THE VADOSE ZONE: FROM THEORY TO PRACTISE

Matthys A Dippenaar, Brendon R Jones, J Louis Van Rooy, Mampho Maoyi, Duan Swart

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Matthys A DIPPENAAR (editor)
Brendon R JONES
J Louis VAN ROOY
Mampho MAOYI
Duan SWART

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Gezina
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orders@wrc.org.za or download from www.wrc.org.za

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EXECUTIVE SUMMARY

Background

This book is the product of a series of projects focused on the role of the vadose zone in the hydrological and geotechnical behaviour of materials, as well as those exacerbated by anthropogenic change (*Box 1*). A number of projects built up to this, working progressively through (i) theory of the vadose zone, (ii) interstitial systems, (iii) fractured systems, (iv) karstic systems, and (v) contaminant transport and flow changes in cemeteries as a case study. These contributions culminated in this project, requiring these systems to be overlain into a complex vadose zone system subjected to anthropogenic change.

Case Studies and Experimental Work

Experimental and field studies incorporated in this project form part of the vadose zone research projects and are listed chronologically as Vadose Zone Study Areas (VZSAs). These are not presented in this report, but are referenced to the original report, various dissertations and theses, and a number of peer reviewed journal and conference publications.

Novel Findings

These studies all address various aspects related to the vadose zone, contributing to a suite of new knowledge advancing our understanding of this complex part of the crust. Advancements relate to:

- Promoting transdisciplinarity in the study of the vadose zone
- Quantification of hydraulic conductivity using empirical and field methods
- Correlation of hydraulic parameters and behaviour through various methods
- Compiling conceptual hydrostratigraphic models based on anticipated hydrological behaviour
- Inferring flow regimes and flow mechanisms for variably saturated interstitial and fractured systems
- Contributing to variably saturated flow across the soil-rock interface and residual soils
- Expanding the understanding of interflow systems on the bedrock interface and processes of pedogenesis
- Considering changing moisture content and changing volume (porosity) as variables in unsaturated systems
- Supplying solutions and design requirements for certain applications, such as dolomite and engineering studies, cemeteries, permeable interlocking concrete pavements, corrosion studies, etc.
- Outlining a vadose zone assessment protocol cognisant of stages of investigation and levels of competence.

Box 1. About this Book

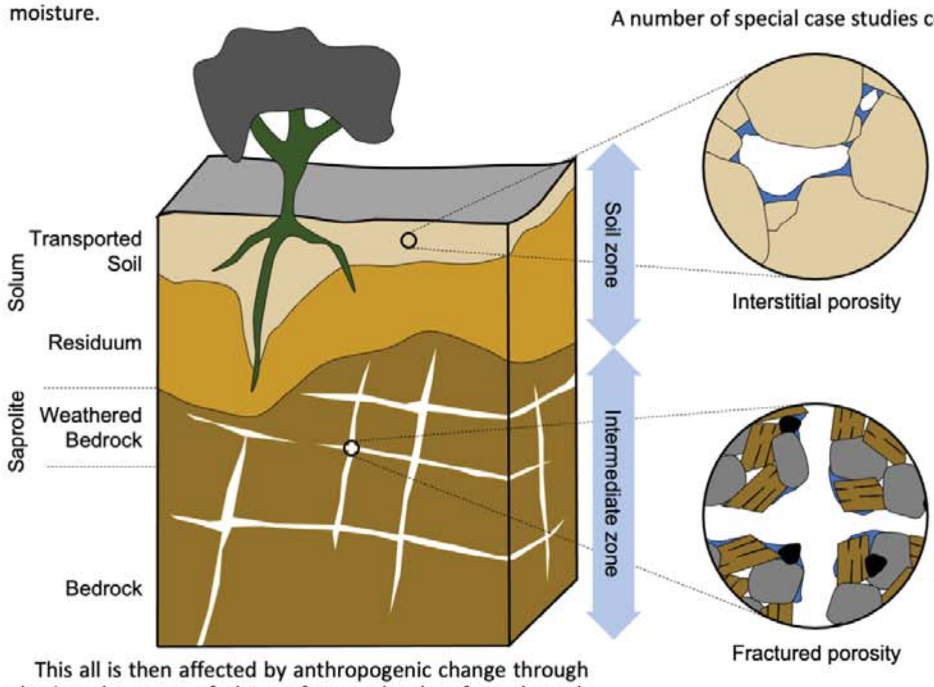
BOX 1. About this Book

(a) Project Background

The vadose zone dictates the hydrological cycle where meteorological and surface water exchanges with subsurface water. Accounting for the vast majority of terrestrial freshwater, subsurface water is classically biased towards the phreatic zone serving its storage reservoir function through aquifers and primarily seen as a water supply solution.

Replenishment of the phreatic zone is through the vadose zone. Attenuation of contaminants, as well as the advective transport of contaminants, are through the vadose zone. And the protection offered to the important aquifers below are due to the properties of the vadose zone.

The vadose zone is therefore fundamental in linking surface water and groundwater, and in controlling the quality of groundwater. Further to this, the role of soil moisture in the soil zone for plant root uptake is well understood, with recent advances in the hydropedological classification of materials providing a very valuable means of interpreting the shallow subsurface hydrological regime. The intermediate vadose zone below, often fractured or karstic at depth, exist at different stress states with somewhat different controls on the retention and movement of moisture.



This all is then affected by anthropogenic change through altering the state of the surface and subsurface through tilling, altering, and replacing materials. Infrastructure development, urbanization, and other land use changes affect not only the distribution and movement of surficial and shallow subsurficial water, but also its quality and its eventual connection to groundwater and surface water.

Often disregarded, the vadose zone is fundamentally important and requires improved consideration.

(a) Project Outline and Findings

This book fundamentally aims to provide up-to-date theory on the behaviour of soil and rock successions under highly variable moisture content, as well as when affected by anthropogenic change, with final comments on how to better assess the vadose zone for hydrogeological and geotechnical applications.

Building on a series of previous projects, this project links knowledge on the behaviour of primary, secondary, tertiary, and anthropogenically altered vadose zone systems at highly variable moisture contents. This project contributes to:

- The behaviour of the vadose zone, including the soil, rock, and water making up the space; how it wets up and dries out; and how water moves in the subsurface
- Applications of vadose zone hydrology in complex intergranular, fractured, and karstic systems, as well as in complex successions of these
- Implications and solutions of anthropogenic change to complex vadose zone systems at highly variable moisture contents.

A number of special case studies contribute to the project:

- Ephemeral wetlands
- Cemeteries
- Karst systems
- Permeable pavements
- Pressure testing

The project supplies improved understanding with respect to especially fractured systems, while incorporating this with advances in karst systems, applications to cemeteries, and other new developments

The project culminates in an initial integration of the complex vertical succession of ground, at highly variable moisture contents, subjected to anthropogenic change.

This project promotes transdisciplinarity, collating input from hydrology, hydrogeology, engineering geology, soil mechanics, pedology, and environmental science. Through this, the principles of vadose zone hydrology can be applied to address not only flow, but also consequences of urbanization and land use changes, and solutions to mitigate damage, quality deterioration, or other disasters.

READ MORE:
ADAPTED FROM: Dippenaar et al. 2014; this document
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LIST OF SYMBOLS

Symbol	Description	Units
A	Area (cross-sectional throughflow)	[L^2]
b	Saturated thickness	[L]
b	Spacing (fracture)	[L]
C_U	Uniformity coefficient	[-/-]
D	Diameter; hydraulic diameter	[L]
d	Particle diameter; percentage passing 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 di(min) and di(max)	[L] typically mm
E	Energy	[ML/T]
e	Void ratio	[-/-]
e	Aperture (fracture)	[L]
f	fraction	[-/-]
f_i	Fraction comprising grain size d_i	[-/-]
g	Gravitational acceleration	[L/T^2]
Gs	Specific gravity	[-/-]
h	Hydraulic head	[L]
h_c	Capillary rise	[L]
h_p	Pressure head	[L]
i	Hydraulic Gradient, dh / dl	[-/-]
K	Hydraulic conductivity	[L/T]
k	Intrinsic permeability	[L^2]
M	Mass	[M]
m	Mass (in Bernoulli's equation)	[M]
P	Pressure (or force per unit area)	[P] [M/LT^2]
Q	Flux; discharge	[L^3]
q	Specific discharge; darcy velocity	[L/T]
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	[-/-]
T	Transmissivity	[L^2/T]
u	Pore water pressure	[F/L^2]
v	Average linear flow velocity	[L/T]
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 centre of gravity above a datum	[L]

[F] Force; [L] Length; [M] Mass; [P] Pressure; [T] Time; [°] angle degrees; [-] dimensionless

Greek Symbol	Description	Units
α	Compressibility of the mineral skeleton	[LT^2/M]
β	Compressibility of water	[LT^2/M]
β	Forchheimer coefficient	[-/L]
γ	Unit weight	[F/L^3]
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	[F/L]
σ	Stress	[F/L^2]
σ'	Effective stress	[F/L^2]
Ψ	Soil water potential	[F/L^2] [L]
ψ	Pressure head (when negative); suction head ($-\psi$)	[L]
v	velocity	[L/T]

[F] Force; [L] Length; [M] Mass; [P] Pressure; [T] Time; [°] angle degrees; [-] dimensionless

Subscript	Description	Relating to
A	Air phase	$M\ V\ P\ \rho$
atm	Atmospheric	P
b	Bulk, total	$M\ V\ \rho\ \Psi$
c	Capillary	$h\ P$
e	Effective	$\eta\ d$
f	fracture	$K\ e$
g	Gravitational	Ψ
h	hydrauli	$K\ e$
if	infill	$K\ e$
L	Liquid phase	W
m	Matric	Ψ
m	matrix	K
m	mineral	$\rho\ f$
min	Minimum	V
max	maximum	V
o	Osmotic	Ψ
r	Residual	$S\ \Theta$
S	Solid phase	$M\ V\ \rho$
S	Specific	S
sat	saturated	K
T	Total, bulk	$M\ V\ \rho\ \Psi$
unsat	unsaturated	K
V	Void space	V
W	Water phase	$M\ V\ P\ \rho\ \gamma\ \mu\ \sigma$

SECTION A: INTRODUCTION

1. THE RELEVANCE OF THE VADOSE ZONE

Knowledge in South Africa is rapidly expanding with reference to the management of runoff, stormwater, water sensitive design and urban hydrogeology. The Anthropocene is being considered as a new epoch defining the age of human influence visible in the future geological records. Infrastructure development, mining, and disruption of the geological environment are expected to remain embedded in the geological record hundreds of thousands of years into the future, and these influences are shaping how water influences our development and how we alter the water cycle in the present.

Site investigation is commonly conducted prior to any proposed development. This is done with specific consideration to the hydrogeological and geotechnical conditions; i.e. how the proposed development will affect groundwater systems, and how the geological conditions will affect the proposed development. Most often, these investigation are based on greenfields conditions and, although we recommend based on in-situ conditions, we very often neglect to adequately address the envisaged site conditions that result due to anthropogenic change to the natural environment. Natural ground materials are replaced with engineered and imported materials; subsurface hydrology and surface runoff are altered; water quality changes; and subsequently the conditions for which we design rarely exist beyond the construction phase.

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. For this reason, input from multiple disciplines may clarify the issues around water movement through the subsurface.

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.

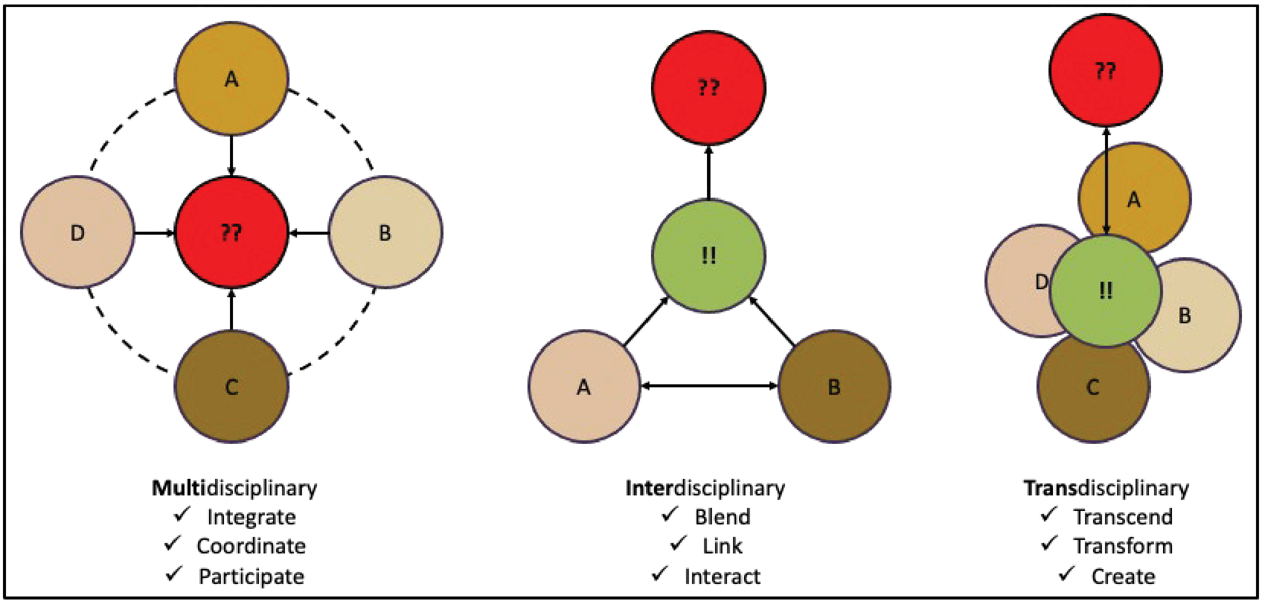
Finally, the geotechnical specialist is interested in the interaction between subsurface moisture and infrastructure, further increasing the importance of including all disciplines interested in subsurface waters, regardless of the reason.

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 (*Figure 1-1*; 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. engineering geology, geobotany)
- Transdisciplinarity – dissolving boundaries between disciplines (e.g. single expert of all relative individual fields, but with feedback between disciplines).



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.

1.1. Environmental Management, Environmental Science and Ecology

Environmental science is an exceptionally broad field of study with a wide range of specialisations. Environmental management typically involves 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 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.

1.2. Hydrogeology and Geohydrology

For the groundwater scientist, the vadose zone essentially play three vital roles, namely (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 Oke (2017), 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).

Hydrostratigraphy, or the classification of the subsurface into hydrogeological units, also relies heavily on understanding the role of the vadose zone in linking critical parts of the water cycle (Diamond et al. 2019). Increasingly, hydrogeologists consider recharge rates, attenuation capacity of the vadose zone, and so forth in groundwater investigations and flow models to improve accuracy and to better envisage long-term changes.

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.

1.3. Engineering Geology and Geotechnical Engineering

Geotechnics and engineering geology are highly dependent on the relationship between the mechanics of solids (soil and rock), fluids (water and air), and discontinuities (structures) (Bock 2006). 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) emphasise the benefit of pedology and Quaternary geology for the engineering geologist.

The South African National Standards SANS 633 and 634 (SABS 2009a,b) highlight the field description of moisture and recommend the inclusion of seepage in the zoning 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.

1.4. Soil Science, Pedology, Hydropedology 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 (1994) 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)." Hydropedology is also well documented by Bouma (2006) and Lin et al. (2015) in international context, and the development of hydropedology in South Africa is described by Van Tol et al. (2013) and Van Tol (2020).

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. About this Book

This book attempts to include vadose zone hydrology as improved site characterization to better pre-empt what ground and water conditions will be during construction and thereafter. Better knowledge regarding the development or drainage of perched systems, inducing or reducing either infiltration or runoff, altering the chemistry and quality of water in the unsaturated zone, and impacts on infrastructure and the receiving environment are some important outcomes to improve our planning for urban development based on vadose zone conditions.

As such, this books aims to:

- Synthesise the available theory related to the vadose zone for better interdisciplinary and transdisciplinary application while advancing understanding of the hydraulic and mechanical properties of the vadose zone
- Improve conceptual vadose zone models and hydraulic parameter estimation, incorporating complexity and comprising the soil zone and the intermediate vadose zone
- Evaluate implications of altered earth materials and subsurface hydrological conditions prior to development, during construction, and during entire life cycle of the proposed development
- Provide appropriate reference to methods and guidelines for assessment of the vadose zone for various applications.

Terminology is defined throughout with appropriate references. However, given the vast number of variables and terms, as well as the overlap of different concepts in different disciplines, it became imperative for the authors to standardise terminology and symbology. Hydraulic conductivity is, for instance, taken to be indicated by uppercase Latin K with units of [length/time], whereas intrinsic permeability is taken to be lowercase Latin k with units of [length*length]. Similarly, porosity is indicated by Greek lowercase *eta*, η, as opposed to Greek lowercase phi, ϕ, or Latin lowercase n.

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.

This book fundamentally aims to provide up-to-date theory on the behaviour of soil and rock successions under highly variable moisture content, as well as when affected by anthropogenic change, with final comments on how to better assess the vadose zone for hydrogeological and geotechnical applications.

Original and new case studies were selected, based on (i) literature, (ii) project team knowledge, (iii) outcomes of previous project outcomes and dialogues, (iv) issues identified during conducting of experimental work, and (v) accessibility of study sites. The case studies referenced throughout this book are summarised in *APPENDIX A*, also supplying the reference to the original publication of the case study results for more details.

Similarly, a shortened section on methods and techniques to quantify hydraulic parameters, notably hydraulic conductivity, is supplied in *APPENDIX B*.

A generic legend for most of the line drawings, cross-sections and figures are supplied in *Figure 2-1*. This applies throughout this report unless another key or legend is supplied.

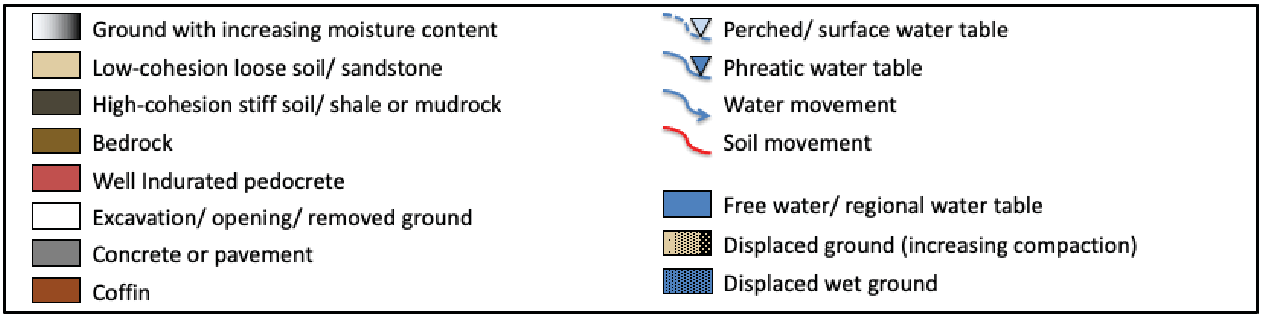


Figure 2-1. Generic legend for figures.

The book is subdivided into a number of sections to allow logical progression through theory, gradually building up in complexity towards an understanding of complex, heterogeneous and anisotropic, natural and anthropogenically altered systems. This is followed by summarised historical case studies, methods and applications, concluding in final contributions to a multidisciplinary and transdisciplinary vadose zone assessment protocol for various applications.

SECTION B: THE SUBSURFACE

3. EARTH MATERIALS OF THE SUBSURFACE

Ground is taken to collectively refer to all geological and pedological materials below land surface, including all soil, rock, and the anthropogenic (manmade materials). The natural ground is defined as follows:

- ***Rock*** (*Box 2*) is formed through igneous (plutonic or volcanic), sedimentary (lithification, precipitation or cementation) or metamorphic processes, and can be fresh (sometimes termed *unweathered*), 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*** (*Box 3*) 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.

The rock cycle describes the relationship between different types of rock (based on formation through igneous, metamorphic or sedimentary processes), as well as the main erosion and deposition pathways resulting in the formation of transported soil deposits, pedocretes, and eventually sedimentary rock (*Box 4*).

3.1. Texture and Structure

Rock and soil are both influenced hydrologically by the primary texture which forms during formation of the material, and the secondary structure which is post-formational. Soil structure refers essentially to unconsolidated materials, but consideration of structure is equally (if not more) significant in rock where secondary structures, typically formed through changes in stress conditions, are generally more pronounced and important in the transmission of fluids.

