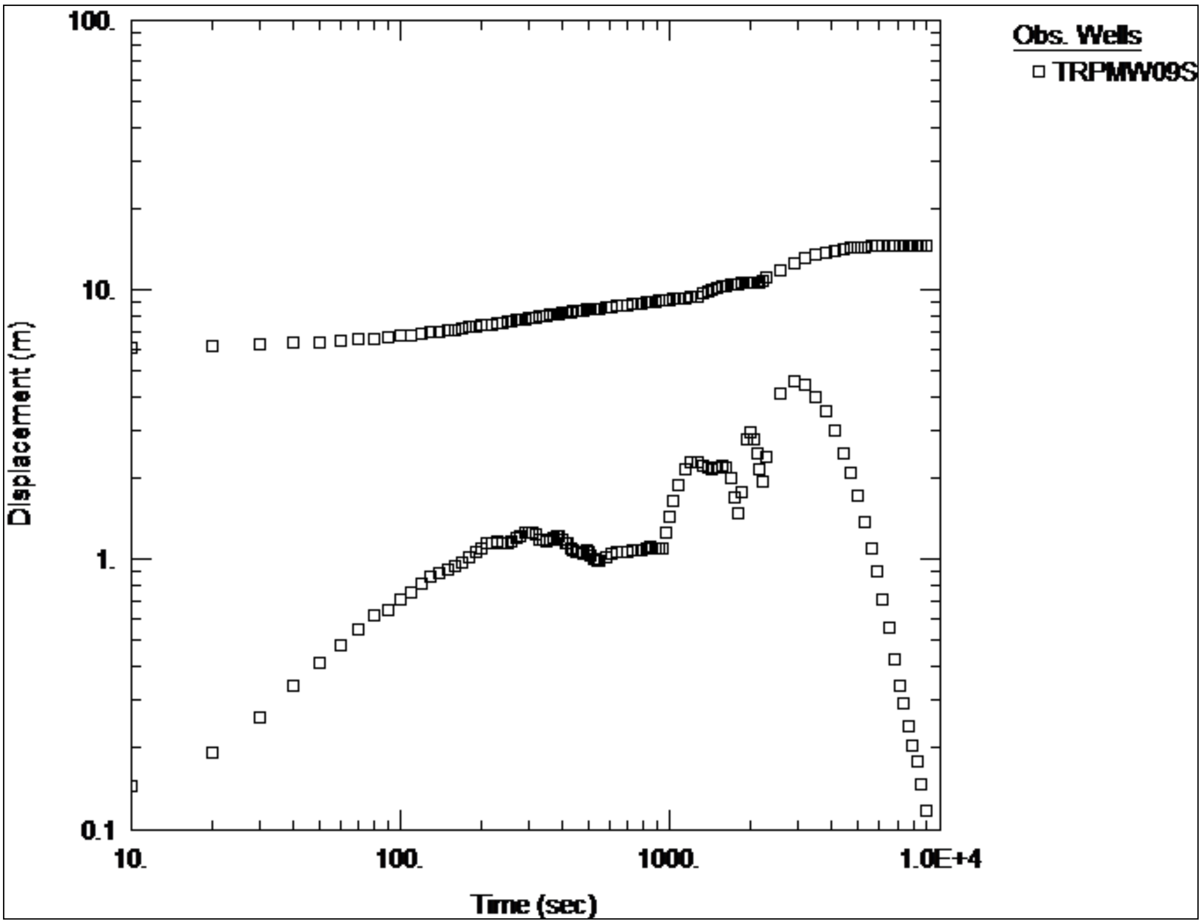


Figure 12-13. Derivative plot for TRPGWM09S.

12.5. Discussion and Findings

Elevated concentrations of major cations and anions were detected in fluid discharging from the tailings and in the groundwater. Discharge was predicted at 0.7 m per decade into the vadose zone and eventual fracture flow at 0.46-0.026 m/d (Huisamen and Van Rooy 2012).

The contact between the fairly uniform tailings material and the fractured vadose zone underlying the TSF has not been adequately addressed. However, improved understanding in the unsaturated tailings system is based on good correlation between empirical, laboratory and field data and details regarding contaminant mobilisation.

Full details of the findings as incorporated in this document are available in Huisamen (2013).

12.6. Contributions to the VZAP

Main issues of importance outlined during investigation of VZSA 2 include:

- The value of simple estimates (e.g. empirical approaches and column permeameters) in uniformly graded materials for a cheap estimate of hydraulic parameters
- The importance of considering both the tailings (primary porosity vadose zone) and the underlying bedrock (fractured vadose zone) in the understanding of the complete unsaturated zone
- The importance of inclusion of chemical data to address the unsaturated hydrological behaviour.

13. VZSA 3: Peri-urban Cemeteries (Temba, City of Tshwane)

13.1. Rationale for Study Area

Cemeteries are generally considered low risk with respect to water contamination. However, poor siting of cemeteries may result in contamination and, as with the Temba Cemetery, may only become problematic well in later years. Investigation for cemeteries is generally based on geotechnical and sanitary aspects, but mostly requires an indexing of observations and no real outlines quantitative approach. Separate specialists generally conduct investigation of geotechnical and hydrological impacts with little attention to the vadose zone as the position of the source of potential contamination. Existing guidelines are qualitative and provide little quantitative estimation of the risk posed by siting of the cemetery and improved methods are required. A re-evaluation of the existing methods may improve understanding of the risk posed by cemeteries.

13.2. Study Area

13.2.1. Locality

The Temba Cemetery is situated in Temba, directly west of Hammanskraal, in the northern suburbs of the City of Tshwane, Gauteng (Figure 13-1). The site is surrounded by peri-urban residential developments to the west, north and east and by commercial activities to the south.

13.2.2. Local geology

The extensive deposits of the Karoo Supergroup generally vary between arenaceous to argillaceous sedimentary rocks with localised coal bed with associated intrusive dolerite dykes and extrusive mafic to ultramafic lavas marking the later stages of the stratigraphy. In the Temba area, bedrock forms part of the Ecca Group deposited within the Springbok Flats Basin (Brink 1983). Temba cemetery is underlain by the Hammanskraal Formation of the Ecca Group and is composed of medium- to coarse-grained immature sandstones, locally interbedded with shaly coal and grey mudrock (Johnson et al. 2009).