Occasionally, and notably with respect to the classification of aquifers 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. In South Africa, this mainly applies to karst aquifers in the dolomite regions.

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. 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, by secondary structures, by tertiary dissolution features, or by any 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.

Box 2. What are Rocks?

BOX 2. What are Rocks?

(a) Rocks

A ***rock*** is a naturally occurring, geologically formed aggregate of different minerals or glasses.

A ***mineral*** is any

- Naturally occurring
- Geologically formed
- Mostly inorganic
- Crystalline (i.e. ordered chemical structure)
- Solid
- With a fixed composition

As opposed to this, a ***glass*** *i*s not typically crystalline, often due to rapid crystallisation from melts (lavas aboveground or magmas underground).

As such, elements make up minerals or glasses, that in turn make up rocks.

Bedrock refers to the immediate rock underlying the soil at depth at a certain locality.

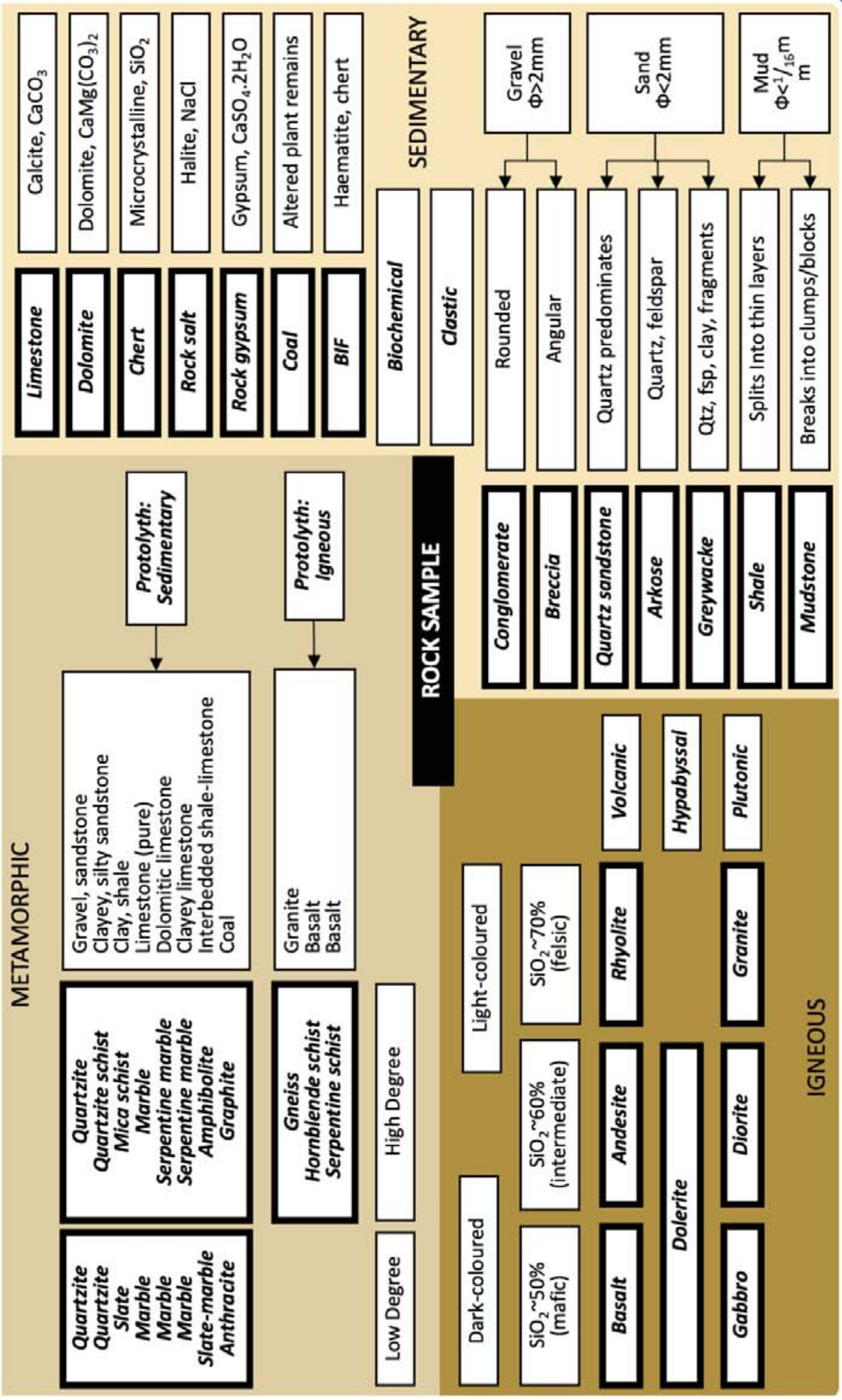
Outcrop refers to any naturally or anthropogenically exposed rock, e.g. cliffs, cuttings, etc.

(b) Rock Types

Major rock types are:

- ***Igneous rocks***; those formed from cooling melts
- ***Sedimentary rocks***; those cemented or lithified under compaction
- ***Metamorphic rocks***; those altered under changing temperature and pressure conditions.

Classification is typically based on texture or structure (i.e. how the rock looks in terms of grain size and shape, including alignment of minerals, etc.) and composition (i.e. minerals of main grains and intergranular cement).



ABOVE: A simplified classification of some of the most common igneous, metamorphic and sedimentary rock types (shown in bold boxes).

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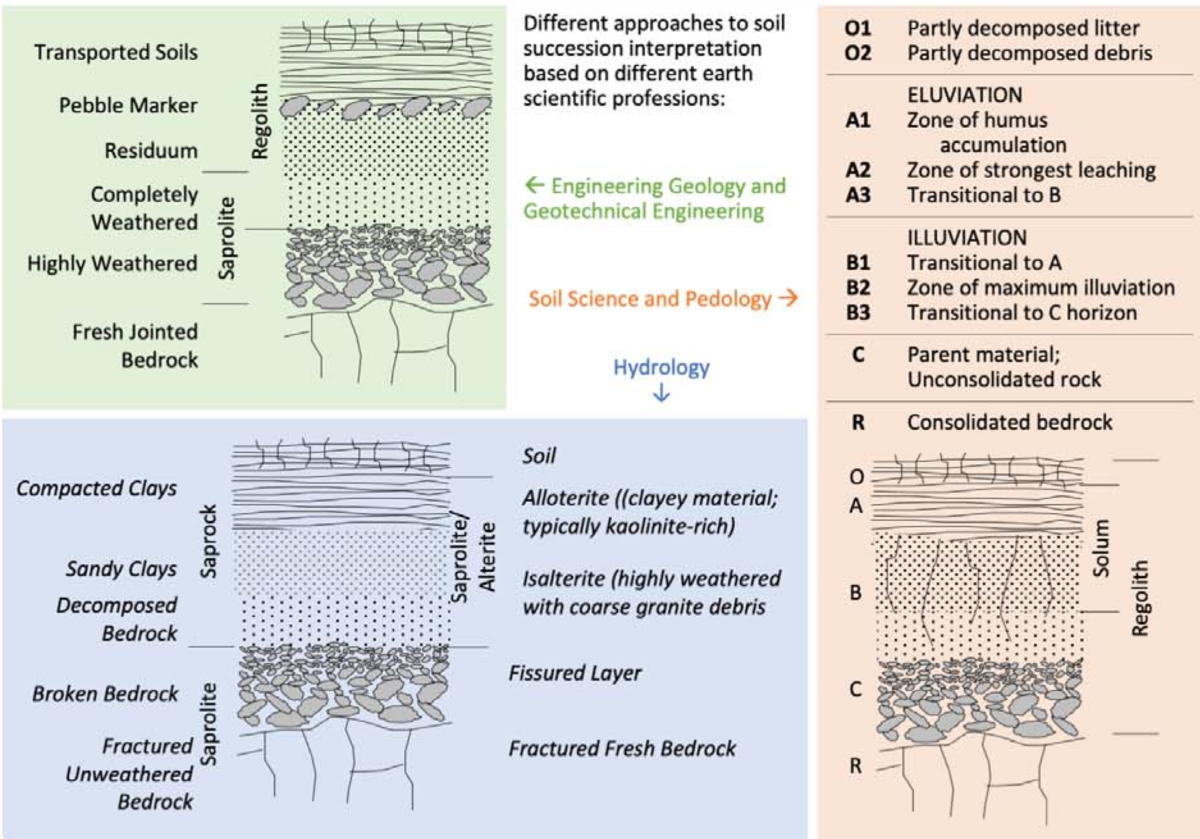
Box 3. What is Soil?

BOX 3. What is Soil?

(a)	Definition of Soil	Interest in Weathering and the Soil Zone
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.	Soil-forming processes; classification; shallow profiles from open pits; one-dimensional A, B and C horizons.
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.	Physical environment; site characterisation; soil/ rock mechanics; one-dimensional rock material versus rock mass.
Hydrology	Uppermost earth materials which can support plant life with sufficient moisture.	Storage reservoir influencing catchment's water balance.
Geomorphology		Weathering processes; spatial context; weathering versus landform evolution; weathering rates; dating of events.
Geology	Dependent on origin, transport and composition; fine weathered rock material and surface deposits with varying amounts of organic matter.	Mineralogy and chemistry (especially clay chemistry); notably intact bedrock and not overburden; one-dimensional movement of elements.

(b) Soil Profiles



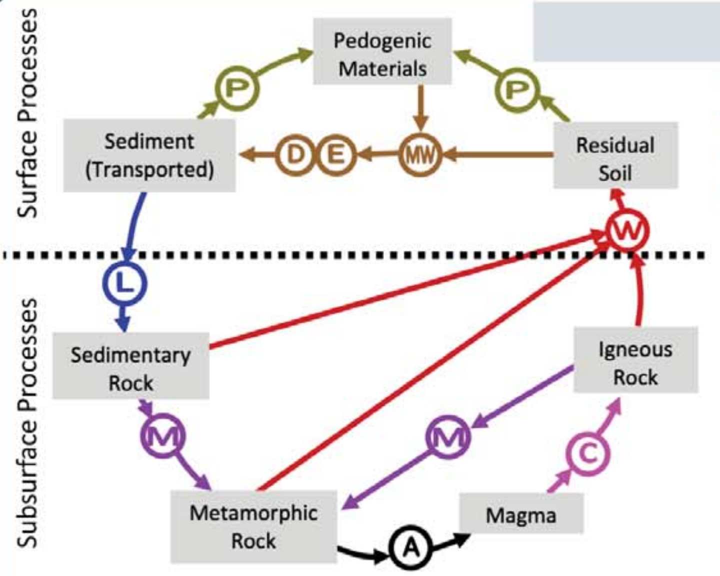
READ MORE: ADAPTED FROM: (© www.wrc.org.za) (a) Blatt & Tracy 1997; Bridges and Van Baren 1997; Craig 1999; Dippenaar 2012; Ehlen 2005; Miller 2000; Rahn 1986; Schaetzl and Anderson 2005; White 1997; Winegardner 1996; Younger 2007; (b) Dippenaar and Van Rooy 2015; Foster 2012; Hillel 2003; Koita et al. 2013

Box 4. *From Rock to Soil*

BOX

4. From Rock to Soil

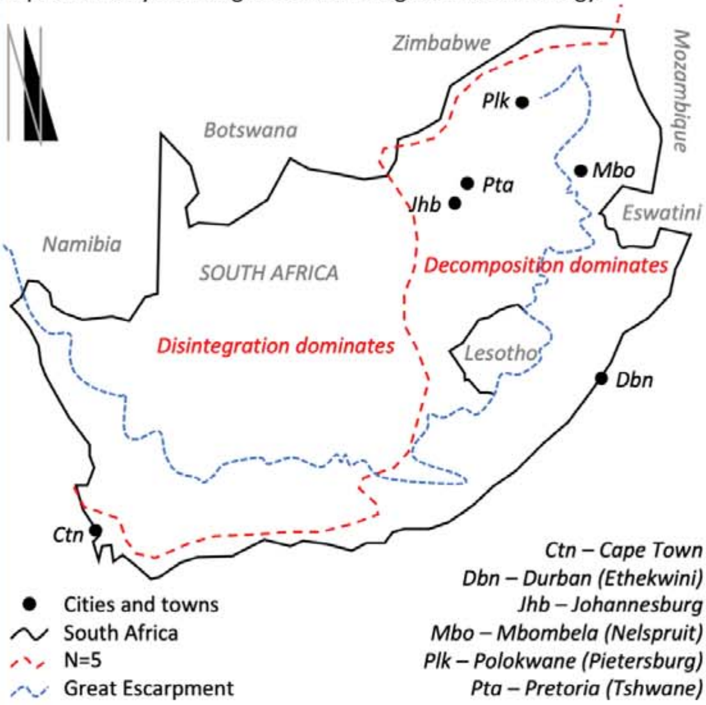
(a) Rock Cycle



C	Crystallization	D	Deposition
W	Weathering	P	Pedogenesis
MW	Mass Wasting	L	Lithification
E	Erosion	M	Metamorphism
		A	Anatexis

(b) Weathering and Climate

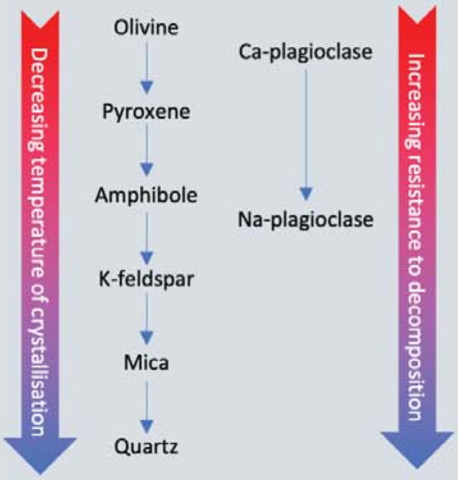
N-values are calculated as a function of the evaporation in January and the annual rainfall. In South Africa, the more values deviate from N=5, the more pronounced chemical weathering (decomposition; N<5) or physical weathering (disintegration; N>5) becomes. With the prior, mineralogy changes, typically resulting in thicker soils comprised of secondary minerals. With the latter, thinner soil cover results, mainly represented by finer fragments of the original rock mineralogy.



(c) Weathering and Mineralogy

Igneous rocks crystallize as magma or lava cools, typically in the sequence of ***Bowen's Reaction Series***.

For major rock-forming minerals, this also serve as an indication of the mineral stability and resistance to chemical change at surface temperatures and pressures through ***Goldich's Weathering Sequence***. The high-temperature minerals at the top will typically be unstable, changing to expansive 2:1 type clays, whereas the quartz at the low-temperature extreme is practically chemically inert, resulting in finer fragments of the same SiO_2 mineralogy forming in even in chemical decomposition environments.



For karst systems this is even more pronounced. Carbonates and evaporites are typically soluble (to some extent) in slightly acidic atmospheric water, resulting in complete dissolution of the rock. As opposed to forming secondary minerals through, for instance, hydration, the rock itself is completely soluble, resulting in no to very small amounts of residual materials remaining. In the instance of karst, this eventually leads to the formation of caves and sinkholes.

READ MORE:
ADAPTED FROM: Brink 1996; Weinert 1984

3.2. Rock

Rock (*Box 2*) 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.

3.2.1. 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.

3.2.2. Rock 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 (*Box 5*). The term ***discontinuity*** has previously been used to refer to fractures in a rock mechanics and geotechnical sense. Presently, the term ***defect*** is most widely employed in this context.

Fresh (also sometimes termed ***intact***, ***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.

3.2.3. Rock description

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, gneissic banding, laminations, crossbedding, ripple marks and other relic structures. Soil structures possibly present in completely to highly weathered rock can also be noted and include, for instance, krotovinas (infilled root voids/ burrows), open root channels, pinholes, slickensides and shattering.

Description of rock is also discussed in SANS 633 (SABS 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.

The description of rock outcrop is often done at the hand of joint line surveys (JLS) where defects in the rock are described at the hand of their respective geometries and orientations (*Box 5*; *Box 6*). These descriptors inevitably affect the hydraulic behavior of the rocks mass and the extent to which the aperture (openness) and roughness (offset from smoothness both in terms of wavelength and amplitude of the roughness profile) will retard the movement of water. 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.

Some examples of structures 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.
- ***Foliation***, i.e. metamorphic textures such as schistosity, gneissic banding, etc.
- ***Other structural influences***, i.e. faults, folds, shear zones, intrusions, etc.

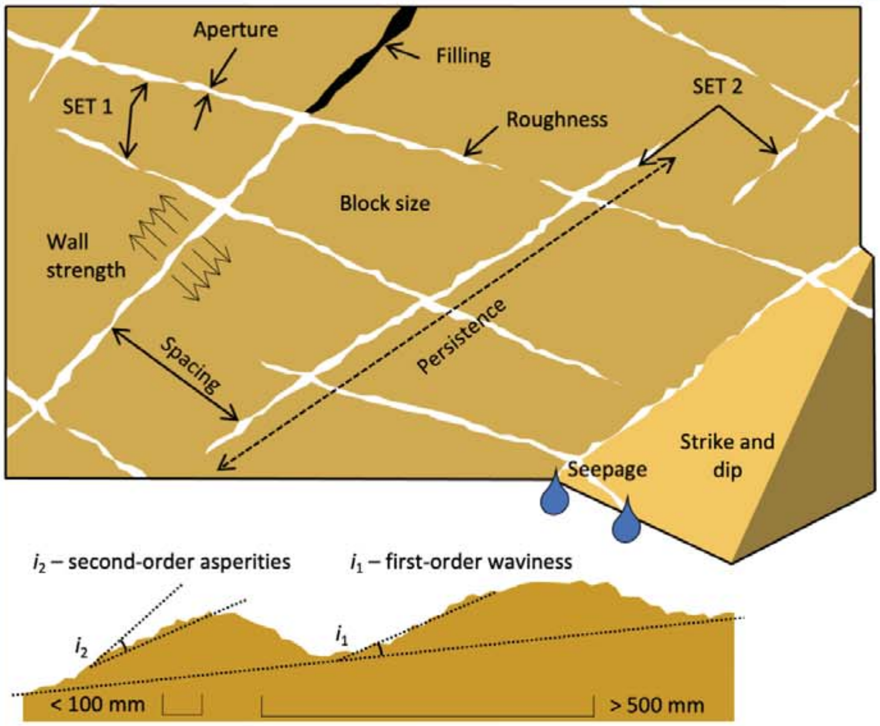
Rock types are described in terms of geological classification with reference to stratigraphical context, where appropriate. Mineralogical specification of the rock and infill material will also aid in addressing the properties. Description of rock weathering is done as follows:

- ***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.
- ***Fresh rock*** shows no visible signs of alteration, although discontinuity planes may be somewhat stained.

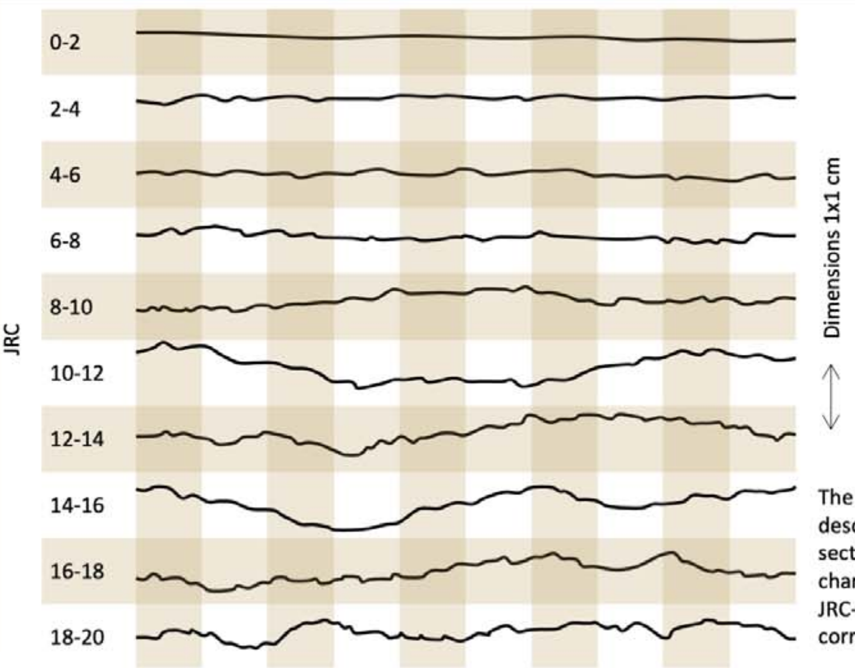
Box 5. Rock Material and Rock Mass

BOX 5. Rock Material and Rock Mass

(a) Rock Mass Descriptors



(b) Joint Roughness Coefficient (JRC)



(b) Weathering Descriptors

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 is 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.