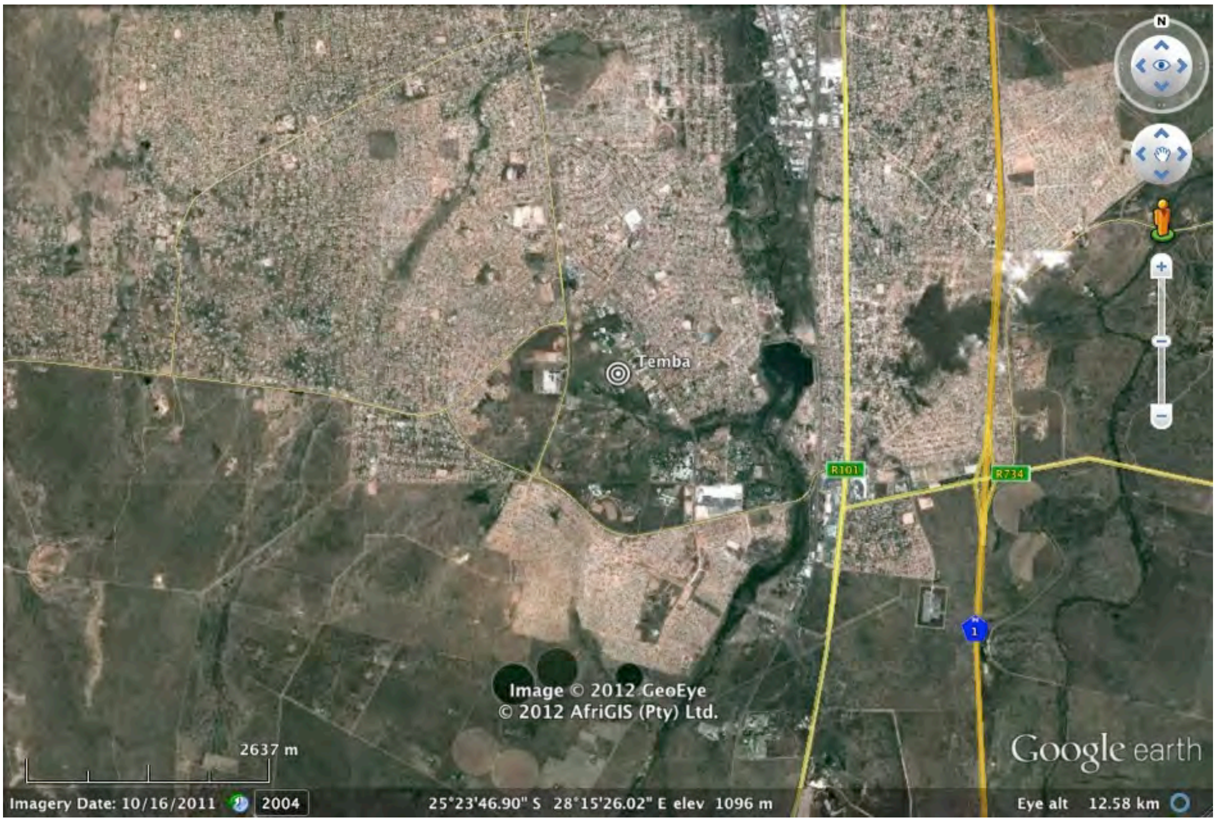


Figure 13-1. Site locality depicted on Google Earth™ imagery (2013).

13.2.3. Climate and drainage

The study area is situated in the A23B quaternary catchment of the Apies-Pienaars tertiary catchment in the Crocodile West/ Marico Water Management Area, WMA3. The Apies River occurs to the west of the site, from where regional drainage is towards the Crocodile River.

13.2.4. Prevailing conditions

The study area presently have 13 673 adult graves and 4 695 child graves amounting to a total of 18 368 sites. The cemetery site was developed in the late 1960s and the burial process is still taking place today, although to a much lesser extent following water influx into newly excavated graves. Burial records are summarised in Table 13-1. The present conditions at the site are shown in the photographic exposé in Figure 13-2.

Table 13-1. Record of burials (supplied by community in charge of Temba Cemetery).

Section	Start year for burial	End year for burial	Total number of buried corpses	Adults/children
A	2002	2008	878	Adults
B	2002	2005	840	Adults
C	2002	2009	724	Adults
D	2003	2009	208	Adults
E	2006	2008	354	Adults
F1	2003	2008	380	Children
F2	2008	2009	37	Children
F3	2009	2012	112	Children
F4	2010	Still in operation	48	Children
G	2008	2010	760	Adults
H	2005	2007	149	Adults
P1	2003	2005	135	Adults
O.S	1966	2005	9 625	Adults
O.S 2	1966	2004	4 118	Children