Fresh rock shows no visible signs of alteration, although discontinuity planes may be somewhat stained.

The JRC is a well established means of describing joint roughness. Each section indicated represent a characteristic length of 10 cm, and the JRC-value is estimated based on visual correlation.

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(a) Anon 1977; Dippenaar and Van Rooy 2016; Gonzales de Vallejo and Ferrer 2011; (b) Barton & Choubey 1977

Box 6. *Rock Mass Description*

BOX 6. Rock Mass Description

(b) Rock Mass Descriptors

Structure	Aperture (mm)	Infill	Roughness	Spacing	Persistence (m)	Strength (MPa)	Water (l/s)
Fault zone Fault Joint Cleavage Schistosity Shear Fissure Tension crack Foliation Bedding	Wide (>200) Mod. Wide (60-200) Mod. Narrow (20-60) Narrow (6-20) Very narrow (2-6) Extr. Narrow (<2) Tight	Clean Surface staining Non-cohesive Inactive clay Swelling clay Cemented Chlorite Talc Gypsum Other – specify	Polished Slickensided Smooth Rough Defined ridges Small steps Very rough	**(m)**: Ext. wide > 6 Very widely 2-6 Wide 0.6-2 **(mm)**: Med. 200-600 Closely 60-200 Very close 20-60 Ext. close < 20	Very high > 20 High 10-20 Medium 3-10 Low 1-3 Very low < 1 Discontinuous	Very soft (<0.04) Soft (0.04-0.08) Firm (0.08-0.15) Stiff (0.15-0.30) Very stiff (0.30-0.50) Hard/very weak (0.6-1.25) Weak (1.25-5) Mod. Weak (5-12.5) Mod. Strong (12.5-50) Strong (50-100) Very strong (100-200) Ext. Strong (>200)	Dry Damp Seepage Flow: <0.010 0.010-0.100 0.1-1 1-10 10-100 >100
Record: Dip Dip direction Wall strength	Note: Consistency in aperture	Record: Strength	**Waviness** Wavelength Amplitude		Terminated: Outside exposure (x) Within rock (r) Against defect (d)	Record for: Wall Infill	
Ext – extreme(-ly); Mod - moderate(-ly); Med - medium							

(b) Rock Material Descriptors

Strength (MPa)	Structure/ Fabric	Colour	Texture	Grain size (mm)	Rock Type
* As for mass; refers to wall strength	Very thick Thick Medium Thin Very thin Thickly */ narrow Thinly */ very narrow * Terms include bedded, laminated, foliated, banded, flow-banded, etc.	As for soils; Red; Orange; Yellow; Brown; Green; Blue; White; Cream; Grey Supplement: Light Dark Mottled	Petrological e.g.: Phaneritic Ophilitic Porphyrytic Srystalline Amorphous Etc.	Coarse-grained > 2 Medium-grained < 2 Fine-grained < 0.06 Very fine-grained < 0.002	* Geological rock name Supply stratigraphic classification if possible Supplement with state of weathering of rock

READ MORE:
ADAPTED FROM: Anon 1977; Norbury 2015
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3.3. Soil

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 3*.

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 3* 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 based on mechanical properties; 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.

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.

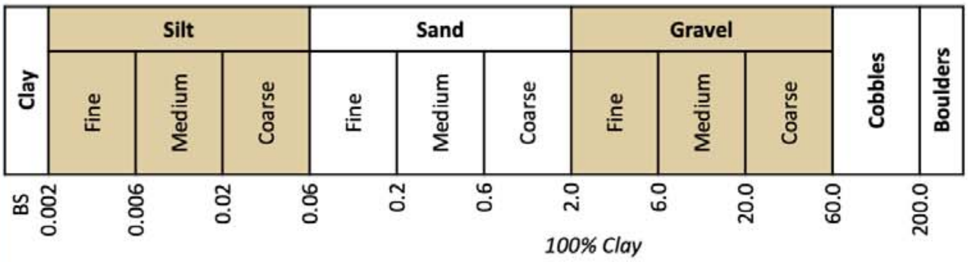
3.3.1. Soil material

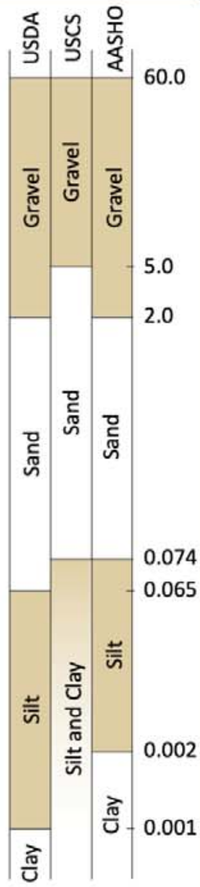
Classification of soil texture is explained in *Box 7*. Particle size analyses refer to the percentage by mass of particles within different size ranges making up the bulk of a disturbed soil sample. For the coarse fraction, this is achieved by passing a soil sample through a series of test sieves, each 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).

Box 7. Soil Texture

7. Soil Texture

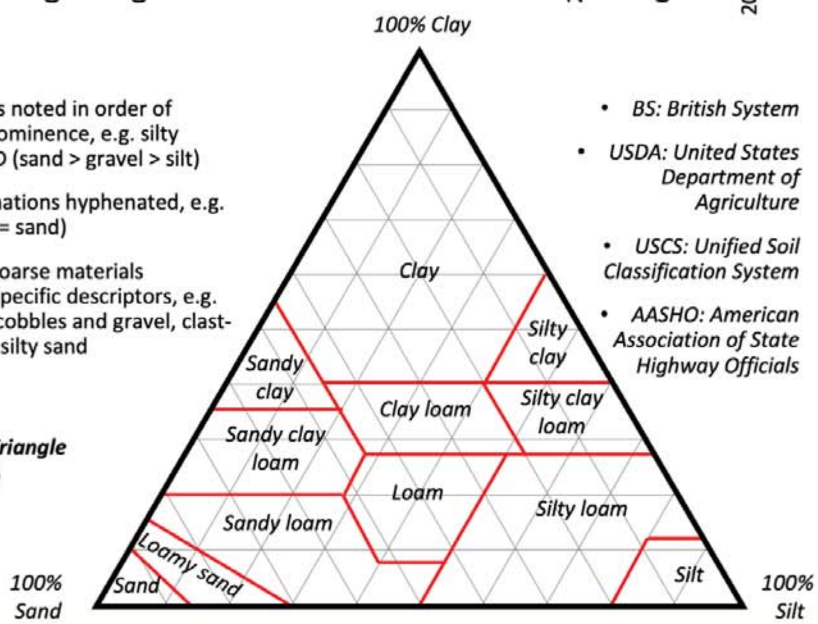
(a) Soil Texture Classes (mm)





- 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

Soil Texture Triangle
(USDA)



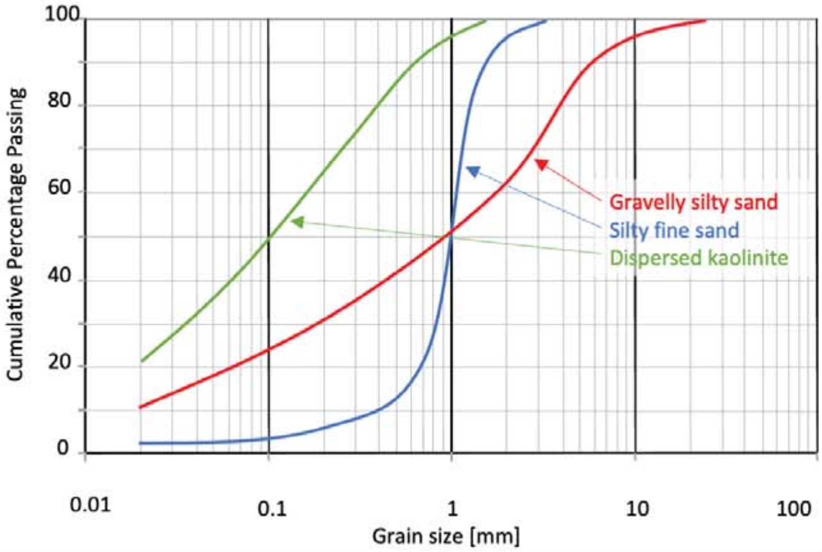
- *BS: British System*
- *USDA: United States Department of Agriculture*
- *USCS: Unified Soil Classification System*
- *AASHO: American Association of State Highway Officials*

(b) Grading, Sorting, and Particle Size Distribution

The ***grading*** or ***particle size distribution (PSD)*** refers to the distribution of different grain size diameters in a soil, and is determined through sieving a sample through a set of standard sieves followed by settling in a hydrometer.

The term ***well-graded*** refers to a medium with a good mix of different particle sizes, in which sufficient finer fractions are present to clog pore space generated by the coarser fraction. This is used as the opposite of sorting, where a well-graded soil is poorly-sorted, and vice versa.

Steeper gradients imply ***poor grading***, and flat middle portions refer to ***gap-grading***.



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(a) Brink and Bruin 2001; Jennings et al. 1973; SABS 633:2009a; SAICE 2010; Soil Triangle: Brady and Weil 1997; Schaetzl and Anderson 2005; (b) e.g. Bear 1988; Gonzales de Vallejo and Ferrer 2010

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 3-1*. 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. The most important d-sizes are shown *Figure 3-1*.

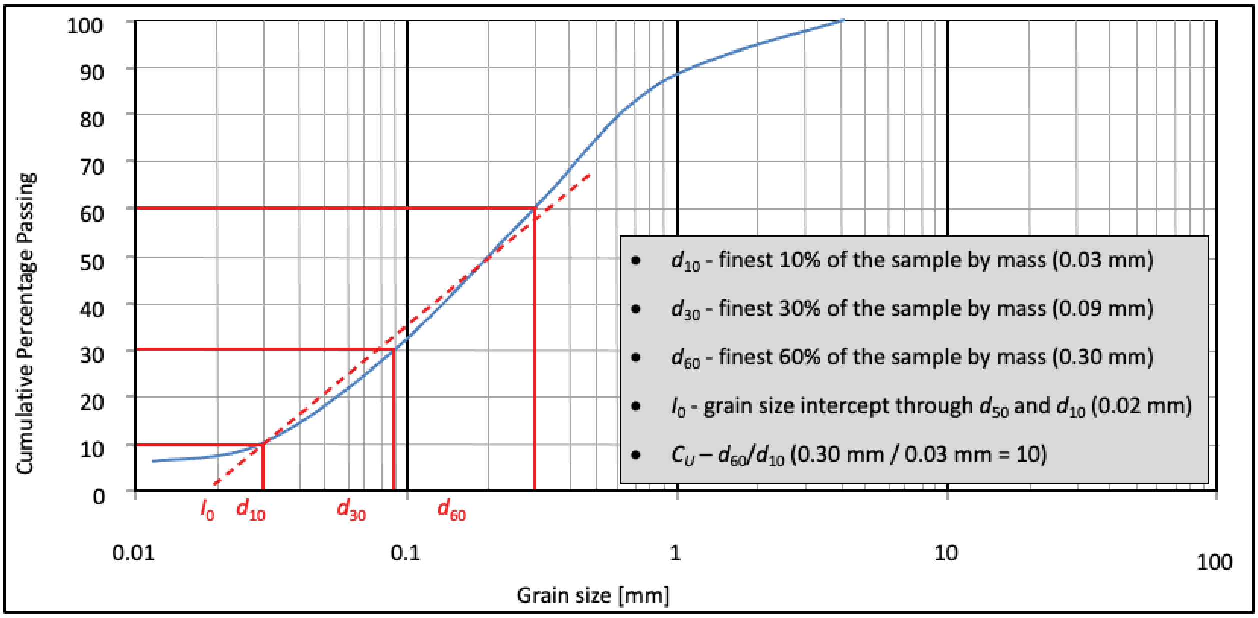


Figure 3-1. Determining the d-values from particle size distribution data.

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 1*. 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. Values exceeding 1 to 10 are very uniform, and those above 100's to 1000's are very poorly sorted and well graded. Determination of the d_{10}-fraction is, however, not always possible as many grading analyses do not determine smaller diameters than 0.002 mm, implying that C_U cannot be determined.

$$C_U = \frac{d_{60}}{d_{10}}$$ ***Equation 1***

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 2 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 3 or Equation 4 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 $d_{i(max)}$.

$$d_e = \frac{1}{\sum_{i=1}^{n}\left(\frac{f_i}{d_i}\right)} \quad \text{or} \quad \frac{1}{d_e} = \sum_{i=1}^{n}\frac{d_i}{f_i}$$ ***Equation 2***

$$\frac{1}{d_e} = \sum_{i=1}^{n} \left(\frac{\sqrt{d_{i(max)} \cdot d_{i(min)}}}{f_i} \right) \qquad \textbf{\textit{Equation 3}}$$

$$\frac{1}{d_e} = \sum_{i=1}^{n} \left(\frac{d_{i(max)} + d_{i(min)}}{2f_i} \right) \qquad \textbf{\textit{Equation 4}}$$

3.3.2. Soil 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 massive (hard mass when dry 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.

Alternatively, soil structure description is based on application to engineering and includes, for instance, ***intact*** (sic. structureless), ***fissured***, ***slickensided***, ***microshattered***, ***shattered***, ***granular***, ***pinholed***, ***honeycomb***, etc. (SABS 2009a).

3.3.3. Soil profile description

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.

Classification of soil varies by discipline, and as such the description of soil successions differ. ***Soil profiles*** 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.

The description of soils for geotechnical purposes is standardised in South Africa and is based on six parameters in the sequence MCCSSO (*Box 8*; after Brink and Bruin 2001; Jennings et al. 1973; SABS 633:2009a; SAICE 2010):

Box 8. Soil Profile Description (MCCSSO)

BOX

8. Soil Profile Description (MCCSSO)

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

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

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

5. SOIL TEXTURE/ SOIL TYPE

Relate abundance of different particle size classes in order of abundance: clay(-ey), silty(-y), sand(-y), gravel(-ly); see preceding *BOX* on Soil Texture.

Denote secondary abundance as matrix-supported or clast-supported, including gravel, cobbles and boulders; if possible, supply approximate proportions.

Specify mineralogy or lithology; shape of coarse fraction

E.g. clayey silty SAND matrix-supporting abundant subangular quartz cobbles (c. 70/30)

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

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

Relics of original rock: jointed; laminated; foliated; etc.
Openings: open; voided; open root channels; etc.

6. ORIGIN

Transported soils: classified based on erosion, transport and/ or deposition agent: e.g. aeolian (wind), alluvium (water); glacial (glacier); colluvium (gravity); etc.

Made ground/ fill: anthropogenically reworked

Pebble Marker: stone line between transported and residual soil horizons

Pedogenic Horizons: layers indurated by authigenic cementation or enrichment

Residual and Weathered Horizons: progression from completely decomposed to fresh bedrock, e.g. residual granite; fresh quartzite

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

- ***Moisture*** relates to the mount of discernible moisture in the soil at in situ conditions
- ***Colour*** is described as primary and secondary colours with clear reference to discolouration (e.g. mottles)
- ***Consistency*** is estimated by means of penetration or pushing of the geological pick into the sidewall of the excavation, and is described differently for cohesive (fine-grained) and non-cohesive (granular) soils
- ***Soil structure*** describes the configuration of soil grains into a random (intact) or open-grained pattern, and possible relics of structures such as jointing, foliation or bedding
- ***Soil type*** relates to proportions of clay, silt, sand and other coarser particle sizes in the soil; refer to *Box 7*.
- ***Origin*** describes means of transport and deposition, pedogenesis, or state of weathering of in-situ bedrock.

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.

In pedology and soil science, 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 (Department of Agricultural Development 1991; Fey 2010):

- Silica (silicic)
- Carbonate or gypsum (calcic)
- Clays (duplex)
- Metal humate (podzolic)
- Iron mottling or cementation (plinthic)
- Uniform iron enrichment (oxidic)
- 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 in (Department of Agricultural Development 1991; Fey 2010), such as unconsolidated sediments (cumulic), 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. Pedological soil classification in South Africa was recently updated and is described by Van Zijl et al. (2020).

3.4. Karst

Karst systems and the behaviour of soluble rock, such as South African dolomites, are summarised in *Box 9*, and thoroughly described in recent literature (Dippenaar et al. 2019a,b; Swart et al. 2019; Swart 2019,2020). Here, large dissolution cavities can behave as high storage receptacles, where fractures aid in the rapid removal of highly mineralise water.

As opposed to being 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.

Soluble rock is mechanically classified as rock, implying that the description of outcrop or samples are the same as for rock previously described. Similarly, weathering products are described according to the system for soil profiles. However, from a hydraulic and hydrological point-of-view, tertiary porosity behave fundamentally different as large erosional openings can be formed through dissolution (dissolving) of minerals.

Box 9. Soluble Rock and Karst

BOX 9. Soluble Rock and Karst

(a) Karst in South Africa

The term **karst** refers broadly to a series of distinctive landforms and underground drainage systems forming from the chemical decomposition, dissolution or solutional erosion of soluble rock such as carbonates and evaporites. **Karstification** is the process of dolomite dissolution. Once karstification has occurred, the dissolution causes variably sized cave systems, crevices and voids which are highly permeable areas and have a high water storage capacity.

Majority of South African soluble rock is dolomite, often interlayered with chert, associated with the Transvaal and Griqualand-West Supergroups. **Dolomite** is a rock formed from chemical or biochemical sediments, and which is mainly composed of the mineral calcium magnesium carbonate ($CaMg(CO_3)_2$). Dolomite is the product of the secondary replacement of the original precipitate limestone ($CaCO_3$), where some of the calcium is replaced by magnesium through the process of dolomitization.

(a) Carbonate Dissolution

Chemical weathering entails the decomposition of a rock by changing its chemical composition which may cause partial or total change in chemical identity. Carbonates such as limestone or dolomite weather in water surplus environments through **chemical decomposition** by means of **carbonate dissolution**. Water becomes slightly acidic due to enrichment with atmospheric CO_2, further enhanced by the movement of water through the ground, causing a weak carbonic acid to form. At these acidic pH values, carbonate rocks can dissolve over time, removing ions in aqueous phase and leaving practically no solid residuum. The reaction results in hard water, enriched in Ca^{2+}, Mg^{2+} and HCO_3^- ions, buffering the acidity and increasing pH values. The extent of carbonate weathering is controlled by numerous variables such as temperature, pCO2 (which affects the pH of the solution), geochemistry, as well as sample size and grain size. In carbonate formations, solutions often achieve saturation within the vadose zone

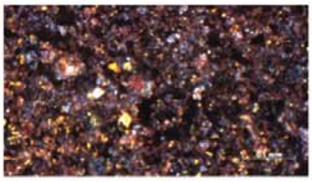
Elephant skin weathering

Interlayered/ interbedded chert (SiO_2)

(a) Weathering Products

Dolomite contributes to hardness in water, and these highly mineralised groundwaters flow as long as the solubility of the carbonates are not exceeded. However, most dolomites contain some impurities, that do leave a solid residue after weathering. This **residual dolomite**, termed **wad** when possessing certain qualitative attributes, forms on the soil-rock interface and in grykes (enlarged vertical joints) through the enrichment by removal of soluble material during leaching of dolomitic rock. Due to the highly soluble nature of both calcite and magnesite in dolomite, there are typically completely removed, and some impurities such as Mn^{4+}, Fe^{3+} and chert (SiO_2) remain.

Where residuum has been transported and redeposited as a transported soil, it is not typically classified as wad. In-situ wad may vary from a soft powdery broken structure to an intact structure which is comparable to that of the dolomite rock from which it originates. The intact fabric is depicted as porous, with a sponge-like structure, which shows an increase in both porosity and permeability compare to dolomite rock. Wad is a dark, fine-grained, insoluble material formed from weathering of manganese-rich dolomite, and that it is assessed based on the fabric as being either structured or laminated, or non-structured or massive wad. It can be structured, or reworked or non-structured. It can have very high porosity with very low density, posing a number of problems buth in terms of hydraulic and mechanical behaviour.