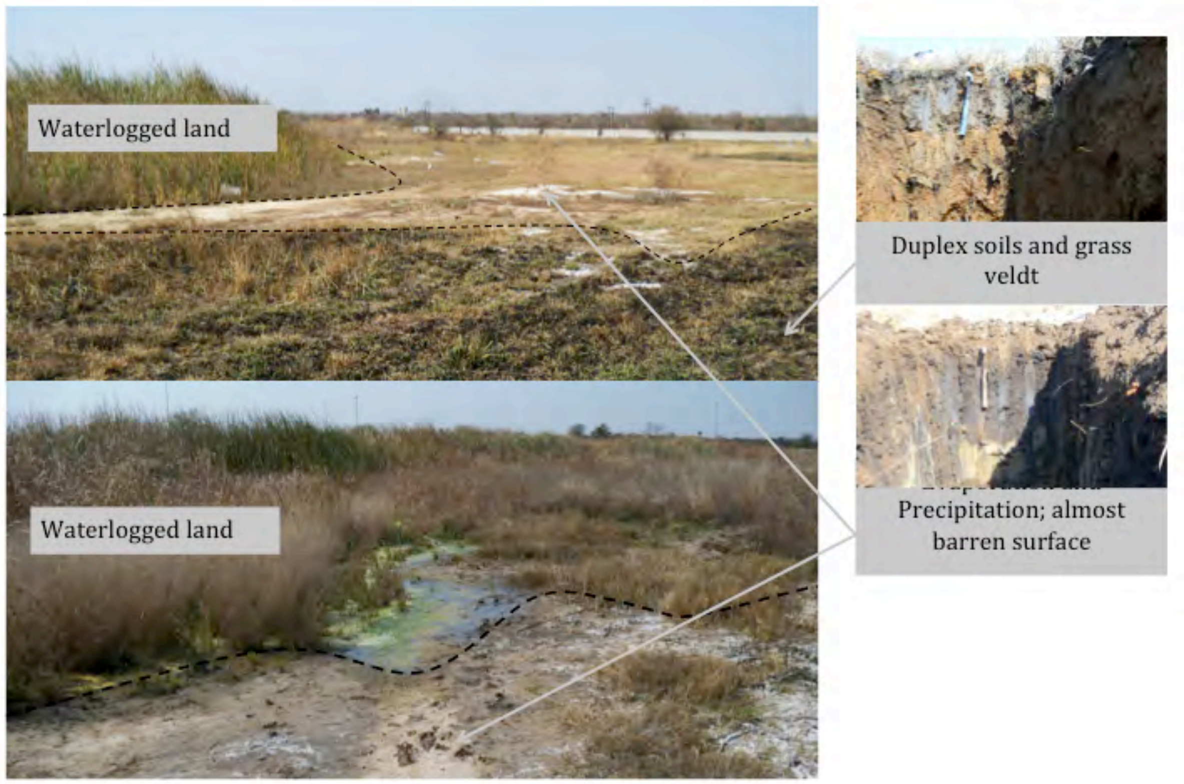


Figure 13-2. Prevailing conditions between the wetland area and the existing Temba cemetery.

13.3. Materials and Methods

The extent of the study area is shown with 5 m contours inferred from Google Earth in Figure 13-3. The existing cemetery (indicated by yellow shading) is directly to the east of the existing wetland. Seven soil profiles were excavated by means of a TLB to depths of TLB refusal or end of reach. The sampling positions were selected to infer change in material properties towards the wetland, as well as along the upper reaches of the wetland itself.

Investigation was based solely on visual investigation and deduction of field evidence. No in-situ or laboratory tests formed part of the study and all findings are based on detailed field observations to accentuate the importance of proper geological characterisation.

Figure 13-3. Surface elevation, present cemetery (yellow), surface drainage (blue) and sampling positions indicated on Google Earth™ imagery (2013)

13.4. Results

Soil profiles are summarised in Table 13-2 and shown in Figure 13-4. Surface materials vary between 0.24 m and 0.96 m in thickness and are underlain by residual sandstone. Weathered sandstone bedrock underlies residual sandstone at depths from 1.09 m (VT04) to almost 2.00 m below surface in VT01, which is the furthest from the wetland area.

Table 13-2. Horizon depths (m) and seepage depths (m) for profiles from Temba Cemetery.

Origin	Alluvium/ Colluvium	Pebble Marker	Residual Sandstone	Test Pit Depth	Seepage
VT01	0.64	absent	1.95	2.30	2.15
VT02	0.96	absent	1.44	2.30	2.10
VT03	0.86	absent	1.40	2.47	1.20
VT04	0.49	absent	1.09	2.32	0.40
VT05	0.79	absent	1.52	1.80	0.90
VT06	0.24	absent	1.07	2.13	0.10
VT07	0.95	absent	1.52	2.42	No seepage

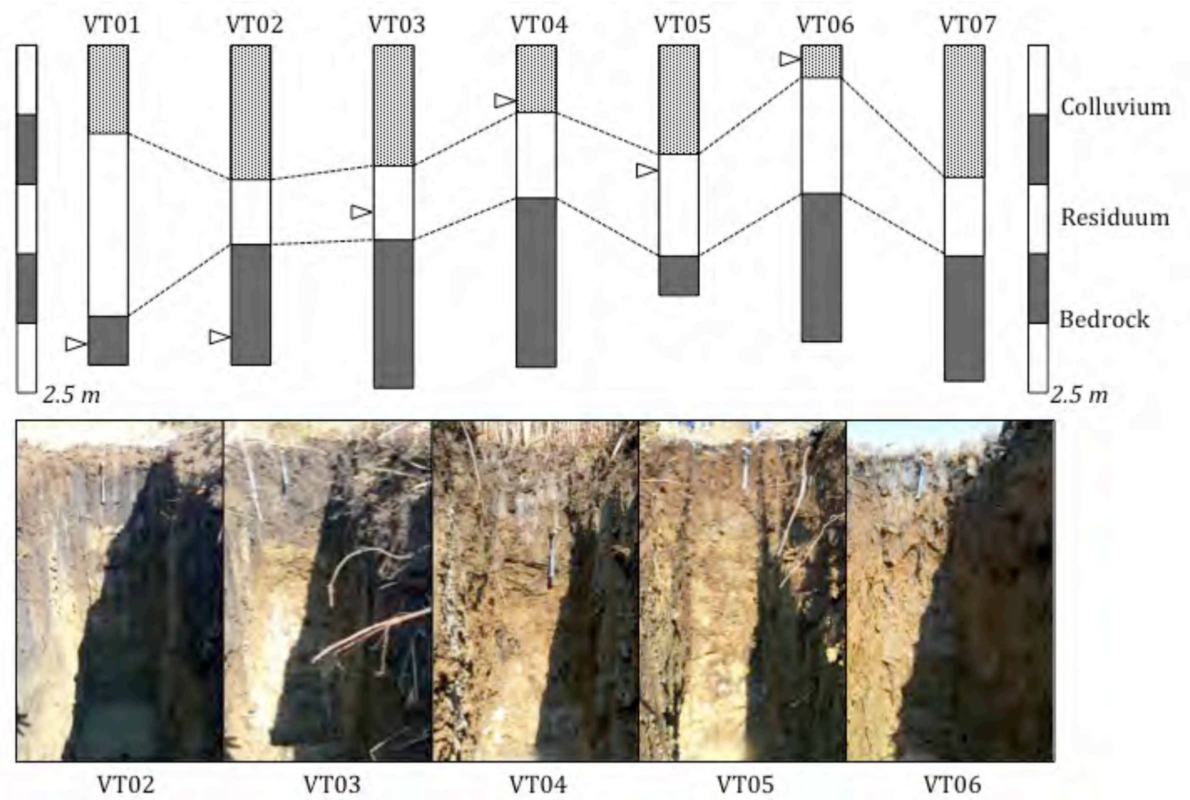


Figure 13-4. Simplified profile logs and photographs showing main soil origins and depths of water seepage.

No seepage was encountered in VT07, representing the upslope area to the west of the wetland. All other test pits had slow to rapid water seepage at depths varying from 0.10 m adjacent to the wetland to more than 2.00 m near the existing cemetery.

13.5. Discussion and Findings

Soil profile descriptions and visual evidence of water seepage were collated to combine a 250-long conceptual model of the site (Figure 13-5). The perching occurs on the weathered bedrock and can potentially be ascribed to the intercalated nature comprising a wide range of grain sizes. Perched water occurs in the soil zone and appears to be a throughflow system with the wetland losing water to the downstream side (VP01-VP06) with no distinct evidence of wet conditions in the upstream side (VP07). Scaled graves (1.80 m depth x 0.90 m width) are indicated to accentuate the influence of burials at the site. Surface water movement in the wetland is towards the south (towards the reader) and the perched water is expected to flow towards the northeast.