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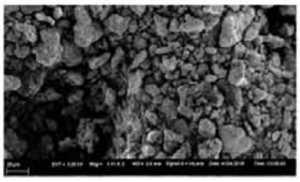

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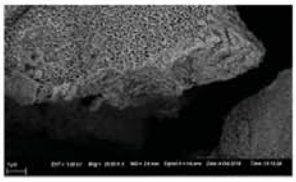

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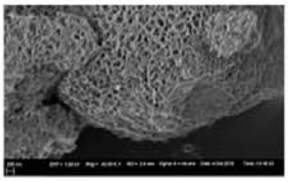


x40000 magnification

READ MORE: ADAPTED FROM: (© www.wrc.org.za) (a) Dippenaar et al. 2019a;b (b) Blatt et al. 1972; Booth 2015; Brink 1996; Richardson 2013 (c) Swart et al. 2019; Swart 2020, as well as Buttrick 1986; Day 1981; Wagener 1982; imagery from Dippenaar et al. 2019b: photos from Dinokana (South Africa); microscopy from Doornhoek (South Africa)

Fractured soluble rock, such as dolomite or limestone, tends to be more subjected to dissolution along defects or fractures, forming large V-shaped vertical joints referred to as grykes. These promote water entry, but can be filled with residues of weathered dolomite (residual dolomite and wad), or with chert rubbles (as chert, a silica-rock highly resistant to dissolution), or with any other transported soil or overburden. This generates high heterogeneity and anisotropy in these terrains.

3.5. Considerations with the Description of Earth Materials

In order for field data to be more applicable to a wider range of professional discipline, this data should become more detailed while also being more specific to a broader audience (*Figure 3-2*). Most of these are discussed in more detail in later sections.

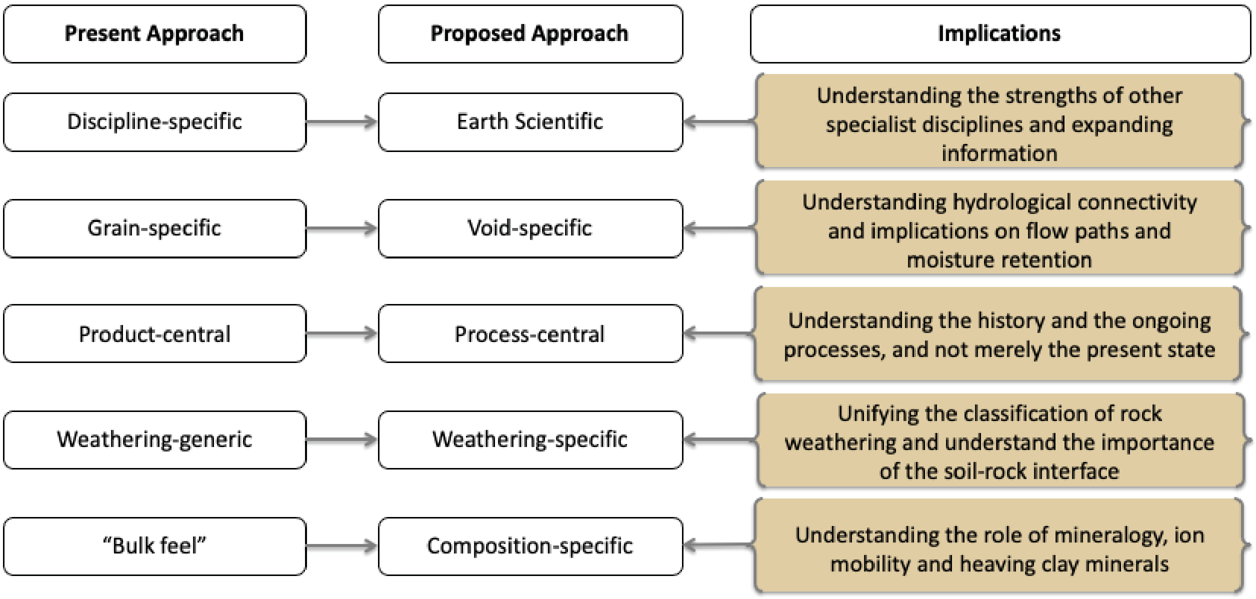


Figure 3-2. Transdisciplinary earth scientific profiling methodology for applications in vadose zone hydrology.

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 are 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 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 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.

4. Water

4.1. Water and other Fluids

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 10*.

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.

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.

4.2. The Hydrological Cycle

The ***hydrological cycle*** (or ***water cycle***) is an intricate interaction between water from the atmosphere, Earth surface and subsurface. This, together with the vertical distribution of water in the Earth's crust, are shown in *Box 10* and *Box 11*. The general hydrological equation governs the water balance through the relationship in *Equation 5*, as a function of precipitation (P), runoff (Ro), Infiltration (I), evapotranspiration (ET), and changes in storage (ΔS).

$$P = Ro + I + ET + \Delta S$$

Equation 5

The ***vadose zone*** (***unsaturated zone*** or ***zone of aeration***) stretches through the soil zone and intermediate zone and incorporates the complete capillary fringe where the medium is saturated but at negative pore water pressures. 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; Poeter et al. 2020; Woesnner and Poeter 2020).

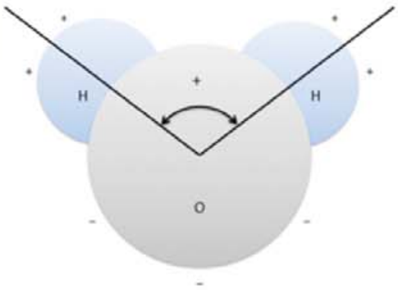
The ***water table*** (or ***phreatic surface***) represents the boundary between the phreatic and vadose zones as well as the surface where pressure equals atmospheric. The water table is represented by the ***water level*** in a well (indicated by an inverted triangle) to account for the deviation 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.

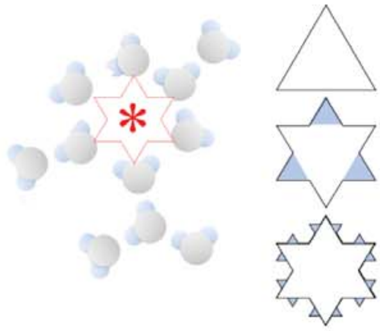
Box 10. Fluids: Water and Air

BOX 10. Fluids: Water and Air

(a) Water

- 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.
- As a solid, in crystalline mineral state, ice forms hexagonal crystals (indicated by the asterisk, *) which can best be explained at the hand of snowflakes. 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.
- 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 denser that its solid form (ice) which, as a result, will float on the liquid.

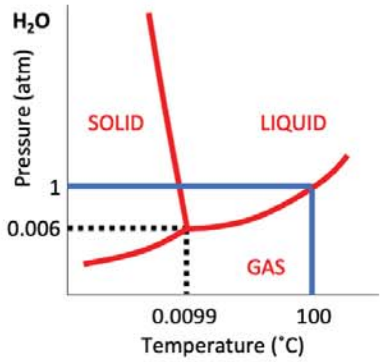


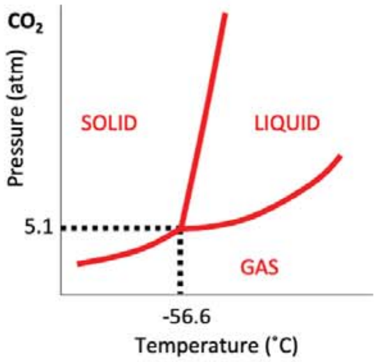


Property	Symbol	Units	Value
Mass density	ρ_W	$[M/L^3]$	1 000 kg/m^3
Weight density	$\gamma = \rho_W g$	$[F/L^3]$	9 810 N/m^3
Compressibility	β	$[L^2/F]$	4.5×10^{-10} m^2/N
Dynamic viscosity	μ	$[FT/L^2]$	1.4×10^{-3} $N.s/m^2$
Boiling point	T_B	[Temp]	100˚ C
Melting/ freezing point	T_M	[Temp]	0˚ C

M – mass; L – length; F – force; T – time; Temp – temperature

(b) Water versus Air





- Air pressure varies with climate and elevation. At sea level, this is roughly equal to 1.013×10^5 N/m^2 (= 1 atm = 1.013 bar = 14.7 psi = 760 torr = 760 mm Hg)
- Atmospheric density at land surface = 1.2 kg/m^3
- Atmospheric air at sea level is composed of approximately 78% N_2, 21% O_2 and < 1% Ar. Traces of other gases are also present, e.g. carbon dioxide (CO_2), water vapour (H_2O) and ozone (O_3).

Whereas air is highly compressible, water is nearly incompressible in liquid state at low temperatures. This is schematically shown above: maintaining the same temperature, water will go from gas through solid to liquid state under increasing pressure (i.e. by moving vertically upwards on the graph). Other fluids (such as carbon dioxide) will go from gas through liquid to solid under increasing pressure (i.e. by moving vertically upwards on the graph). This results in water being in densest state as a liquid at surface temperature. Triple points (where the compound exists in all three phases) are indicated by dotted lines where the red lines intersect. Water's boiling point at Earth's surface is indicated by the blue lines.

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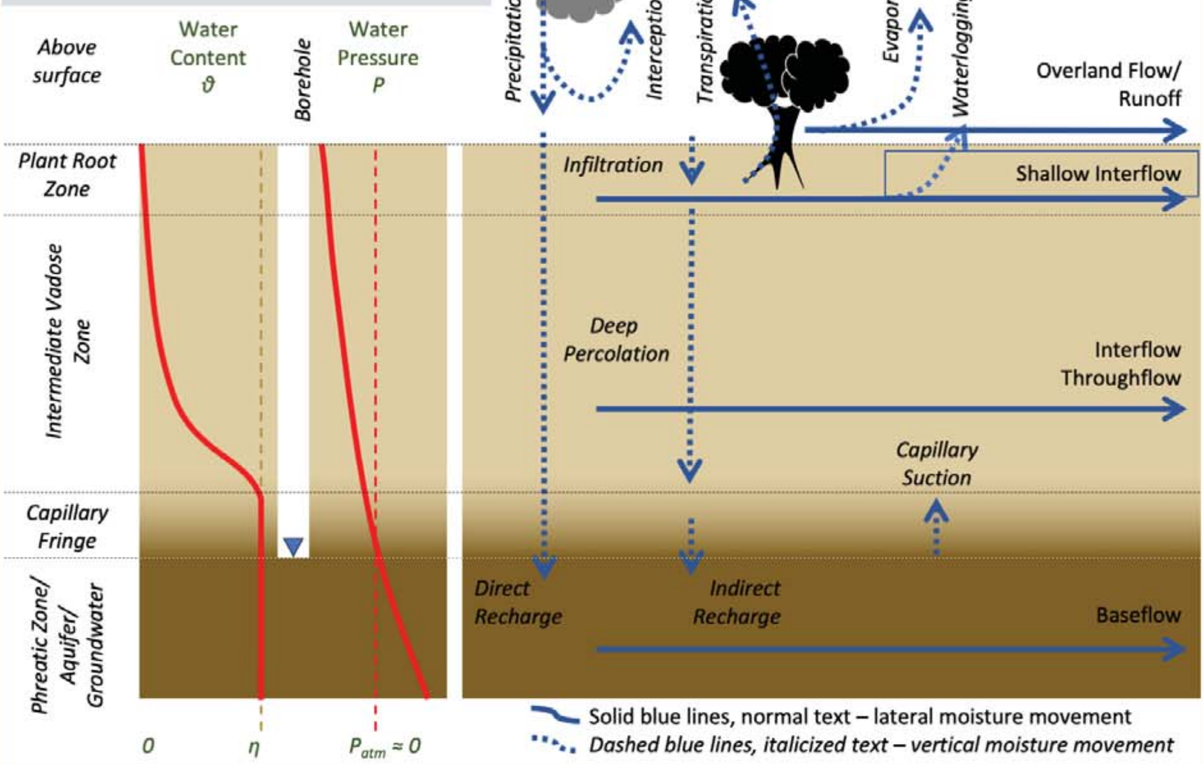
(a) Dippenaar 2013, Fitts 2002; (b) Phase diagrams not to scale; from Penn State University (https://behrend.psu.edu/school-of-science/academic-programs/chemistry) downloaded 2020/04/13.

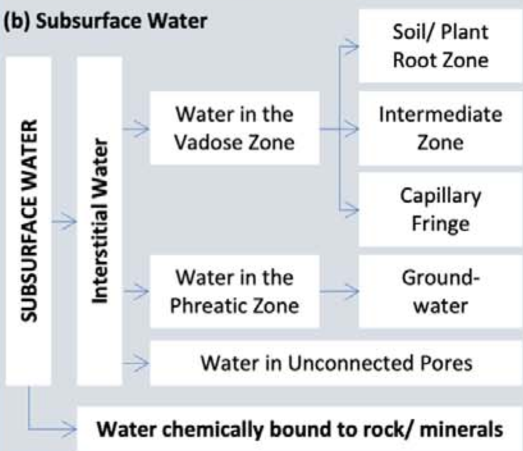
Box 11. Water in the Subsurface

BOX 11. Water in the Subsurface

(a) Water Cycle



(b) Subsurface Water

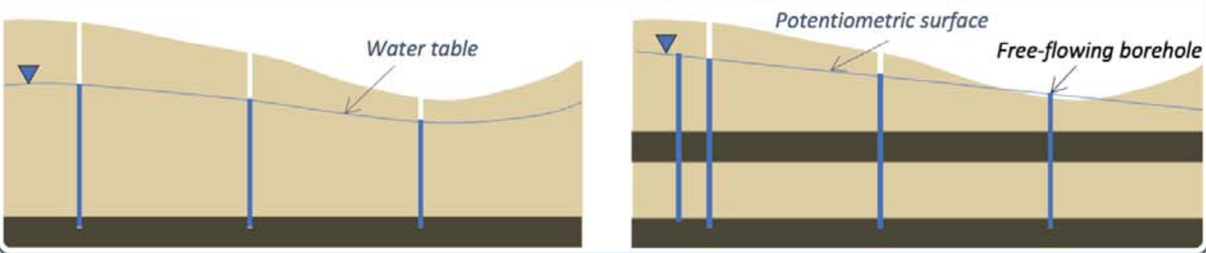


Subsurface water comprise water chemically bound to rocks or its minerals, and interstitial water. The latter forms the vadose and phreatic zones and include dead-end pore space.

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 is saturated, but at negative pore water pressures).

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

The ***phreatic zone*** has positive pore water pressures and complete saturation of pores with water, and can be unconfined (bottom left) or confined (bottom right)



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Diamond et al. 2019; Driscoll 1989; Fetter 1994; Fitts 2002; Poeter et al. 2020; Todd and Mays 2005; Younger 2005; Woessner and Poeter 2020;

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. Saturation entails the water content equal to the porosity; namely where all pore spaces are filled completely with water. This applies to the phreatic zone, but also to the capillary fringe where water is being pulled upward due to negative pore water pressures. The saturation 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).

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).

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). In this context, the following definitions apply:

- ***Infiltration*** refers to water entering the subsurface from the surface (due to the primary porosity or texture and secondary porosity or structure of the surficial soils which creates openings) and which is still affected by evapotranspiration; then moving sub-vertically downwards under the influences of gravity and dispersing three-dimensionally under the influence of capillary action.
- ***Interflow*** refers to water migrating laterally due to less permeable horizons (or perching on these horizons and then moving down-slope) marring the further percolation of water to either discharge as a spring or to percolate at a point further down-slope.
- ***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.

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).

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.

4.3. Surface Water—Groundwater Interaction

Groundwater, surface water and water in the vadose zone are in constant interaction. Seeps and springs represent some of these environments where subsurface water emerges on land surface. However, numerous more exist where surface water collects to allow further surface water-groundwater interaction through, for instance, losing or gaining streams.

Surface water and groundwater interact through the vadose zone, and is linked by processes such as groundwater recharge and groundwater discharge. Water percolating through the vadose zone and reaching the water table becomes ***recharge***. From here, groundwater is stored in the subsurface, and it flows gradually towards surface water bodies such as rivers, marshes, and the ocean as eventual ***groundwater discharge***. This can supply water to these surface water bodies even during periods of drought. Streamflow persisting through dry seasons is referred to as ***baseflow***, and is very often almost exclusively from groundwater discharge (Poeter et al. 2020)

Groundwater can supply water to streams, or streams can supply water to the aquifer. These can result in terrestrial groundwater dependent ecosystems (GDE) where ecosystems are driven by the discharge of groundwater on surface (Colvin et al. 2003).

In some instances, the hydraulic gradient results in flow through streams, or the vadose zone connects surface water to groundwater (*Figure 4-1*). These often result in wetlands (§12.1), which is land that is transitional between terrestrial and aquatic, and can also result in the formation of some types of ***springs*** that is inherently characterized on surface by a ***wetland*** and the early development of stream channels (*Figure 4-2*).

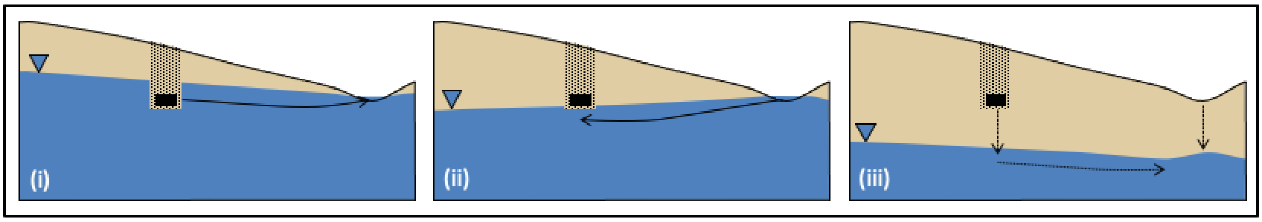


Figure 4-1. Interaction between streams and groundwater where one generally feeds the other, or the vadose zone represents the connection between them (Dippenaar et al. 2019c).

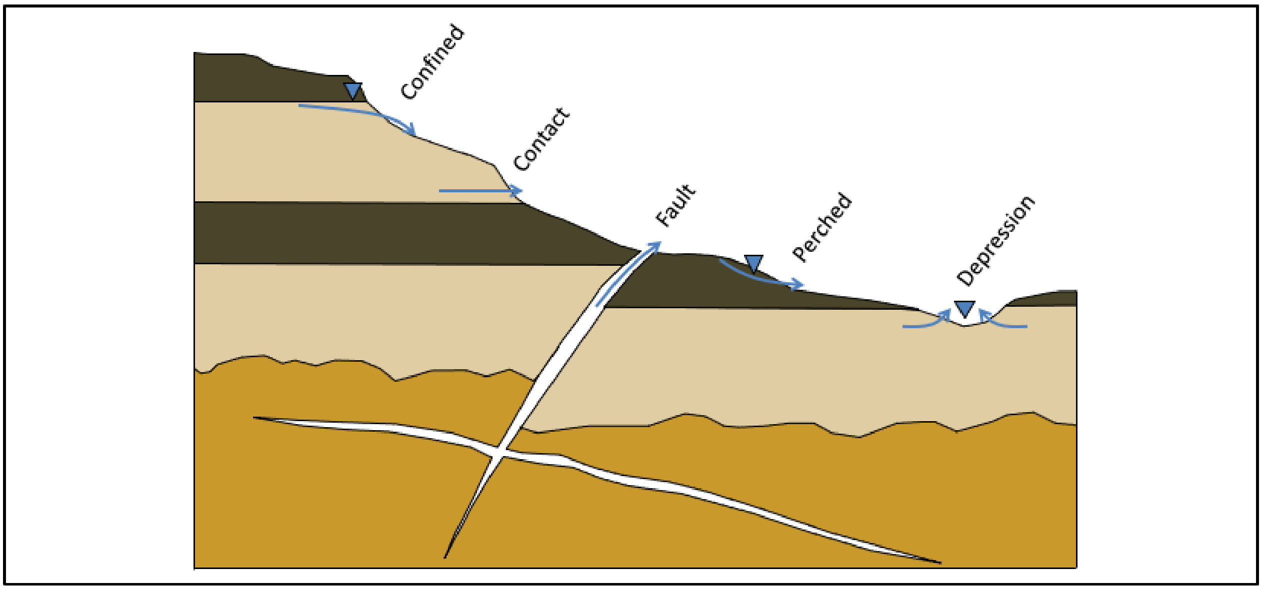


Figure 4-2. Types of springs in the vadose zone and from the phreatic zone (Dippenaar 2016).