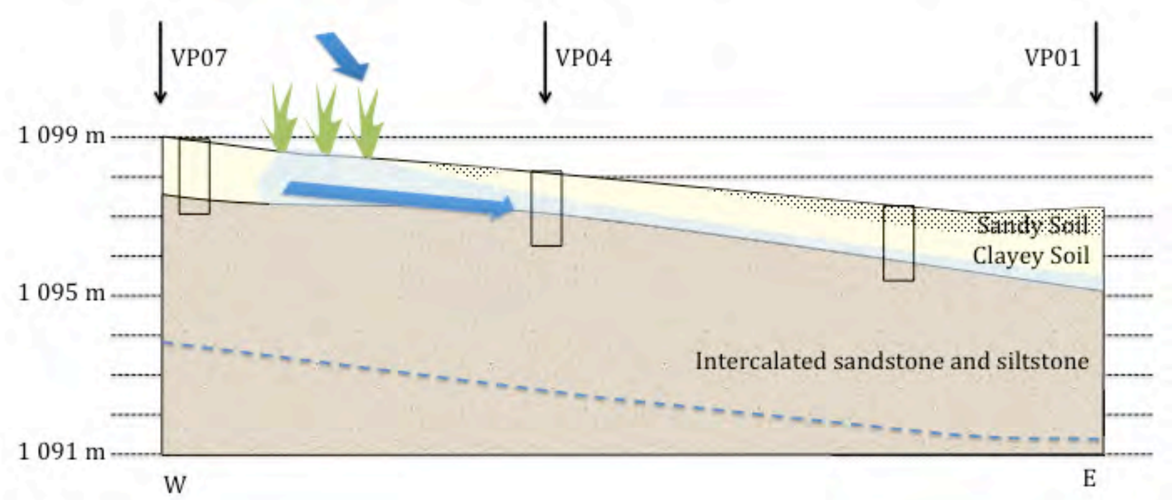


Figure 13-5. Conceptual WE section depicting clayey silty surface soils overlying bedrock with the wetland and perched water table inferred from visual seepage evidence from the trial hole; the anticipated regional groundwater table is also indicated.

Regarding cemeteries, water influence from the Temba cemetery and others (as discussed during a South African Local Government Authority (SALGA) SA Cemeteries Association (SACA) conference in 2013) are common years to decades after first interments at cemeteries. Long-term impacts are generally not well understood, and water influx into existing graves, new excavations, and altered subsurface flow may likely change over time.

13.6. Contributions to the VZAP

Main issues of importance outlined during investigation of VZSA 3 include:

- The importance of vadose zone investigation in general to mitigate long-term impacts from expected low-risk sources of contamination
- The importance of properly interpreting surface water, groundwater and vadose zone interactions
- The value of proper soil profiling to deduce hydrological behaviour.

14. BIBLIOGRAPHY

Allaby, A., and Allaby, M. (2003). Dictionary of Earth Sciences. University Press. Oxford.

Allen, D. M., Schuurman, N., Deshpande, A. and Scibek, J. (2007). Data integration and standardization in cross-border hydrogeological studies: a novel approach to hydrostratigraphic model development. Environmental Geology. **53**:1441-1453.

Amer, A. M., and Awad, A. A. (1974). Permeability of cohesionless soils. J. Geotech. Eng. Div., Am. Soc. Civ. Eng., **200**(12):1309-1316.

American Geological Institute. (1976). Dictionary of Geological Terms. Anchor Press. USA.

Angelone, M., Cremisini, C., Piscopo, V., Proposito, M. and Spaziani, F. (2009). Influence of hydrostratigraphy and structural setting on the arsenic occurrence in groundwater of the Cimino-Vico volcanic area (central Italy). Hydrogeology Journal. **17**:901-914.

Anon. (1977). Description of rock masses for engineering purposes. Geological Society Engineering Group Working Party Report. Quarterly Journal of Engineering Geology. **10**:355-388.

ASTM [American Society for Testing and Materials]. (1994). Standard test method for infiltration rate of soils in field using double-ring infiltrometer. Designation D 3385-94. USA. 6pp.

Bear, J. (1988). Dynamics of Fluids in Porous Media. New York: Dover Publications.

Bear, J. (2007). Hydraulics of Groundwater. New York: Dover Publications.

Bear, J., and Cheng, A. H.-D. (2010). Theory and Applications of Transport in Porous Media: Modeling Groundwater Flow and Contaminant Transport. Springer. Heidelberg.

Beekman, H. E., and Xu, Y. (2003). Review of Groundwater Recharge Estimation in Arid and Semi-Arid Southern Africa. In Y. Xu, and H. E. Beekman,. Groundwater Recharge Estimation in Southern Africa. Cape Town: Unesco IHP Series No 64. 3-18.

Berkowitz, B. (2002). Characterising flow and transport in fractured geological media: a review. Advances in Water Resources. **25**:861-884.

Blatt, H., and Tracy, R. J. (1997). Petrology: igneous, sedimentary, and metamorphic (2 ed.). USA: W. H. Freeman and Company.

Bock, H. (2006). Common ground in engineering geology, soil mechanics and rock mechanics: past, present and future. Bull Eng Geol Environ. **65**:209-216.

Boulding, R. J., and Ginn, J. S. (2004). Practical Handbook for Soil, Vadose Zone and Groundwater Contamination: Assessment, Prevention and Remediation (2nd ed.). Lewis Publishers. New York.

Bouma, J. (2006). Hydropedology as a powerful tool for environmental policy research. Geoderma. **131**:275-286.

Brady, N. C., and Weil, R. R. (1999). The Nature and Properties of Soils. Prentice Hall. New Jersey.

Bridges, E. M. and Van Baren, J. M. V. (1997). Soil: an overlooked, undervalued and vital part of the human environment. The Environmentalist. **17**:15-20.

Brink, A. B. A. (1983). Engineering Geology of Southern Africa. Volume 3: The Karoo Sequence. Building Publications. Pretoria.

Brink, A. B. A. and Bruin, R. M. H. (2001). Guidelines for soil and rock logging in S. A. Association of Engineering Geologists – South African Section (AEG-SA Section)/ South African Institution of Civil Engineering – Geotechnical Division (SAICE)/ South African Institute for Engineering and Environmental Geologists (SAIEG). Pretoria.

Brison, M. M. (1993). A Hydrogeomorphic Classification for Wetlands. Greenville: East Carolina University.

Brooks, P.M. and Corey, A.T. (1964). Hydraulic properties in porous media. Hydrol. Paper 3, University of Colorado, Fort Collins.

Carrier, W. D. (2003). Goodbye, Hazen; hello, Kozeny-Carman. Journal of Geotechnical and Geoenvironmental Engineering. **129**(11):1054-1056.

Cashman, P. M. and Preene, M. (2013) Groundwater Lowering in Construction: A Practical Guide to Dewatering. 2nd Ed. CRC Press. Cornwall.

Cawthorn, R.G., Eales, H.V., Walraven, F., Uken, R., Watkeys, M.K., 2006, The Bushveld Complex, In M. R. Johnson, C. R. Anhaeusser, & R. J. Thomas, The Geology of South Africa. Johannesburg/ Pretoria: Geological Society of South Africa/ Council for Geoscience. 261-281.

Cheong, J., Hamm, S., Kim, H., Ko, E., Yang, K. and Lee, J. (2008). Estimating hydraulic conductivity using grain-size analyses, aquifer tests, and numerical modeling in a riverside alluvial system in South Korea. Hydrogeology Journal. **16**:1129-1143.

Clauss, K. A., Netterberg, F. and Williams, A. B. A. (1969). The role of the engineering geologist. The Civil Engineer in South Africa. **11**(7):167-173.

Cowardin, C.M., Carter, V. Golet, F.C., LaRoe, E.T. (1979). Classification of Wetlands and Deepwater Habitats of the United States. U.S. Fish and Wildlife Service Report No. FWS/OBS/-79/31. Washington, D.C.

Craig, R. F. (1999). Soil Mechanics (6th ed.). E & FN Spon. Cornwall.

Croucamp, L., and Richards, N. (2002). Guidelines for Cemetery Site Selection. Pretoria: Council for Geoscience.

Culligan-Hensley, P. J. and Savvidou, C. (1996). Environmental geomechanics and transport processes. In: Taylor, R. N. (ed.) Geotechnical Centrifuge Technology. Blackie Academic & Professional (Chapman & Hall). London. 196-263.

Dahan, O., Nativ, R., Adar, E. M., Berkowitz, B. and Ronen, Z. (1999). Field observation of flow in a fracture intersecting unsaturated chalk. Water Resour Res. **35**(11):3315-26.

Dahan, O., Nativ, R., Adar, E. M., Berkowitz, B. and Weisbrod, N. (2000). On fracture structure and preferential flow in unsaturated chalk. Ground Water. **38**(3):444-51.

Dahan, O., Nativ, R., Adar, E.M. and Berkowitz, B. (1998). A measurement system to determine water flux and solute transport through fractures in the unsaturated zone. Ground Water. **36**(3):444—449.

Das, B. M. (2008). Advanced Soil Mechanics (3rd ed.). Taylor & Francis Group. New York.

Das, B. S., Haws, N. W. and Rao, P. S. C. (2005). Defining geometric similarity in soils. Vadose Zone Journal. **4**:264—270.

Day, J., Day, E., Ross-Gillespie, V., & Ketley, A. (2010). Wetland Health and Importance Research Programme: The Assessment of Temporary Wetlands during Dry Conditions (Vol. 2). WRC Report No. TT 434-09. Water Research Commission. Pretoria.

De Vries, J. J., and Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal. **10**:5-17.

Deer, W., Howie, R., & Zussman, J. (1996). An Introduction to the Rock-forming Minerals. Prentice Hall.

Deming, D. (2002). Introduction to Hydrogeology (1st ed.). McGraw-Hill. Indiana.

Dent, B. B. and Knight, M. J. (1998). Cemeteries: a Special Kind of Landfill. The Context of their Sustainable Management. Proceedings: Groundwater: Sustainable Solutions (International Association of Hydrogeologists, Melbourne, February 1998). 451-456.

Department of Agricultural Development. (1991). Soil Classification: a Taxonomical System for South Africa. 262pp.

Dexter, A. R. (2004). Soil physical quality. Part III: unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma. **12**:227-239.

Dexter, A. R., and Richard, G. (2009). The saturated hydraulic conductivity of soils with n-modal pore size distributions. Geoderma. **154**:76-85.

Dippenaar, M. A., van Rooy, J. L., and Witthüser, K. T. (2009). Groundwater occurrence in Basement aquifers in Limpopo Province, South Africa: model-setting-scenario approach. Environmental Earth Science. **59**:459-464.

Dippenaar, M. A. (2012). How we lose ground when earth scientists become territorial: defining "soil". Natural Resources Research. **21**(1):137-142.

Dippenaar, M. A. (2013). Hydrogeological Heritage Overview: Pretoria's Fountains – Arteries of Life. WRC Special Publication SP 44/13. Water Research Commission. Pretoria.

Dippenaar, M. A. (2014). Porosity reviewed: quantitative multi-disciplinary understanding, recent advances and applications in vadose zone hydrology. Geotechnical and Geological Engineering. **32**:1-19.

Dippenaar, M. A. and Van Rooy, J. L. (2014). Review of engineering, hydrogeological and vadose zone hydrological aspects of the Lanseria Gneiss, Gouplaats-Hout River Gneiss and Nelspruit Suite Granite (South Africa). Journal of African Earth Sciences. **91**:12-31.

Dippenaar, M. A., Van Rooy, J. L., Moyo, A., Freëse, R., and Makonto, O. T. (2010). Preliminary Vadose Zone Classification Methodology (Molototsi and Middle Letaba Quaternary Catchments). Water Research Commission. Pretoria.

Doe, T. W. (2001). What do Drops do? Surface Wetting and Network Geometry Effects on Vadose-Zone Fracture Flow. In U. S. Mechanics, Conceptual Models of Flow and Transport in the Fractured Vadose Zone. Washington D. C.: National Academy Press. 243-270.

Domenico, P. A. Ad Schwartz, F. W. (1990). Physical and Chemical Hydrogeology. John Wiley & Sons. New York (as in Karamouz et al. 2011, p68).

Driscoll, F. G. (1989). Groundwater and Wells (2nd ed.). Johnson Filtration Systems Inc. Minnesota.

Dudoignon, P., Causseque, S., Bernard, M., Hallaire, V., and Pons, Y. (2007). Vertical porosity profile of a clay-rich marsh soil. Catena. **70**:480-492.