4.4. Groundwater Recharge

Recharge occurs through the vadose zone and is, as such, dictated by the likelihood of surface water reaching the phreatic surface. This can occur as ***direct***, ***localised*** or ***indirect*** recharge, and is mostly through preferential flow mechanisms. Recharge rates are often reported as a percentage of mean annual precipitation. This averages the amount of water added to the phreatic surface over the catchment area, and does not indicate the rate of recharge at local scale.

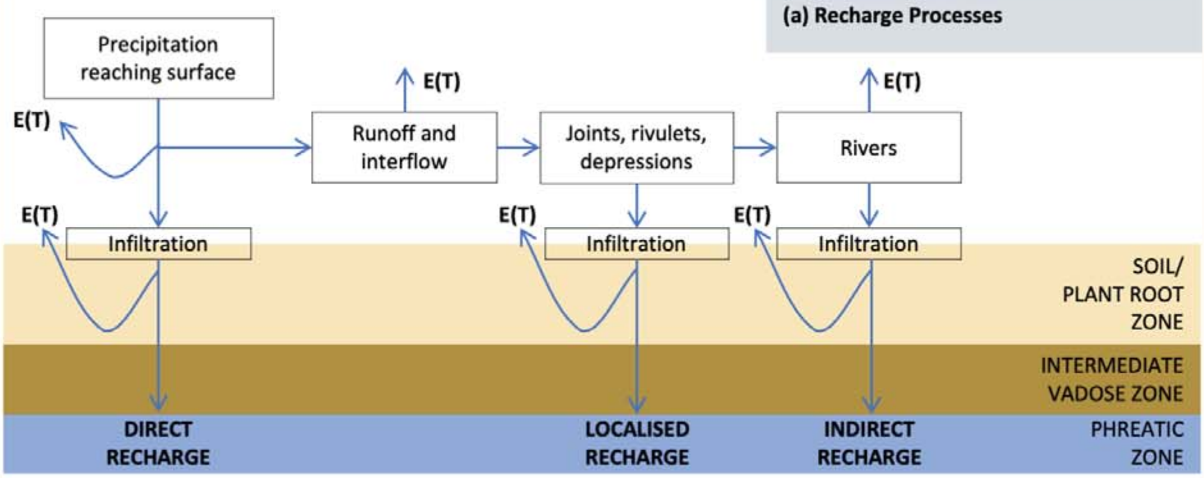
Recharge estimation is very well described both globally and for South Africa in particular (e.g. Healy & Scanlon 2010; Scanlon et al. 2002; Xu & Beekman 2003). Methods for estimating groundwater recharge are mostly based on hydraulic or chemical, although it is usually mot advisable to employ more than one method. Some of those pertaining to the vadose zone specifically are described in *Box 12*.

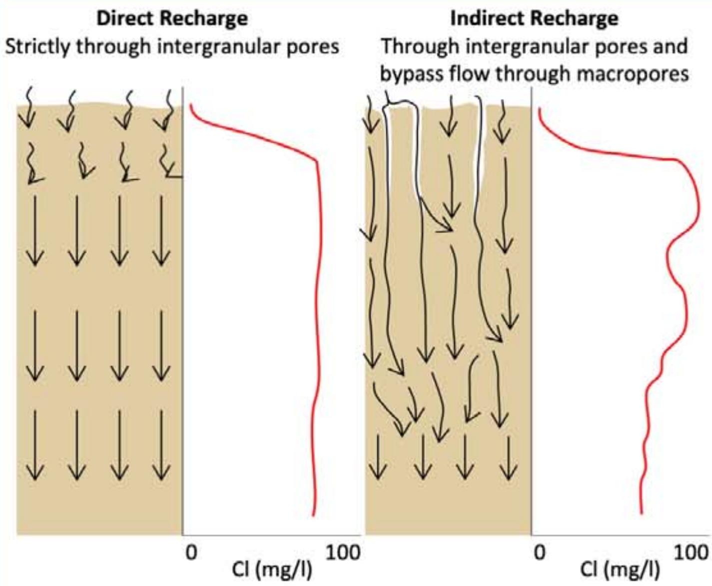
In arid countries and/ or areas where groundwater is not in direct contact with the land surface or with surface water bodies, the vadose zone forms a fundamental component of the recharge process. This thicker vadose zone and possible low-permeability horizons occurring in it can serve as additional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

Box 12. Groundwater Recharge

BOX 12. Groundwater Recharge

(a) Recharge Processes





Infiltration and percolation can move as a continuous wetting front according to the piston flow model. However, these processes mostly involve some preferential flow due to changes in grading or pore space distribution.

This results in different flow rates for water in different pore spaces, implying that some can be held in small openings for long periods and taking long to release, whereas others rapidly move along larger openings in a near-vertical orientation.

It therefore becomes imperative to understand both the recharge rate (i.e. the amount of water from precipitation added to the groundwater system), and the rate of groundwater recharge (i.e. the travel velocity of individual molecules).

(b) Recharge Estimation Methods

The ***zero flux plane*** (ZFP) represents a theoretical line is identified where all water movement above is upward through evaporation and transpiration, and all water movement below is downward to eventual recharge. In situ soil suction measurements are required to identify the ZFP. **Darcy methods** can of course also be employed under the understanding of the vadose zone application of Darcy's Law and the Richards' Equation.

Lysimetry entails a subsurface installation to collect water draining from the overlying soil column. It is usually placed below an undisturbed section of soil ensuring that the top of lysimeter has good hydraulic connection with the soil above. These collect free-draining water, or alternatively use applied pressure heads or tension to collect draining water, for chemical testing and to aid in the estimation of drainage rates in the vadose zone.

Mass balance methods estimate groundwater recharge rates by relating atmospheric to groundwater concentrations of a given element. The chloride mass balance (CMB) methods, for instance, compares the preservation of mass between precipitated chloride and the chloride flux in the subsurface, with the drainage being inversely proportionate to the Cl in pore water. Similarly, stable isotopes can be used to the same purpose.

READ MORE: ADAPTED FROM: (© www.wrc.org.za) (a) Lerner 1997 in De Vries and Simmers 2002; Younger 2007; (b) Gburek and Folmar 1999; Healy and Mills 1991; Healy & Scanlon 2010; Heppner et al., 2007; Khalil et al. 2003; Kumar & Seethapathi 2002; Scanlon et al.2002; Xu & Beekman 2003

5. VOIDS AND PORES

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.

5.1. Phase Relationships and Porosity

Phase relationships determined by volume or weight of air, water, voids and solids are shown in *Box 13*. Porosity and void ratio relate volume of voids to total volume or the volume of solids only respectively.

Although porosity is idealized (*Box 14*), deviation is common through processes altering soil grain sizes, shapes and distribution. As perfectly spherical uniform grains 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 5-1*. This also applies to rock, where, for instance, bedding, jointing, laminations, foliation or other structures can result in anisotropy and heterogeneity.

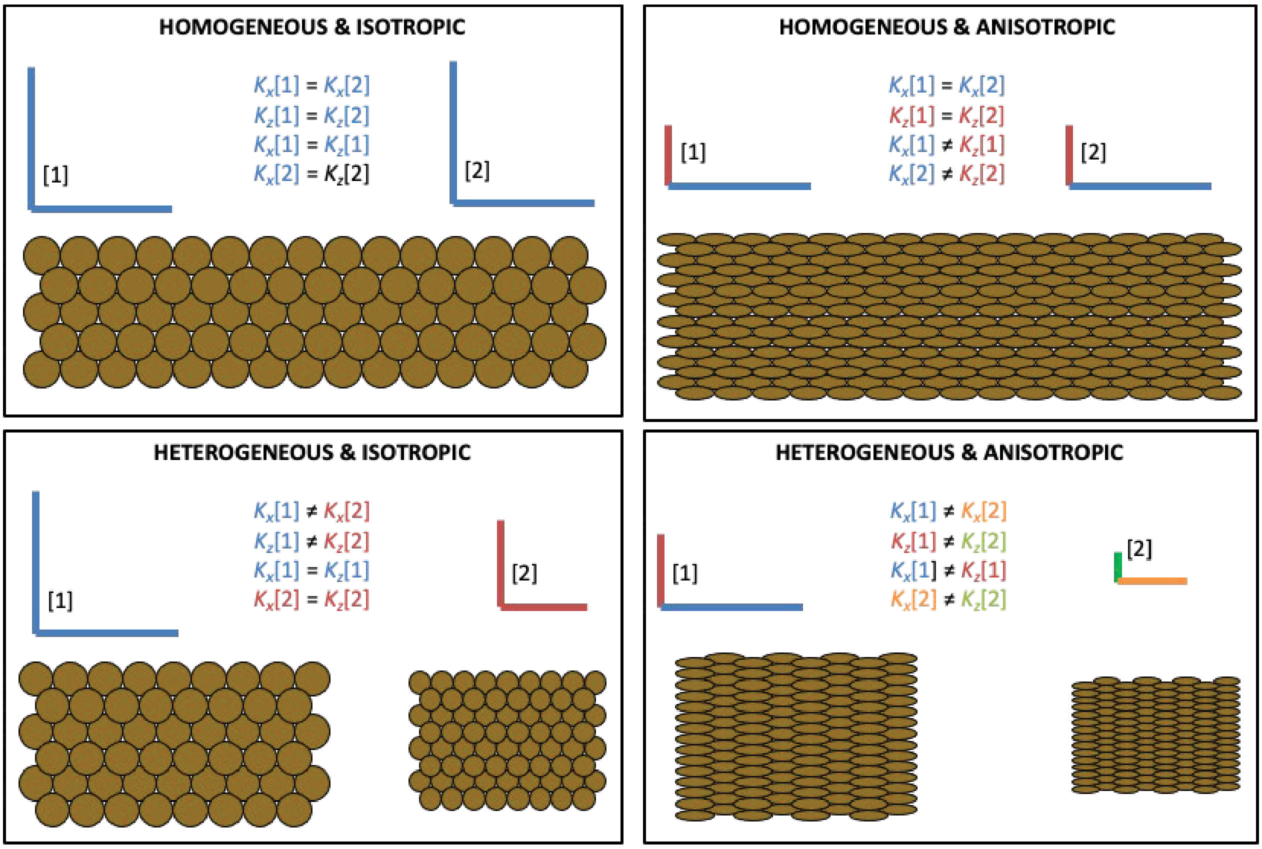


Figure 5-1. Homogeneity and heterogeneity versus isotropy and anisotropy (after Shaw 1994).

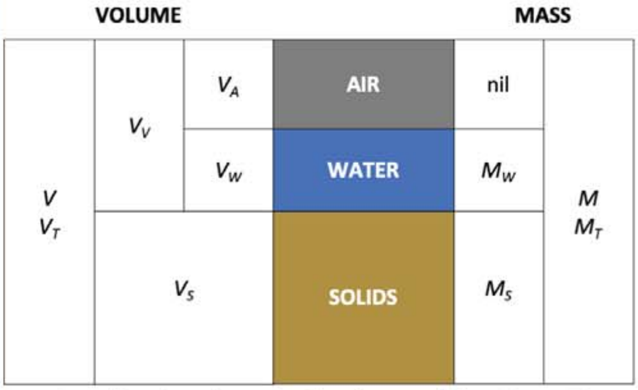
Classification of porosity can be based on a number of aspects. Mainly, it depends on type and scale of porosity. For most hydraulic applications, however, it becomes imperative to also understand how much of the total porosity effective porosity constitutes, and how it behaves under partial saturation where some moisture may be immobile, effectively further reducing the pore space available for flow (Dippenaar2014a).

Box 13. Porosity

BOX 13. Porosity

(a) 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, specific gravity G_s, degree of saturation S_w, void ratio e, porosity η, the relationship between e and η, and a variety of density and unit weight parameters (e.g. density $\rho = M / V$ and unit 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.

$$w = \frac{M_W}{M_S} \text{ and } \theta = \frac{V_W}{V_T}$$

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

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

$$e = \frac{V_V}{V_S}$$

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

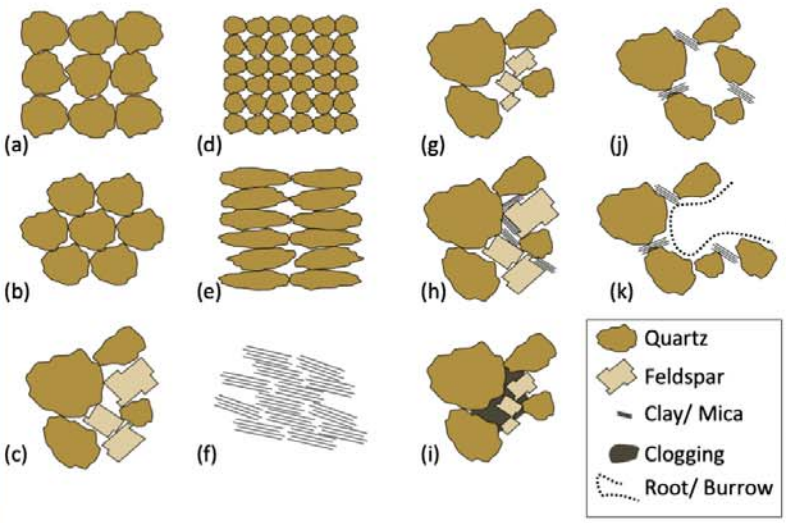
$$\eta = \frac{e}{1+e} \text{ and } e = \frac{\eta}{1-\eta}$$

Porosity is therefore the ratio of voids to total by volume. 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.

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

(b) Porosity in Soils

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.



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.

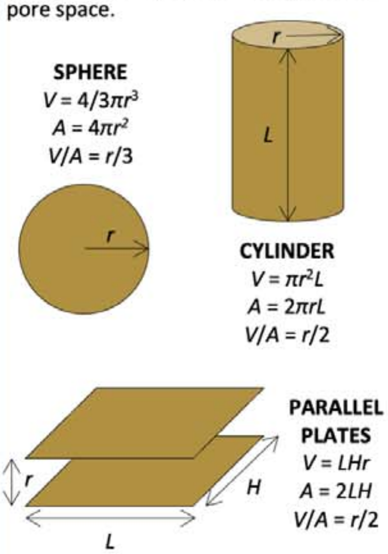
READ MORE:
ADAPTED FROM: (a) Craig 1999; Das 2008; Hillel 2002; Knappett and Craig 2012; (b) Dippenaar 2014a

BOX 14. Idealised Pore Space

(a) Idealized Pore Space Geometries

Idealized 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 examples, as well as the calculation of the volume *V* and area *A* of each.

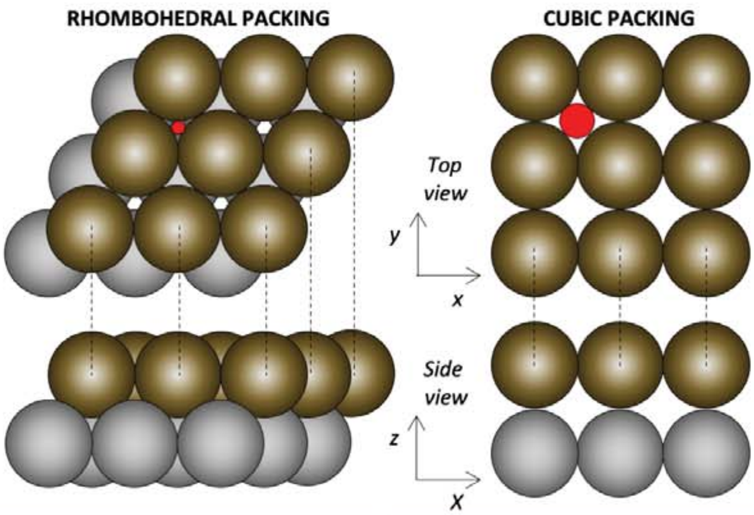
These mimic capillary tubes, parallel plates, and spherical intergranular pore space.



(b) Idealized Packing of Spherical Grains

The pore space or geometry can 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, namely cubic and rhombohedral, the latter being denser and less porous than the prior.

Pore space geometry can best be understood by starting with basic geometric packing variations of perfectly spherical uniformly distributed grains. 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.



(c) Fractal Models and Simplifications

Fractal models such as the Serpieński carpet and the three-dimensional Menger sponge aim to account for infinitesimal pores.

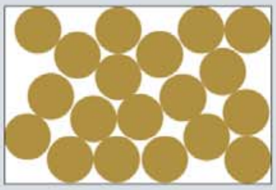
For fractured media, the properties of both the fractures and rock material need to be accommodated. A natural fractured system can be idealized as follows:

Natural fractured porous medium | Non-homogeneous | Double porosity | Equivalent continuum

(d) Random Densest Packing

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



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Dippenaar 2014a; Furukawa et al. 2000; Giménez et al. 1997; Hilfer 2001; Samardzioska and Popov 2005; Straughan 2010; Vita et al. 2011

Type refers here as to whether porosity is mostly primary (textural, intergranular) porosity, or secondary (structural) porosity to account for the differences in the nature of the void spaces and connectivity. ***Scale*** refers to how observable these are, namely as submicroscale, microscale, mesoscale and macroscale porosity to account for variations in porosity with varying scales of consideration (the concept of representative elementary volume).

Effective porosity is that part of the total porosity that can transmit water as opposed to porosity which cannot contribute to the flow of water. Even though part of the total porosity can store water, some moisture (notably at low moisture contents) are immobile. Some pore spaces also cause dead ends that can fill but do not connect to new pores.

Water saturation governs whether and, if so, the rate at which water can drain under gravity, and depends on various factors such as residual saturation and field capacity.

Importantly, for geotechnical applications, where volume change commonly results due to changing loads or moisture contents, it becomes imperative to relate the change in void space and subsequently the volume (§10.4.3).

5.1.1. 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.

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.

In terms of the scales of porosity it is important to realise that multiple types of porosity can coexist depending on the scale of investigation. It is, for instance, possible that a sample of 1 cm^3 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. This is referred to as the ***representative elementary volume (***REV).

The porosity can be defined as indicated in *Box 15* 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 this 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). These initial volumes of observation can also be represented by a point in solid grain or void pore space (in this instance indicated in a set of parallel fractures).

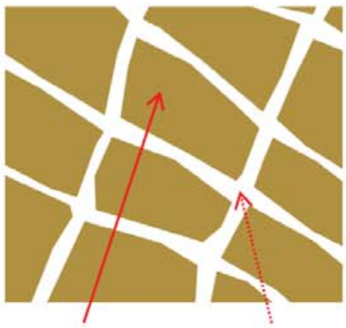
Table 5-1 shows typical influences of soil texture and soil structure (the same applicable to rock) over four broadly defined scales of porosity. Although the boundaries are not as clearly defined, it is important to note that different scales of measurement will influence the REV and the voids formed 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.

Box 15. Representative Elementary Volume (REV)

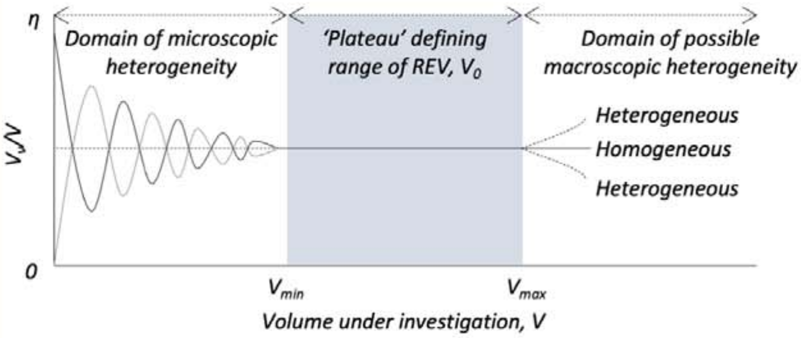
BOX 15. Representative Elementary Volume (REV)

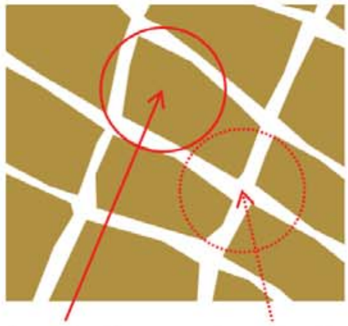
Porosity of a medium is quantified by V indicating the volume of a three-dimensional space exceeding a single pore or grain in size. With increasing V, porosity fluctuates and gradually stabilizes to a plateau range where the porosity remains constant over a representative elementary volume or REV. Increasing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

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.