DWA [Department of Water Affairs]. (2005). A Practical Field Procedure for Identification and Delineation of Wetland Riparian Areas. Pretoria: Department of Water Affairs.

DWA [Department of Water Affairs]. (Retrieved 2010). Water Quality Management Policy with regard to the Management of and Control over Cemeteries as a Source of Water Pollution. Document number: GraveR. Available on the Internet at http://www.dwaf.gov.za/Documents/Policies/WDD/Cemetery.pdf. 2 pages.

ECA. (1989). Environmental Conservation Act No 73. Pretoria: Government Printer

Ehlen, J. (2005). Above the weathering front: contrasting approaches to the study and classification of weathered mantle. Geomorphology. **67**:7-21.

Engelbrecht, J. (2000). Groundwater Pollution for Cemeteries. CSIR.

Ewart-Smith, J. L., Ollis, D. J., Day, J. A., and Malan, H. L. (2006). National Wetland Inventory: Development of a Wetland Classification System for South Africa. WRC Report No KV 174/06. Water Research Commission. Pretoria.

Fetter, C. (1994). Applied Hydrogeology (3rd ed.). Prentice-Hall Inc. New Jersey.

Fisher, G. (1992). Selection Criteria f or the Placing of Cemetery Sites. Johannesburg: Geological Survey of South Africa.

Fisher, G. J. (1994). The Selection of Cemetery Sites in South Africa. Proceedings: 4th Terrain Evaluation and Data Storage Symposium. Midrand.

Fisher, G., and Croucamp, L. (1993). Groundwater Contamination and its Consequences resulting from the Indiscriminate Placing of Cemeteries in Third World Context. Vol 1: Africa needs Groundwater Convention. (Vol. 1). Johannesburg.

Fitts, C. R. (2002). Groundwater Science. Academic Press. London.

FitzPatrick, E. (1983). Soils: Their Formation, Classification and Distribution. Longman Group Limited. Hong Kong.

Foster, S. (1984). African groundwater development: the challenges for hydrological science. IAHS Publ. 144. IAHS. Wallingford UK. 3-12.

Foster, S. (2012). Hard-rock aquifers in tropical regions: using science to inform development and management policy. Hydrogeology Journal. **20**:659-672.

Freeze, R. and Cherry, J. (1979). Groundwater. Prentice-Hall. Englewood Cliffs, NJ. 604pp.

Furukawa K, Imai K, Kurashigo M (2000) Simulated effect of box size and wall on porosity of random packings of spherical particles. Acta Mech **140**:219-231

Giménez, D. Perfect, E., Rawls, W. J. and Pachepsky, Ya. (1997). Fractal models for predicting soil hydraulic properties: a review. Engineering Geology. **48**:161-183.

Glass, R. J., Steenhuis, T., and Parlange, J. Y. (1988). Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. Journal of Contaminant Hydrology. **3**:207-226.

Gleeson, T. and Cardiff, M. (2013). The return of groundwater quantity: a mega-scale and interdisciplinary "future of hydrogeology"? Hydrogeology Journal. **21**(6):1169-1171.

González de Vallejo, L. I. and Ferrer, M. (2011). Geological Engineering. CRC Press/Balkema. Leiden. 678pp.

Hall, B. H. and Hanbury, R. (1990). Some Geotechnical Considerations in the Selection of Cemetery Sites. IMIESA March 1990. 21-25.

Hartzer, F.J., 1995, Transvaal Supergroup inliers: geology, tectonic development and relationship with the Bushveld Complex, South Africa. Journal of African Earth Science. **21**(4):521-547

Hazen, A. (1911). Discussion of 'dams on sand foundations' by A. C. Koenig. Trans. Am. Soc. Civ. Eng. **73**:199-203.

Hazen, A. (1930). Water Supply: American Civil Engineers Handbook. Wiley. New York.

Heinz, J. and Aigner, T. (2003). Hierarchical dynamic stratigraphy in various Quaternary gravel deposits, Rhine glacier area (SW Germany): implications for hydrostratigraphy. Int. J. Earth. Sci. (Geol. Rundsch.). **92**:923-938.

Hencher, S. (2012). Practical Engineering Geology. Applied Geotechnics Volume 4. Spon Press. Great Britain. 450pp.

Hilfer, R. (2002). Review on scale dependent characterization of the microstructure of porous media. Transport in Porous Media. **46**:373-390.

Hillel, D. (2003). Introduction to Environmental Soil Physics. Academic Press. (eBook). 494pp.

Huisamen, A. (2013). Contaminant mobilisation by fluid-rock interaction and related transport mechanisms in platinum tailings. Masters Dissertation (unpublished). University of Pretoria.

Huisamen, A. and Van Rooy, J. L. (2012). Contaminant mobilisation by fluid-rock interaction and related transport mechanisms in platinum tailings. IGCP/SIDA Project 594. Proceedings: Annual Workshop, Windhoek, Namibia. ISBN 978-80-7075-781-9.

Indraratna, B. & Ranjith, P. (2001). Hydromechanical Aspects and Unsaturated Flow in Jointed Rock. Balkema. Meppel. Netherlands.

Istomina, V. S. (1957). Seepage Stability of the Soil. Moscow. Translated from Russian.

Jenn, F., Knödel, K., Liese, M. and Voigt, H.-J. (2007a). Chapter 5.2.4. Infiltration. In: Knödel, K., Lange, G. and Voigt, H.-J. (eds.) Environmental Geology: Handbook of Field Methods and Case Studies. Springer. Heidelberg. 603-611.

Jenn, F., Knödel, K., Liese, M. and Voigt, H.-J. (2007b). Chapter 5.2.5. Groundwater Recharge. In: Knödel, K., Lange, G. and Voigt, H.-J. (eds.) Environmental Geology: Handbook of Field Methods and Case Studies. Springer. Heidelberg. 612-619.

Jenn, F., Nagare, R., Porzig, M. and Voigt, H.-J. (2007c). Chapter 5.2.7.1. Infiltrometer and Permeameter Tests. In: Knödel, K., Lange, G. and Voigt, H.-J. (eds.) Environmental Geology: Handbook of Field Methods and Case Studies. Springer. Heidelberg. 649-680.

Jennings, J. E., Brink, A. B. A. and Williams, A. A. B. (1973). Revised guide to soil profiling for civil engineering purposes in South Africa. Die Siviele Ingenieur in Suid-Afrika/ The Civil Engineer in South Africa. 15:1.

Jones, B. R. (2013). Geotechnical centrifuge modelling of a compressible clay horizon underlying a reinforced sand foundation. Masters Dissertation (unpublished). University of Pretoria.