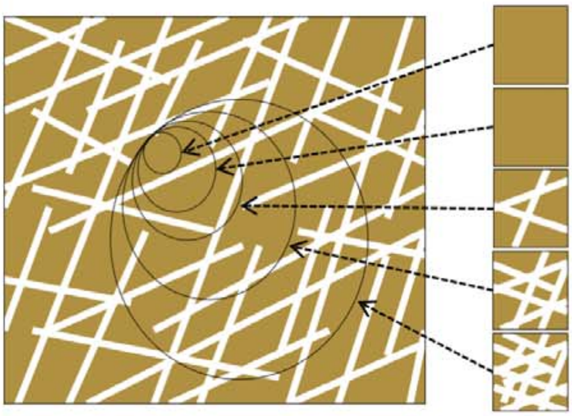
η = 0; only matrix *η = 1; only voids*





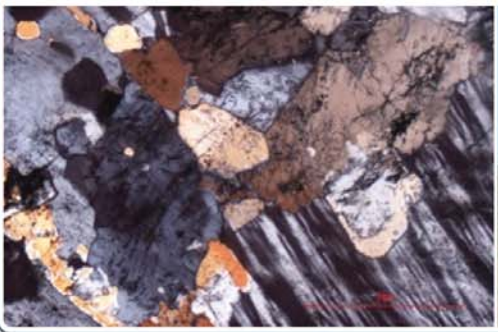
Increasing V, increasing η *Increasing V, decreasing η*

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.



The REV becomes increasingly important when modelling natural systems. As indicated in the instance of a rock mass, different scale of investigation will result in the rock mass being considered as a porous medium; a medium with one discreet or multiple intersecting fractures; a fracture network; and/ or a fracture network behaving again as an equivalent porous continuum.

BELOW: The concept of REV shown at the hand of granite under petrographical microscope showing mineralogical differences (LEFT) and as a whaleback in a landscape showing macroscopic variation (RIGHT). Both the thin section and landscape photograph represent the Nelspruit Suite near Skukuza (north of Mbombela, South Africa).



READ MORE:
ADAPTED FROM: REV: e.g. Bear 1988;2007
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Table 5-1. Summary of some types and scales of porosity.

Scale.	Primary/ Textural Porosity/ Material	Secondary/ Structural Porosity/ Mass
Macroporosity (non-capillary)	Corestones, differential grading and heterogeneity; gravel and coarse	Fractures, joints, ,fissures, discontinuities, piping, dongas
Mesoporosity (cusp of capillarity)	Grading variations; sand and silt	Bedding, foliation, desiccation or shrinkage cracks, termite nests, root voids
Microporosity (capillary pores)	Soil grading (notably clay); effective pore diameter	Near-closed structures; roughness on defects; laminations; leached zones
Submicroporosity (effective clogging)	Clay content, adsorption and diffusion of water, water molecules and composition	Joint infilling, precipitates

5.1.2. Pore space geometry

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 (*Box 13*, *Box 14*).

Volume change over time can also result in porosity changing. As media densify, pore space is reduced. Conversely, dilation and shrinkage, for instance, result in the proportional increase of void space compare to solids.

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.

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.

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, ferrets can be used where a ferret represents the spacing between two parallel tangents to a void feature in a given direction. The maximum ferret refers to the maximum possible distance between two such lines and the minimum ferret to the minimum distance or to that distance perpendicular to the maximum ferret (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 5-2*).

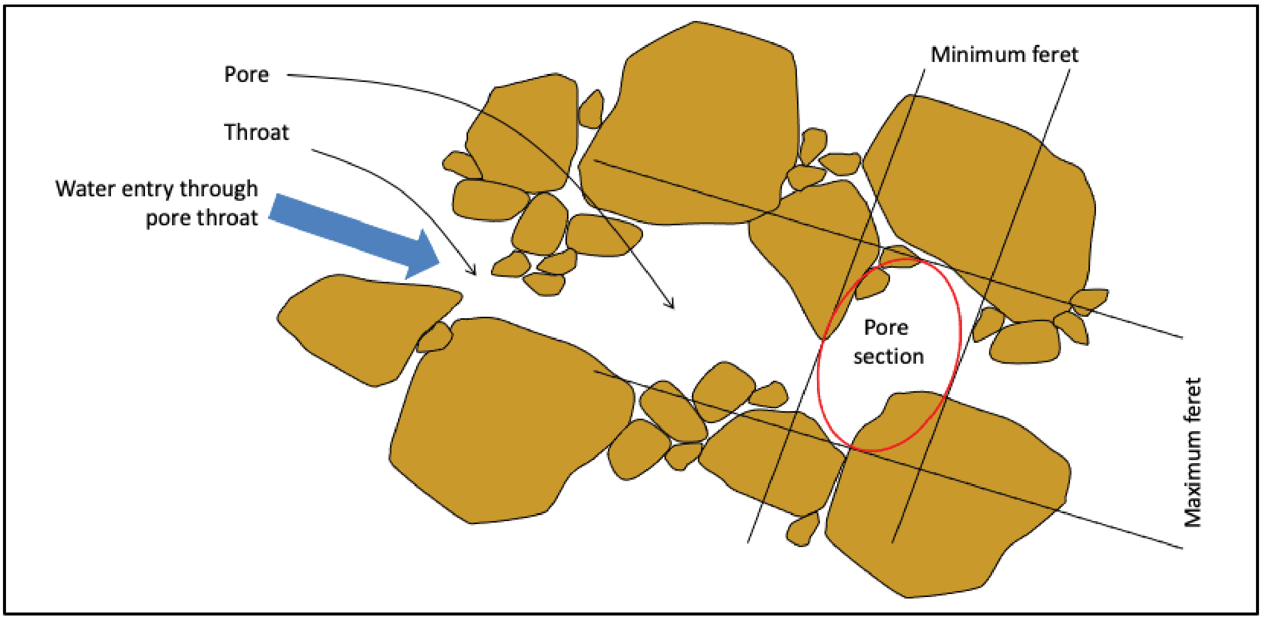


Figure 5-2. Pores, throats and the minimum and maximum Ferret diameters (adapted from Mathews et al. 1997).

Pores can also be classified based on their sizes and degree of connectivity. 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.

5.2. 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 6*. This is, however, only applicable to soils with fairly uniform fractions and cannot be applied when clay is present in the soil.

$$\eta = 0.255(1.83)^{C_U}$$ ***Equation 6***

Another means of determining porosity in the laboratory is the density relationships at saturation ($V_V = V_W$) compared to oven-dried ($V_V = V_A$) as shown in *Equation 7*.

$$\eta = \frac{V_V}{V_T} = \frac{V_W}{V_T} = \left(\frac{V_W}{1} \cdot \frac{V_V}{V_T}\right)$$ ***Equation 7***

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 8*. 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 (Dippenaar 2014b).

$$\eta = 1 - \frac{\rho_B}{\rho_S} \ \ where \ \ \rho_S = \sum f_M \cdot \rho_M$$ ***Equation 8***

Numerous authors have evaluated trends in the quantification of porosity. These are discussed by Dippenaar (2014a) 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.

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).

5.3. Effective Porosity, Specific Yield and Storativity

The relationship between porosity and specific yield is described in *Box 16*. Not all pore space plays a part in the movement of water, with some pore space being dead-end or non-contributing to flow. Water can enter these and be stored there, but they essentially play no part on the movement of water.

Box 16. Moisture Content and Porosity

BOX 16. Moisture Content and Porosity

(a) Effective Porosity and Specific Yield

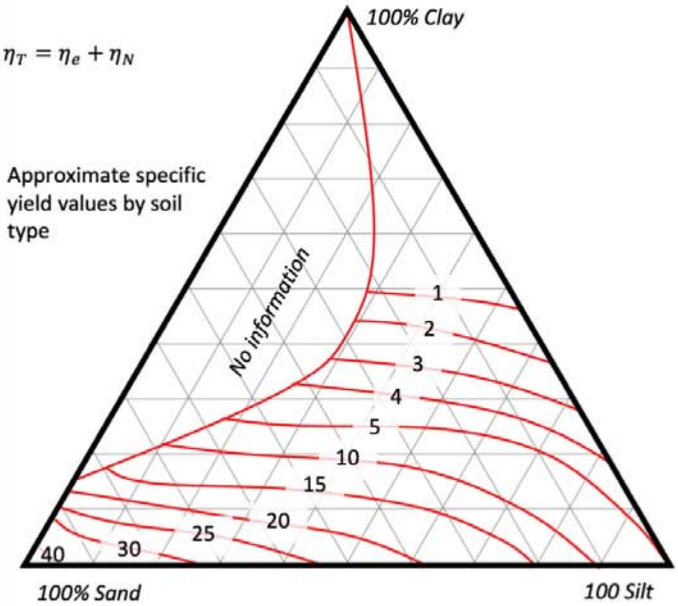
Once mobile, available pore space and its connectivity dictate if and how water will be retained in a medium, or with what ease it will seep through the medium. In order to achieve this, moisture contents need to be high enough, and the balance between retardation and acceleration of the moisture need to be in balance.

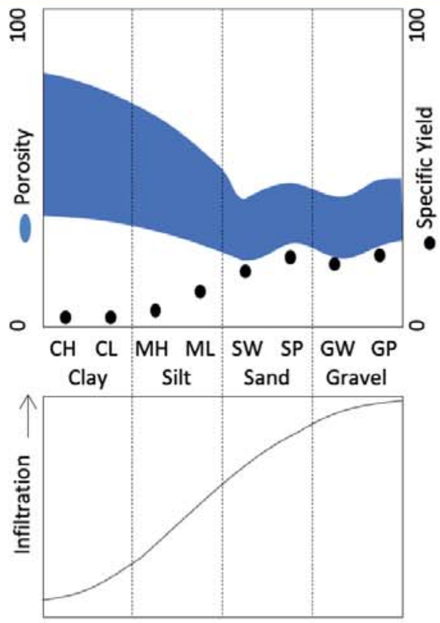
Total porosity is a function of that porosity which can contribute to flow and porosity which cannot contribute to flow. Various terminologies exist, but in essence total porosity is a function of the **effective flow porosity**, **diffusion porosity** and **residual porosity** or the unconnected porosity and the connected porosity. The following applies to these types of porosities and can be calculated:

$$\eta_T = \eta_F + \eta_D + \eta_R = \eta_N + \eta_C$$

$$\eta_T = \eta_e + \eta_N$$

Approximate specific yield values by soil type

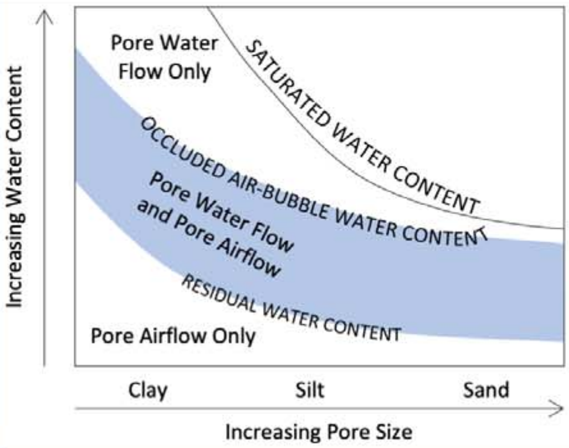


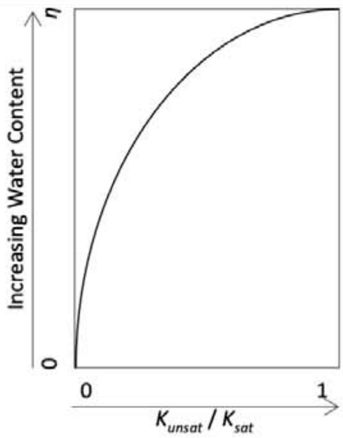


To avoid confusion, the subscript *F* has been kept for the effective flow porosity. In order to simplify the terminology, only two concepts are really required, namely the **effective porosity** η_e referring to the pores through which water can move, versus the **unconnected pores** η_N where water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

Specific yield relates to the amount of water released per unit change in hydraulic head.

(b) Changing Moisture Content





Saturated hydraulic conductivity (i.e. where moisture/ water content = porosity) is the maximum possible value. Different soil types require different moisture contents to enable flow, with clayey soils generally requiring higher degrees of saturation, and sands draining more readily.

READ MORE: Dippenaar 2014a; Fetter 1994; Norton and Knapp 1977; Tullborg and Larson 2006

ADAPTED FROM: Lu and Likos 2004; Fitts 2002

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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 (*Box 16*), specific storage S_S and saturated aquifer thickness *b* (Equation 9). 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 9

In the instance of confined aquifers, the volume of released water becomes dependent on the properties of the aquifer material and water, namely compressibility of the mineral skeleton, α, and the compressibility of water, β (Equation 10).

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

Equation 10

Effective porosity is very important in contaminant transport studies as it aids in determining contaminant transport velocities or advection rates. Similarly, parameters related to storage are fundamental in understanding changes to the vadose zone as rising or dropping phreatic surfaces relate directly to a change in storage to either make the vadose zone thinner or thicker.

SECTION C: PRINCIPLES OF UNSATURATED FLOW

6. PARTIAL SATURATION

6.1. Wetting and Capillarity

Water and solids interact in a complex manner at partial saturation. Whether water will be attracted to the solid mineral surface or to other water molecules depend on the work required to wet the mineral surface or to create a surface area of the liquid (*Box 17*). These processes result in capillarity and attraction of moisture to solid surfaces (*Box 18*); processes very important in the development of saturated capillary fringes and the enhancement of shear strength under suctions induced by partially saturated materials.

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).

6.2. Adhesion and Cohesion

Water can occur in soils as gravitational, capillary or hygroscopic water (*Box 19*). ***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. ***Hygroscopic water*** moves essentially in the vapour phase and is attracted to the soil surfaces at suctions exceeding 31 bar (FitzPatrick 1983).

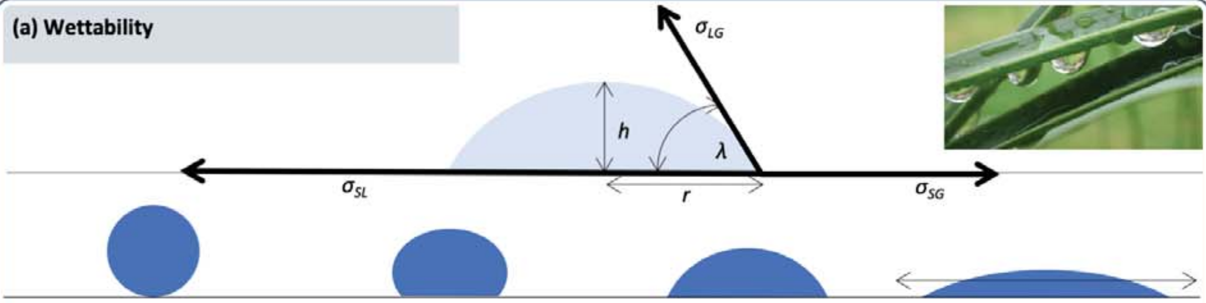
FitzPatrick (1983) distinguishes between three types of water movement in soil depending on the moisture content and soil properties, namely saturated, unsaturated and vapour flow (*Box 19*). ***Saturated flow*** – as the name implies – takes place where all the pores are water filled and are typically 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.

Field capacity dictates the cut-off between adhesive and purely cohesive water, water gravity overtakes capillarity as the main driver of water movement. Whether actual field capacity 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).

Box 17. Water-Solid Relationships

BOX 17. Water-Solid Relationships

(a) Wettability

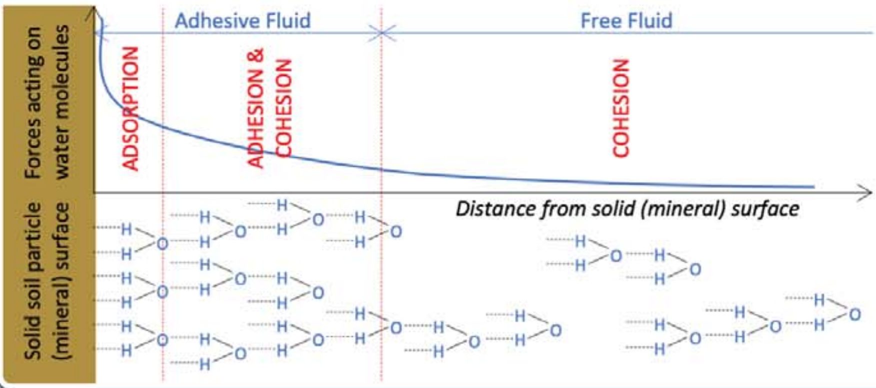


Contact Angle	180°	90°	0°	Contact Angle

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

(b) 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. It 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.
- **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. It relates to the water's attraction to itself, and W_C 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.
- **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.
- **Spreading** W_S 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. 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. The subscripts denote the interphases between the solid (S), liquid (L) and gas (G) phases.



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

$$W_C = 2\sigma_L$$

$$W_W = \sigma_{SG} - \sigma_{SL}$$

$$W_S = W_C - W_A = \sigma_S - \sigma_L - \sigma_{SL}$$

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

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

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

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

READ MORE:
ADAPTED FROM: Bear 2007, Bear & Cheng 2007, Brady & Weil 1997, Doe 2001, FitzPatrick 1983

Box 18. *Potential and Capillarity*

BOX 18. Potential and Capillarity

Forces affect the energy level of soil water include:

- **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.

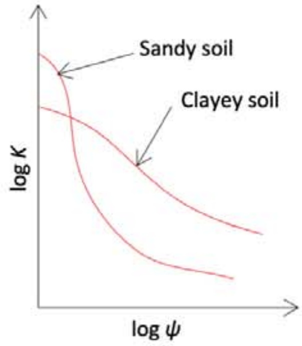
These three forces define the difference in energy level of water between sites or conditions that can be defined as the soil water potential. Water always moves from a point with high potential to a point with lower potential and the total soil water potential Ψ_T can be defined as the sum of the gravitational potential Ψ_g, matric potential Ψ_m, osmotic potential Ψo and any other possible contributions of additional potentials. 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.

Quantification of total potential is the sum of the other potentials. Gravitational potential is the product of the height of the water column above a reference elevation h and gravitational acceleration g. 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.

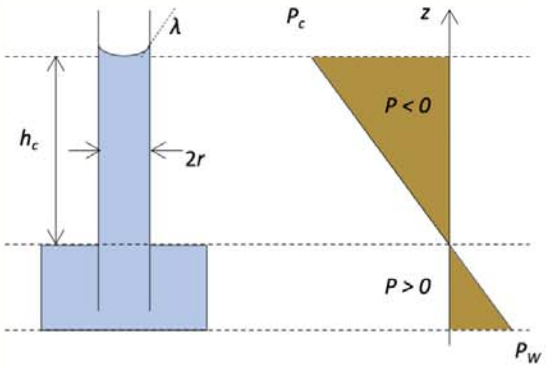
(a) Potential

$$\Psi_T = \Psi_g + \Psi_m + \Psi_o + \cdots$$

$$\Psi_g = gh$$



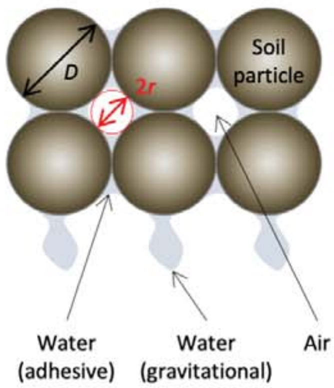
(b) Capillarity

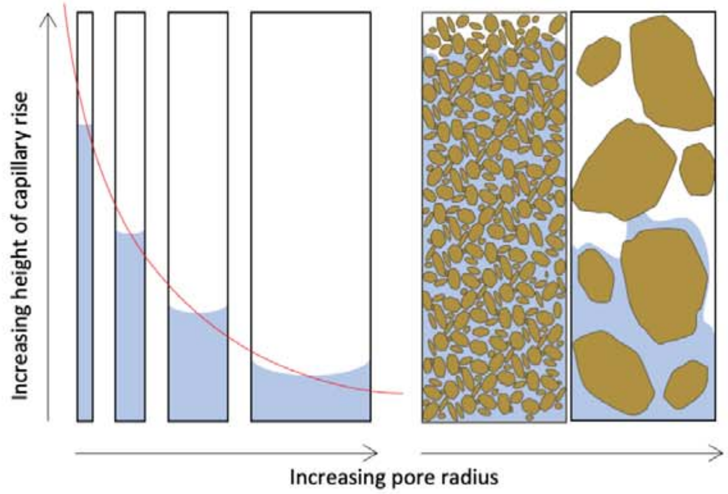


The importance of the critical angle λ = 90° becomes evident when considering capillary rise. If r can be defined as the radius of a tube through which water can flow and ½D indicates the radius of uniform spherical grains forming the solid cubic-packed phase of the system, the capillary rise h_c can 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). Assuming pure water in a clean glass tube (where $\lambda = 0$ and at 20°C, σ = 0.074 g/cm^1 and ρ = 1 g/cm^3), the height of capillary rise can be estimated as follows:

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.