Jury, W. A., Gardner, W. R., and Gardner, W. H. (1991). Soil Physics (5th ed.). John Wiley & Sons Inc. USA.

Karamouz, M., Ahmadi, A. And Akhbari, M. (2011).Groundwater hydrology – engineering, planning, and management. CRC Press. USA. 648pp.

Keary, P. (2001). The New Penguin Dictionary of Geology. (2nd ed.). Penguin Books. England.

Kenney, T. C., Lau, D. and Ofoegbu, G. I. (1984). Permeability of compacted granular materials. Canadian Geotechnical Journal. 21(4):726-729 (in Van Schalkwyk and Vermaak 2000).

Knappett, J. A. and Craig, R. F. (2012). Craig's Soil Mechanics. Spon Press. Oxon. 552pp.

Koita, M., Jourde, H., Koffi, K. J. P., Da Silveira, K. S. and Biaou, A. (2013). Characterization of weathering profile in granite and volcanosedimentary rocks in West Africa under humid tropical climate conditions. Case of the Dimbokro Catchment (Ivory Coast). J Earth Syst Sci. **122**(3):841-854.

Kovács, G. (1981). Developments in Water Science: Seepage Hydraulics (Vol. 10). Elsevier. Sitzungber Oesterr Akad.

Kutílek, M. (2004). Soil hydraulic properties related to soil structure. Soil & Tillage Research. **79**:175-184.

Lapidus, D. F. (1990). Dictionary of Geology. HarperCollins. Glasgow.

Le Roux, P. A. L., Van Tol, J. J, Kuenene, B. T., Hensley, M., Lorentz, S. A., Everson, C. S., Van Huyssteen, C. W., Kapangaziwiri, E. and Riddell, E. (2011). Hydropedological interpretations of the soils of selected catchments with the aim of improving the efficiency of hydrological models. WRC Report No. 1748/1/10. Water Research Commission. Pretoria. 246pp.

Lerner, D. N. (1997) Groundwater recharge. In: Saether, O. M. and de Caritat, P. (eds) Geochemical processes, weathering and groundwater recharge in catchments. AA Balkema. Rotterdam. 109-150.

Liu, H. H. (2004). A constitutive-relationship model for film flow on rough fracture surfaces. Hydrogeology Journal. 12:237-240.

Lorentz, S., Bursey, K., Idowu, O., Pretorius, C. and Ngeleka, K. (2008). Definitions and upscaling of key hydrological processes for application in models. WRC Report No. 1320/1/08. Water Research Commission. Pretoria.

Lu, N., and Likos, W. J. (2004). Unsaturated Soil Mechanics. John Wiley & Sons. New Jersey.

Makonto, O. T. and Dippenaar, M. A. (2014). Aquifer Vulnerability using Recharge, Depth to Groundwater, Soil Type and Slope to classify the Vadose Zone (Molototsi and Middle Letaba Quaternary Catchments, Limpopo Province, South Africa. Environmental Earth Sciences. DOI 10.1007/s12665-014-3065-4.

Martin, J. P. and Koerner, R. M. (1984a). The influence of vadose zone conditions on groundwater pollution. Part 1: basic principles and static conditions. Journal of Hazardous Materials. 8:349-366.

Martin, J. P. and Koerner, R. M. (1984a). The influence of vadose zone conditions on groundwater pollution. Part 2: fluid movement. Journal of Hazardous Materials. 9:181-207.

Mathews, T., Matthews, G. P., Ridgway, C. J., and Moss, A. K. (1997). Measurement of void size correlation in inhomogeneous porous media. Transport in Porous Media. 28:135-158.

Mathewson, C. C. (1981). Engineering geology. Charles E. Merrill Publishing Company. Ohio USA. 450pp.

McCandless, T.E., Ruiz, J., Adair, B.I., Freydier, C., 1999, Re-Os isotope and Pd/Ru variations in chromitites from the Critical Zone, Bushveld Complex, South Africa, Geochimica et Cosmochimica Acta. **63**:911-923

McFarlane, M. J. (1976). Laterite and Landscape. Academic Press. Kent.

Miller, C. T. and Gray, W. G. (2002). Hydrogeological research: just getting started. Ground Water. **40**(3):224-231.

Miller, G. T. (2000).Living in the Environment: Principles, Connections, and Solutions. Brooks/Cole. Pacific Grove, California. 815pp.

Mitsch, W. J., & Gosselink, J. G. (2000). Wetlands (3rd ed.). New York: John Wiley & Sons Inc.

Moraes, M. A., and De Ros, L. F. (1990). Infiltrated clays in fluvial Jurassic sandstones of Reconavo Basin, northeastern Brazil. Journal of Sedimentary Petrology. **60**(6):809-819.

Narasimhan, T. N. And Goyal, K. E. (1984). Subsidence tue to geothermal fluid withdrawal. In: man-induced land subsidence. Reviews in Engineering Geology. V,VI. Geological Society of America. (as in Karamouz et al. 2011, p68).

National Department of Housing. (2002). Geotechnical Site Investigations for Housing Developments. Generic Specification GFSH-2. September 2002.

Norton, D., and Knapp, R. (1977). Transport phenomena in hydrothermal systems; the nature of porosity. American Journal of Science. **8**:913-936.

NWA. (1998). National Water Act No 36. Pretoria: Government Printer.

Odong, J. (2007). Evaluation of empirical formulae for determination of hydraulic conductivity based on grain-size analysis. Journal of American Science. **3**(3):54-60.

Phillips, R. (1996). Centrifuge modelling: practical considerations. In: Taylor, R. N. (ed.) Geotechnical Centrifuge Technology. Blackie Academic & Professional (Chapman & Hall). London. 34-60.

Podgorney, R. K., & Fairley, J. P. (2008). Investigation of episodic flow from unsaturated porous media into a macropore. Vadose Zone Journal. **7**(1):332-339.

Price, W.A. (1997). Draft guidelines and recommended methods for the prediction of metal leaching and acid rock drainage at mine sites in British Columbia. British Columbia Ministry of Employment and Investment. Energy and Minerals Division. Smithers, BC. p143.

Rahn, P. H. (1986). Engineering Geology: An Environmental Approach. Elsevier Science Publishing Company Inc. New York.

RAMSAR [Ramsar Convention]. (2006; downloaded 7 March 2013). The Ramsar Convention Manual: A Guide to the Convention on Wetlands. 4th Ed. Ramsar Convention Secretariat. Available on the Internet at: http://www.ramsar.org/pdf/lib/lib_manual2006e.pdf. 114pp

Reynolds, W. D. and Elrick, D. E. (1986) A method for simultaneous in situ measurement in the vadose zone of field saturated hydraulic conductivity, sorptivity and the conductivity pressure head relationship. Groundwater Monitoring Review. **6**(1):84-85.