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





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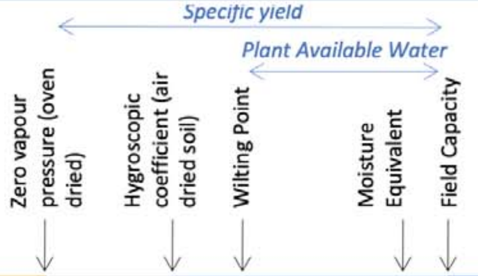
Allaby & Allaby 2003, Bear 2007; Brady and Weil 1999; Deming 2002; Doe 2011; Fetter 1994; FitzPatrick 1983; Rose 2006; Todd and Mays 2005

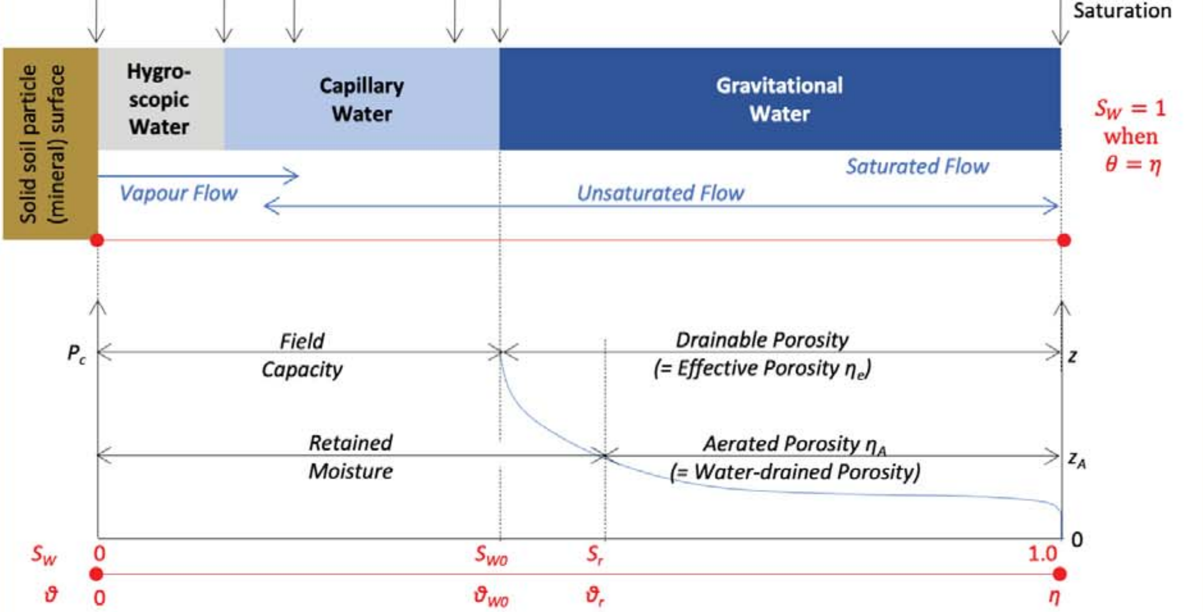
Box 19. Moisture Content at Partial Saturation

BOX 19. Moisture Content at Partial Saturation

(a) Moisture Content-Saturation Relationships

Illustration of the occurrence of water as a function of distance from mineral surfaces where adhesion occur (upper portion), and as a function of capillary pressures (lower portions). The horizontal axis is from zero saturation to full saturation (S_W = 1) that correlates to zero moisture content to moisture content equal to porosity ($\vartheta = \eta$).





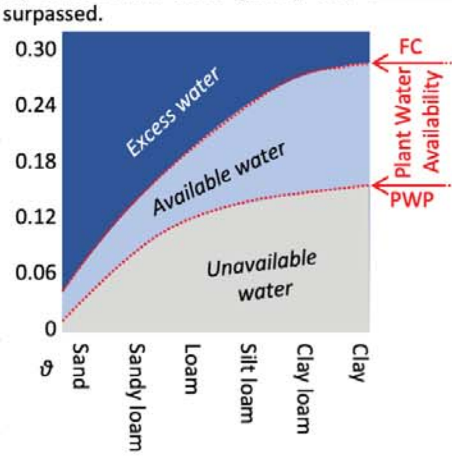
(b) Moisture Content-Saturation Relationships

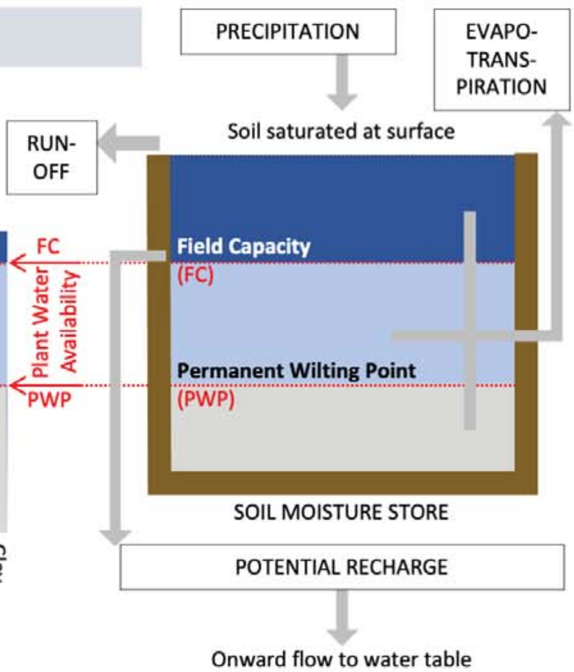
Potential Recharge refers to water beyond influences of plant roots, evapotranspiration or surface runoff. This water has the potential to eventually recharge the aquifer and is only termed recharge when entering the phreatic surface. Moisture content below field capacity cannot drain under gravity,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

Field Capacity (FC) is the moisture content the soil can retain after excess water has seeped away under gravity; volume of water introduced to the subsurface but available for percolation; entire effective porosity is air-filled.

(Permanent) Wilting Point (PWP) is the ϑ where water becomes unavailable to plants.

Plant Water Availability (PWA) = FC – PWP.





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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

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 11* 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 12* 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 1984a).

$$K(\theta) = K_{sat}\left(\frac{\theta - \theta_r}{\theta_{sat} - \theta_r}\right)^{1/\beta}$$ ***Equation 11***

$$S_e = \frac{S - S_r}{S_{sat} - S_r}$$ ***Equation 12***

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).

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.

The Hagen-Poiseuille equation 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 13*) (e.g. Das 2008) or as the cross-sectional area $a = \pi r^2$ (*Equation 14*).

$$Q(r) = \frac{\gamma_W S}{8\mu_W} r^2 a$$ ***Equation 13***

$$Q(r) = \frac{\pi \rho_W g}{8\mu_W} r^4$$ ***Equation 14***

Water remains fairly stationary in the subsurface at low moisture contents. Plant roots can start moving water through osmosis at moisture contents exceeding wilting point. However, in order to induce actual flow, even below full water saturation, moisture content needs to first exceed field capacity (*Box 19*).

7. PRINCIPLES OF FLOW

7.1. Acceleration and Retardation of Water

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 the water table which mimics unsaturated porous media, but is 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.

7.2. Bernoulli's Equation

Box 20 describes Bernoulli's Law and the concept of hydraulic head. The concept of hydrostatic conditions and effective stress relate directly to the pressure 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.

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 15. 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 16.

$$h = h_p + z = \psi + z \qquad \textbf{\textit{Equation 15}}$$

$$(-\psi) = z = -(\psi) \qquad \textbf{\textit{Equation 16}}$$

Bernoulli's principle also implies that, should the elevation head be constant, a reduction in pressure should coincide with an increase in velocity. For flowing systems, this balance between head difference (or hydraulic gradient) and pressure drop (or pressure gradient) this becomes very important, seeing that different flow velocities will overcome different retardation forces (e.g. high-flowing velocities will be less affected by friction than inertia, whereas very low moisture content slow flow systems will be more affected by friction than inertia).

7.3. Darcy's Law and the Richards' Equation

The term ***seepage*** applies to moisture moving through a porous material. Engineers and geologists tend to interchange the symbols used, but a scientists we use 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 throughout.

The concepts pertaining to Darcy's Law and the important parameter, hydraulic conductivity, are discussed in *Box 21*. For unsaturated conditions, K_{unsat} is determined through so-called characteristic curves of moisture content and pore water pressure. Where Darcy's Law applies, flow is said to be ***darcian*** and ***linear***, and this can be adapted for fractured rock as well.

Extended for unsaturated flow, Darcy's Law can be written as the Richards' Equation to accommodate changing potentials (ψ) or moisture contents (θ) (*Equation 17*). This does not, however, solve for hysteresis, and assumes continuous monotonic increases or decreases in moisture content or suction (Hillel 2003).

$$q = -\mathrm{K}(\psi)\nabla h \;\; or \;\; = -\mathrm{K}(\theta)\nabla h \qquad \textbf{\textit{Equation 17}}$$

BOX 20. Energy, Pressure and Stress

(a) Bernoulli's Equation

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:

$$P = \frac{F}{A}$$

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 follows:

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

For unit volume: $V = 1; \frac{m}{V} = \rho$

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

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.

(b) Hydraulic Head

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 hp 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.

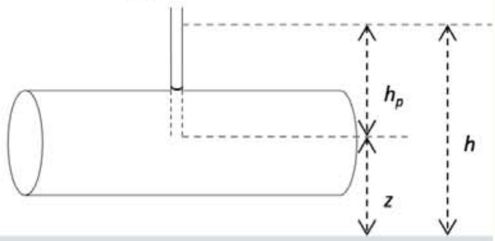
Hydraulic Head (h):

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

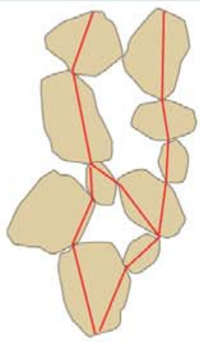
$$h_v + z + h_p = h$$

Hydrostatic Conditions (v → 0)

$h = z + \frac{P}{\rho g} = z + u$ and $P = (h - z)\rho_w g$



(c) Pore Water Pressure and 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."

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 soil skeleton only (inter-particle forces)

Then, ***effective stress*** = ***total stress – pore pressure***:

$\sigma_1' = \sigma_1 - u$; $\sigma_2' = \sigma_2 - u$; $\sigma_3' = \sigma3 - u$;

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

Excess pore water pressure (u_e) will induce:

Drainage (without becoming unsaturated)

Consolidation (vertical direction only due to lateral confinement)

READ MORE:
ADAPTED FROM: Driscoll 1989, Fetter 1994, Fitts 2002, Todd and Mays 2005; Younger 2005
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Box 21. Darcy's Law and Associated Parameters

BOX 21. Darcy's Law and Associated Parameters

(a) Hydraulic Conductivity and Permeability

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/ 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.

$$K = \frac{k\rho g}{\mu} \text{ and } K(m/s) \cong (9.77 \cdot 10^6)k(m^2)$$

(b) Darcy's Law

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.

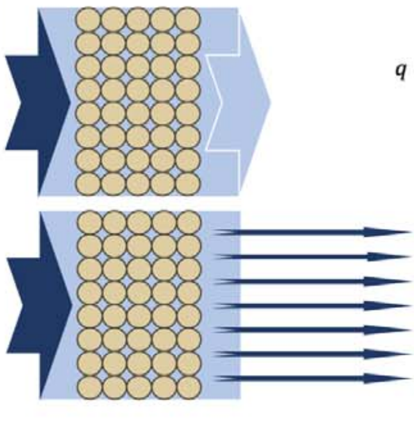
$$Q = -KiA = -K\frac{dh}{dl}A$$

(c) Specific Discharge and Average Linear Flow Velocity

The **darcy velocity** or **specific discharge**, q, and the **average linear flow velocity**, v, are calculated as per Darcy's Law. 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, $q < v$.

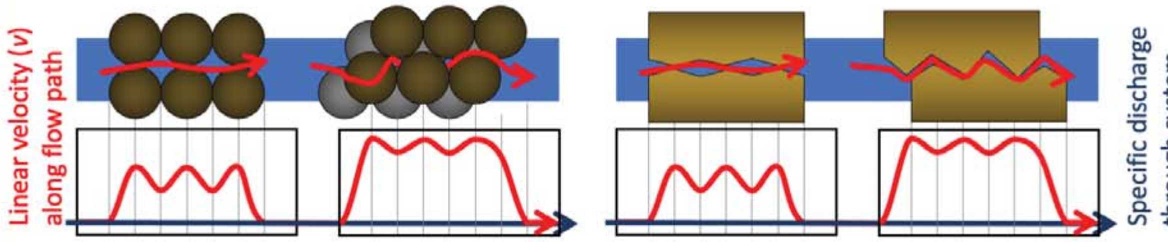
In contaminant transport studies, the **advection** rate is taken to be v.

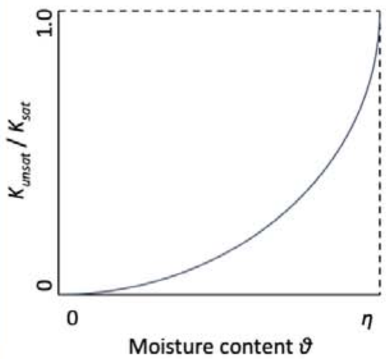
Below compares q and v for soils (left) and a fracture (right) respectively.



$$q = \frac{Q}{A} = Ki$$

$$v = \frac{q}{\eta_e} = \frac{Ki}{\eta_e}$$





(d) Relative Hydraulic Conductivity

For saturated conditions, K is a constant value including the intrinsic properties of the porous medium and water. At saturation, $\vartheta = \eta$ and $K_{un} = K_{sat}$. However, K is a function of ϑ and, where $\vartheta < \eta$, unsaturated K_{unsat} 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.

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Das 2008; Deming 2002; Driscoll 1989; Fetter 1994; Fitts 2002; Todd and Mays 2005; Woessner and Poeter 2020; Younger 2005

In some instances, hydraulic conductivity is converted to ***transmissivity*** *T* as being distributed over the saturated thickness *b* of the aquifer (*Equation 18*).

$$T = Kb$$

Equation 18

7.4. Quantifying Hydraulic Parameters

It is generally easiest to quantify saturated hydraulic conductivity in the laboratory or by means of empirical methods, or to assume that field-based tests reach full water saturation. As saturated hydraulic conductivity is generally related to the most rapid possibly flow rate, it is a conservative estimate, albeit not always directly helpful in understanding the role of suctions and seepage or flow not controlled predominantly by gravity. Quantification of these parameters is addressed briefly in the *APPENDIX B* to this report.

7.5. Flow Regimes

Moving fluids can be ***laminar*** (orderly, smooth regular path of the particles) or ***turbulent*** (irregular movement of particles). Laminar flow is more common at lower velocities and higher viscosities, and involves minimal lateral mixing with fluid adjacent to a flow stream. As opposed to this, eddying and mixing are commonly associated with more turbulent flows.

Flow regimes (such as turbulent and laminar flow) are typically described in terms of a variety of dimensionless index values such as the Reynolds Number. Some of the most important of these numbers are described in *Box 22*, all mostly relating different forces of acceleration and retardation to each other. In terms of hydraulics, the Reynolds Number is by far used most as it distinguishes between laminar and turbulent water flows in porous media adequately to determine whether the flow equations are valid.

Additional flow regimes (sic. as regimes are strictly used as per *Box 23* in this document) 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.

Box 22. Dimensionless Similarity Parameters

BOX 22. Dimensionless Similarity Parameters

(a) Dimensionless Similarity Parameters in Fluid Mechanics

A series of dimensionless numbers can be used to classify the behaviour of different fluids in the dimensional analysis of fluid mechanics. These all relate different forces to each other to give an indication as to how fluids and fluid mixtures will behave. Not all numbers apply to the same conditions, as some require very low static interfaces between fluids, whereas others relate more to high velocity open-channel or pipe flow.

Most of these rely on some linear flow relationship where there is a linear relationship between flow rate and drops in pressure. When this is not the case, as when inertial forces are not negligible but do in fact counteract viscous forces, flow is no longer linear, and adaptions are needed (see subsequent *BOX* on the Cubic Law).

For those described below: g = gravitational acceleration; L, D = characteristic dimension (e.g. curvature radius, length, diameter); ρ = density of fluid; σ = surface/ interfacial tension; v = fluid velocity; μ = fluid dynamic viscosity; P = pressure.

(b) Reynolds Number

$$Re = \frac{\rho v D}{\mu} = \frac{inertia}{viscosity}$$

The **Reynolds Number (Re)** relates inertial to viscous forces and is probably the most widely used of these parameters in the context of subsurface water. Darcy's law applies under small enough groundwater velocities to ensure laminar flow. Re < c.1-10, flow in granular media can be considered laminar and Darcy's law applies. Beyond this, flow is most likely turbulent. In fractured media, however, much higher Re numbers can be tolerated while maintaining laminar flow (see subsequent *BOX*).

(c) Bond Number

$$Bo = \frac{\rho g L^2}{\sigma} = \frac{gravity}{curvature}$$

The **Bond Number (Bo)**, or Eötvös Number, is a dimensionless number that is used in fluid dynamics to study the shape of bubbles and drops moving through a fluid. The number is used to quantify the relationship between the gravitational forces and the surface tension forces in a pendant drop in order to determine its dimensions and surface tension.

(d) Capillary Number

$$Ca = \frac{\mu v}{\sigma} = \frac{viscous}{curvature}$$

The **Capillary Number (Ca)** is a dimensionless parameter that shows the ratio of viscous forces to capillary drag forces acting across an interface between a liquid and a gas or two immiscible liquids. The Capillary Number is often used to recover oil and characterize oil trapping, leading to the residual oil saturation and the mobilization of residual oil. At very high Ca-values > 10^{-5}, viscous forces dominate and a drop is able to deform and squeeze through a porous medium. For very low Ca-values, capillary forces dominate, and droplets remain spherical.

(e) Euler Number

$$Eu = \frac{\Delta P}{\rho v^2}$$

The **Euler Number (Eu)** expresses the relationship between a local pressure drop caused by a restriction and the kinetic energy per volume of flow. It is applied in conduit flow where pressure variations are significant and has significance in cavitation. A perfect frictionless flow corresponds to a Euler number of 1

(f) Froude Number

$$Fr = \frac{v}{\sqrt{gD}} = \frac{inertia}{gravity}$$

The **Froude Number (Fr)** relates the inertial to gravitational forces and represents the partitioning between kinetic and potential energy. It is significant in the case of free surface flow where gravitational forces predominate over other force, where friction losses are small, and where flow is highly turbulent (e.g. spillways, overflow weirs and flow past bridge piers). It is most important whenever gravity dominates, when friction losses are small, and the flow is highly turbulent.

- Fr < 1 the flow is classified as subcritical and the flow disturbance can travel upstream
- Fr = 1 (unity) the flow is critical; disturbance is stationery
- If Fr > 1 flow is supercritical and disturbance is swept downstream.

(g) Weber Number

$$We = \frac{\rho v^2 L}{\sigma} = \frac{inertia}{curvature}$$

The **Weber Number (We)** is the ratio of inertial forces to surface tension forces. It is used where liquid-liquid or gas-liquid phases interact, as well as where these interfaces are in contact with a boundary. Surface tension causes small capillary waves and droplet formation and influences discharge at openings orifices and weirs at very small hydraulic heads. The We is also of great importance in the study of surface tension and the stability of droplets and liquid films.

- We < 1: surface tension forces predominate
- We < 10: fluid takes a form of a continuous stream, with not as many droplets forming
- We >> 10: water will form a mist as more droplets are formed due to a higher velocity.