Robb, L. J., Brandl, G., Anhaeusser, C. R., & Poujol, M. (2009). Archaean Granitoid Intrusions. In M. R. Johnson, C. R. Anhaeusser, & R. J. Thomas, The Geology of South Africa. Johannesburg/ Pretoria: Geological Society of South Africa/ Council for Geoscience. 57-94.

Robins, N. S., Chilton, P. J. And Cobbing, J. E. (2007). Adapting existing experience with aquifer vulnerability and groundwater protection for Africa. Journal of African Earth Sciences. **47**:30-38.

Rose, C. (2006). An Introduction to the Environmental Physics of Soil, Water and Watersheds. Cambridge University Press. Cambridge.

Ruan, H. and Illangasekare, T. H. (1999). Estimation of relative hydraulic conductivity of sandy soils based on a sheet flow model. Journal of Hydrology. **219**:83-93.

Saaiman, I. Beekman, H. E., Adams, S., Campbell, R. B., Conrad, J., Fey, M. V., Jovanovic, N., Thomas, A. And Usher, B. H. (2007). Assessment of Aquifer Vulnerability in South Africa. WRC Report No. 1432/1/07. Water Research Commission. Pretoria.

SAICE [South African Institution of Civil Engineering – Geotechnical Division]. (2010). Site investigation code of practice. 1st ed. Available on the Internet at http://www.geotechnicaldivision.co.za/.

Samardzioska, T. and Popov, V. (2005). Numerical comparison of the equivalent continuum, non-homogeneous and dual porosity models for flow and transport in fractured porous media. Advances in Water Resources. **28**:235-255.

SANBI [South African National Biodiversity Institute]. (2009). Further Development of a Proposed National Wetland Classification System for South Africa. Pretoria: Freshwater Consulting Group (FCG) of South African National Biodiversity Institute (SANBI).

SANS [South African National Standards]. (1993). Code of Practice: Water Supply and Drainage for Buildings. Part 2: Drainage Installations for Buildings. SANS 10252-2. South African Bureau of Standards. Pretoria.

SANS [South African National Standards]. (2009a). Profiling, and Percussion and Core Borehole Logging in Southern Africa for Engineering Purposes. Draft SANS 633. South African Bureau of Standards. Pretoria.

SANS [South African National Standards]. (2009b). Geotechnical Investigations for Township Development. Draft SANS 634. South African Bureau of Standards. Pretoria.

Schaetzl, R. J. and Anderson, S. (2005). Soils: Genesis and Geomorphology. Cambridge University Press. New York.

Semeniuk, C. A. and Semeniuk, V. (1995). A geomorphic approach to global classification for inland wetlands. Vegetatio. **118**:103-124.

Shababi, A. A., Das, B. M., and Tarquin, A. J. (1984). An Empirical Relation for Coefficient of Permeability for Sand. Proceedings of the Fourth Australia – New Zealand Conference on Geomechanics. **1**:54-57.

Shaw, E. M. (1994). Hydrology in Practice (3rd ed.). Chapman & Hall. Cornwall.

Sililo, O. T. N., Saayman, I. C. and Fey, M. V. (2001). Groundwater vulnerability to pollution in urban catchments. WRC Report No. 1008/1/01. Water Research Commission. Pretoria. 56pp.

Šimůnek, J. and Van Genuchten, M. T. (1996). Estimating unsaturated soil hydraulic properties from tension disc infiltrometer data by numerical inversion. Water Resources Research. **21**(9):2683-2696.

Skolasinska, K. (2006). Clogging microstructures in the vadose zone – laboratory and field studies. Hydrogeology Journal. **14**:1005-1017.

Stevens, J. B. and Buys, F. (2012). Training Manual for Extension Advisors in Irrigation Water Management. Volume 2: Technical Learner Guide. Part 4: Irrigation Water Management. WRC Report No. TT 540/4/12. Water Research Commission. Pretoria.

Stevens, J. B. and Laker, M. C. (2012). Training Manual for Extension Advisors in Irrigation Water Management. Volume 2: Technical Learner Guide. Part 2: Assessing of Soil Resources. WRC Report No. TT 540/2/12. Water Research Commission. Pretoria.

Straughan, B. (2010). Structure of the dependence of Darcy and Forschheimer coefficients on porosity. International Journal of Engineering Science. **48**:1610-1621.

Taylor R. N. (1996). Centrifuges in modelling: principles and scale effects. In: Taylor, R. N. (ed.) Geotechnical Centrifuge Technology. Blackie Academic & Professional (Chapman & Hall). London. 19-32.

Todd, D. K., and Mays, L. W. (2005). Groundwater Hydrology. (3rd ed.) John Wiley & Sons. New Jersey.

Tullborg, E.-L., and Larson, S. A. (2006). Porosity in crystalline rocks – a matter of scale. Engineering Geology. **84**:75-83.

Turner, K. A. (2006). Challenges and trends for geological modelling and visualisation. Bull Eng Geol Environ. **65**:109-127.

Van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. **44**:892-898.

Van Schalkwyk, A., & Vermaak, J. J. (2000). The Relationship between the Geotechnical and Hydrogeological Properties of Residual Soils and Rocks in the Vadose Zone. Water Research Commission. Pretoria.

Venter, F. J. (1986). Soil patterns associated with the major geological units of the Kruger National Park. Koedoe. **29**:125-138.

Vita, M. C., De Bartolo, S., Fallico, C. and Veltri, M. (2011). Usage of infinitesimals in the Menger's Sponge Model of porosity. Applied Mathematics and Computation. DOI 10.1016/j.amc.2011.06.013.

Vuković, M., & Soro, A. (1992). Determination of Hydraulic Conductivity of Porous Media from Grain-size Composition. Water Resources Publications. Littleton Colorado.

Weight, W. D. (2008). Hydrogeology Field Manual (2nd ed.). McGraw-Hill. New York.

White, R. E. (1997). Principles and Practice of Soil Science: The Soil as a Natural Resource (3rd ed.). Blackwell Science Ltd. Victoria.

Winegardner, D. L. (1996). An Introduction to Soils for Environmental Professionals. CRC Press Inc. Florida.

Younger, P. L. (2007). Groundwater in the Environment: An Introduction. Blackwell Publishing. (eBook).

9781431205073