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Bastian 2017; Berthier 2002; Brouwers & Dippenaar 2019; Chanson 1999; Donaldson & Alam 2013; Engineering Toolbox 2020; Fitts 2002; Incropera et al. 2007; Jowett 1993; Li et al. 2019; Mayer & Fringer 2017; Owczarek 1968; Pierre 2007; Shires 2011; Streeter & Wyllie 1975; Yunus 2010

Box 23. Linear Flow Regimes

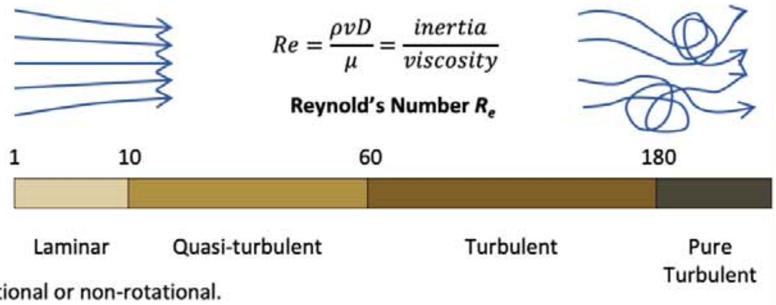
BOX 23. Linear Flow Regimes

(a) Laminar and Turbulent Flow

Laminar flow is characterised by high viscous forces, small velocities and momentum, and the absence of swirls or eddies.

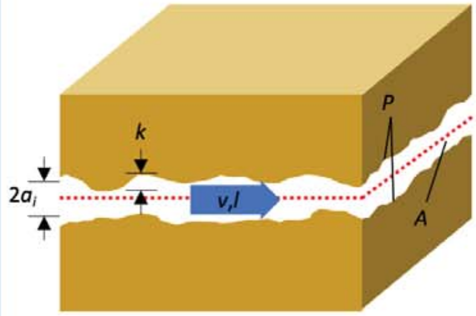
Turbulent flow, on the other hand, is characterised by eddies.

Roughness of natural rock defects influences the flow through the fracture, and it may also induce turbulence from onset.



Laminar and turbulent flow can also be rotational or non-rotational.

Flow regimes of partially saturated flow through natural defects are often done by means of calculating the Reynolds numbers (Re) that relates inertial to viscous forces, aiming to infer whether flow is Darcian and laminar. An Re number of approximately 2300 distinguishes between laminar and turbulent flow in natural defects as opposed to a value of 10 for granular materials. The Reynolds number increases with increasing fracture roughness. As the fracture walls diverge, the flow streamlines which induces turbulence and flow tortuosity. The increase in Reynolds numbers demonstrates significant inertial forces and non-Darcian flow



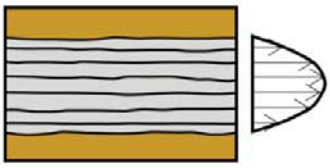
(b) Rotational and Irrotational Flow

Defects may be hydraulically rough, implying that some offset from a standard velocity profile for near-parallel sidewalls (with so-called irrotational flow) can result in rotational flow. This can be despite flow still being laminar; i.e. without eddying and in general in the same direction of flow. The hydraulic diameter (*D*) is determined as a function of the cross-sectional area (*A*), width (*w*), wetted portion of the fracture (*P*), average aperture ($2a_i$), and maximum roughness amplitude (*k*):

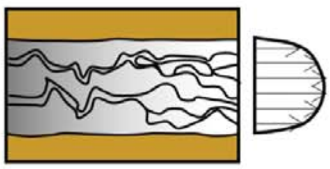
$$D_h = 4\frac{A}{P} = 4\frac{2a_i w}{2w} = 2(2a_1) \text{ and } \frac{k}{D_h} = \frac{2}{2(2a_1)}$$

Irrotational Flow

$\frac{k}{D_h} \leq 0.032$



Turbulent Irrotational Flow

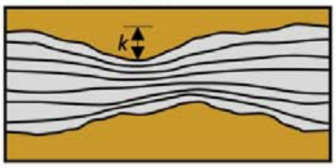


$\frac{k}{D_h} \leq 0.0168;$ $Re \geq 2300$

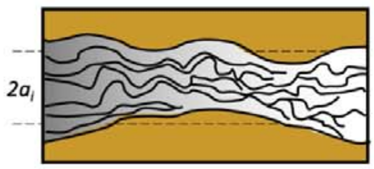
$0.0168 < \frac{k}{D_h} \ll 0.032;$ $Re > 845\left(log\frac{3.7}{k/D_h}\right)^{1.14}$

Rotational Flow

$\frac{k}{D_h} > 0.032$



Turbulent Rotational Flow



$\frac{k}{D_h} > 0.032$ $Re > 845\left(log\frac{1.9}{k/D_h}\right)^{1.14}$

The hydraulic roughness of natural rock defects is described by the relative roughness which, in turn, relates to the Reynolds number, the quotient of maximum amplitude, and the average aperture of the fracture. Based on the relative roughness it can be deduced whether flow that streamlines within the defect walls are rotational or irrotational.

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(a) Fitts 2002; Dippenaar et al. 2014; Maoyi et al. 2020; Ranjith & Darlington 2007; Zimmerman et al. 2004 (b) Lomize (1951) Wittke (1990;2014)

8. Flow through Rock Fractures

8.1. Smooth Parallel Plate Model and the Cubic Law

Darcy's law applies under small enough groundwater velocities to ensure laminar flow, implying that flow is ***linear*** and ***darcian***. Simplification of a discreet fracture to a set of smooth, parallel plates of equal aperture or spacing (*Box 14*) can to some extent be used as representation of a hydraulic aperture (*Figure 8-1*). As rock masses incorporate the fractures, the fracture infill and the rock material itself, hydromechanical behaviour require a vaster input than merely as single parameter, as explained in *Table 8-1*. Open problems regarding flow through fractured rock, are discussed by Berkowitz (2002) and Neumann (2005).

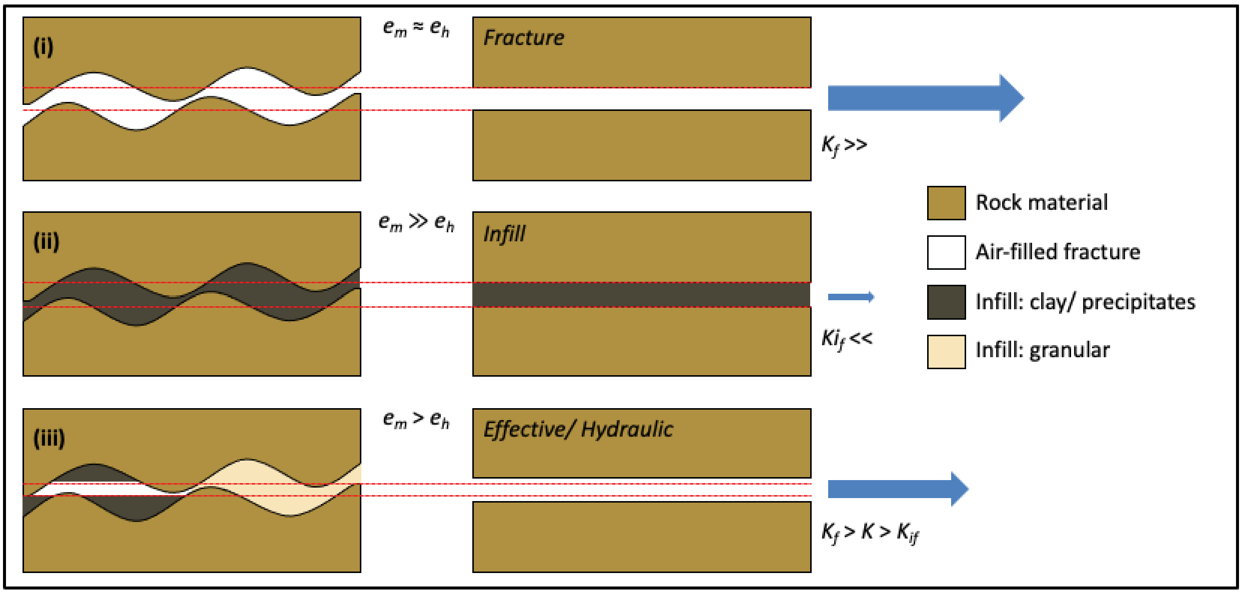


Figure 8-1. ***Hydraulic (e_h) versus mechanical (e_m) aperture and resulting fracture (K_f), infill (K_{if}) and effective overall (K) hydraulic conductivities (Dippenaar and Van Rooy 2016; Jones et al. 2016).***

Table 8-1. ***Aperture and hydraulic conductivity of fractures in rock masses (Jones et al. 2016).***

Scale.	Aperture	Hydraulic Conductivity
Matrix	n/a	(K_m) relates to the interstitial conductivity of the intact rock material.
Fracture	(e_f) the average (smoothed) distance, normal to the discontinuity planes, whether open or infilled.	(K_f) relates to the secondary (fractured) conductivity of the rock mass; i.e. of open non-infilled discontinuities.
Infill	(e_{if}) the thickness of the infill in the discontinuity.	(K_{if}) relates to the secondary (fractured) conductivity of the rock mass; i.e. of infilled discontinuities.
Effective/ Hydraulic	(e_h) the distance, normal to the discontinuity planes, which are open and can contribute to the storage and movement of water (for cubic law).	(K_h) of the open portion of the fracture, as required for use in the cubic law.

Defects as described in rock mass characterisations generally see the aperture as a plane with no shear strength. This mechanical definition is distinctly different from the one applied for hydrological purposes. We use the term fracture in hydrogeology and defect in rock mechanics to better clarify these fundamental differences. The aperture in a fracture can be entirely open (i.e. filled with a fluid such as air or water), or infilled by granular material of any texture, or infilled by secondary precipitates. Whereas the mechanical aperture remains essentially unchanged, and one specifically notes the type of infill to better understand the influence on the rock mass properties, the hydraulic aperture varies. Infill affects the fracture's permeability, and also the flow mechanisms.

In fractured systems, flow is often more affected by frictional energy losses adjacent to the fracture wall rather than inertial energy losses obstructing the flow path. As such, the Reynolds Number become less applicable due to the lower significance of inertia. Darcy's Law is then converted to the Cubic Law (*Box 24*) under assumption of a smooth parallel plate model, albeit tolerating very high Reynolds Numbers given that friction tends to dominate over inertia. Experimental work is advancing with respect to testing the geometrical influences of fractures on flow (e.g. Maoyi 2019a,b, 2020; Maoyi et al. 2020; Segole 2018; Segole and Van Rooy 2017).

In certain instances, rock systems comprise additional complexity through being, for instance, double porosity systems comprising both matrix (primary intergranular) and secondary (fractured) porosity. Further to this, flow systems can be more complex through flow regimes not being solely laminar or turbulent, but also subject to friction additionally making flow rotational or irrotational. Given non-linear relationships between velocity and pressure gradients, flow can also be nonlinear, implying that Darcy's Law and the Cubic Law no longer directly apply, and correction is needed by means of, for instance, the Forchheimer Equation (*Box 25*).

Numerous limitations exist when simplifying fractured systems. Some of these, for example, relate to (*Figure 8-2*):

- Geometrical simplifications of complex discreet fractures
- Variability of velocity under variable saturation and changing cross-sectional throughflow area
- Contact obstacles inducing inertial energy losses
- Turbulence resulting in eddying and inertial energy losses
- Rotationality resulting from frictional energy losses
- Pulsating or threshold-type flow at low saturation causing a fill-and-spill effect to induce flow at highly variable saturation and velocity.

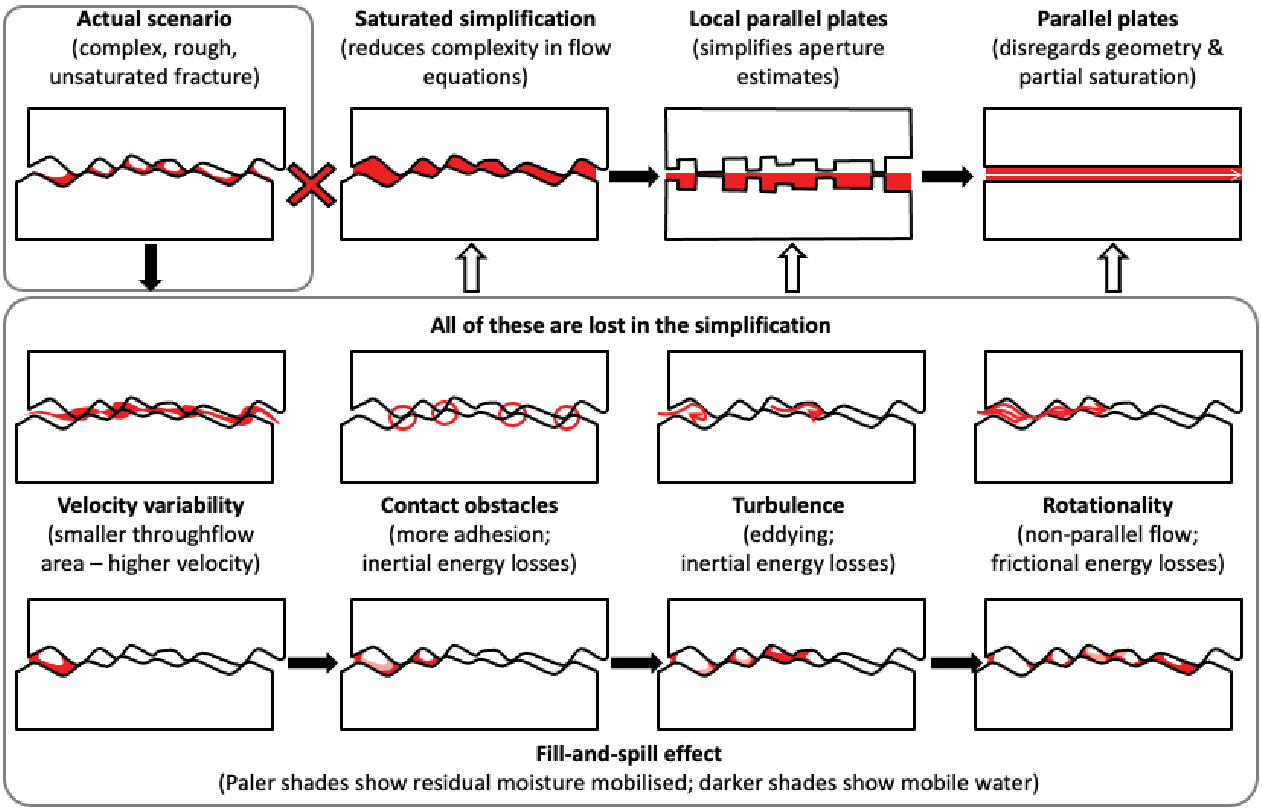


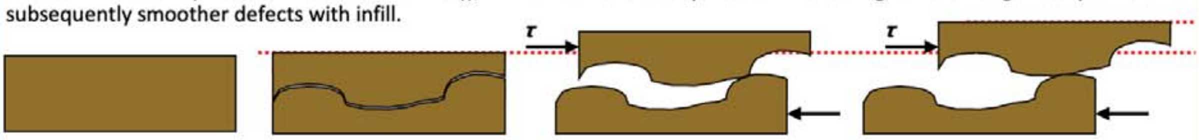
Figure 8-2. Limitations of discreet fracture simplifications (Dippenaar et al. 2020).

Box 24. *Parallel Plate Model and Cubic Law*

BOX 24. Parallel Plate Model and Cubic Law

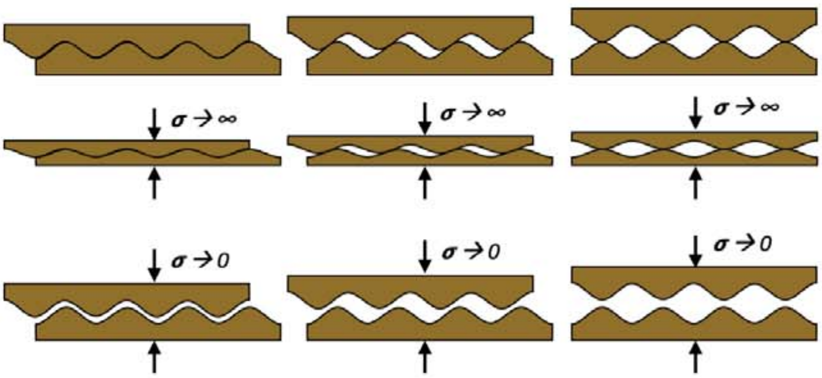
(a) Natural Rock Defects

BELOW: Natural rock defects are any discontinuity or break through intact rock. When rock first fractures, the sidewalls are matching. Under later shear stress (**τ**), the aperture opens as the sides of the fracture are nudged past each other. This results in dilation (shown in red dotted lines)), which can eventually result in shearing of the roughness profile and subsequently smoother defects with infill.



RIGHT: Normal stress (**σ**) generates substantial overburden pressures than can close fractures. This is especially true for near-horizontal defects (near perpendicular to the applies normal stress) that are not water-filled (as water is nearly incompressible and will keep the fractures open).

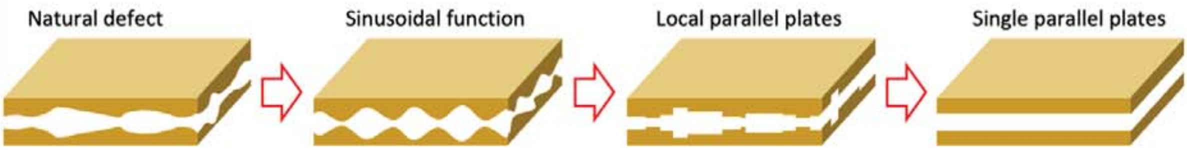
When normal stresses are relieved during, for instance, removal of overburden (either naturally through erosion or by man), fractures may once again dilate resulting in increased aperture.



(b) Simplification of Natural Rock Defects

A rough, natural rock defect (fracture, discontinuity, joint) can be simplified by visualising it as either representative by a sinusoidal curve best mimicking its aperture, of as a set of local parallel plates representing localised changes in aperture, or as a single continuous smooth parallel plate. These all require different mathematical solutions, with the single smooth parallel plate model probably being most widely used due to the ease of its simplification.

Deviations are inevitable given some very likely changes to the morphology of the defect. This includes historical shear stress (lateral offset to "unmatch" the roughness profile), existing normal stress (overburden pressure to reduce the aperture), or infilling that effectively reduces the hydraulic aperture.



(c) Cubic Law

The cubic law assumes a fracture comprising two smooth parallel plates. The aperture between the plates is constant (e) with a uniform pressure gradient, as well as a velocity gradient changing along the aperture direction (i.e. nearer or farther from the walls), and not along the direction of flow. This fulfils the conditions of the Navier-Stokes equation, allows combination of Darcy's and Poiseuille's Laws, and then yields the cubic law as a function of the cube of the aperture:

Saturated fractures with spacing *b*

$$K_f = \frac{ge^3}{12\upsilon b} = \frac{\rho g e^2}{12\mu b}$$

$$K_f = \frac{ge^2}{12\upsilon}$$

Individual saturated fracture

Where K_f represents the fracture hydraulic conductivity as a function of water's kinematic viscosity (υ), dynamic viscosity (μ), density (ρ), and gravitational acceleration (g)

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Box 25. Deviations from the Parallel Plate Model

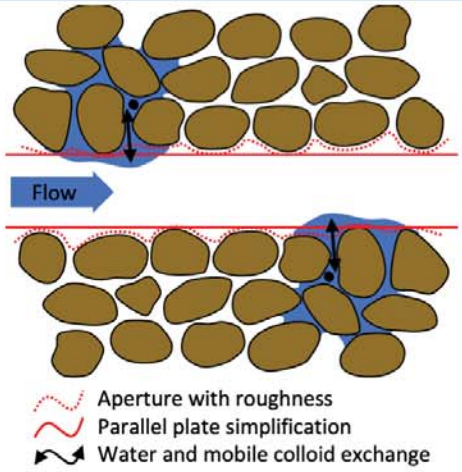
BOX 25. Deviations from the Parallel Plate Model

(a) Double Porosity

Rock material has matrix porosity associated with a matrix hydraulic conductivity *(K_m)* that is generally much lower than the fracture hydraulic conductivity (K_f). Fractures can be seen as pathways of lower resistance to the movement of water, whereas rock material poses greater resistance to flow given the very small size of interstitial pore space. As such, the following generally applies:

$$K = K_m + K_f \;\; and \;\; K_f \gg K_m$$

The matrix is, however, not negligible as it is seen as supplying water to fractures over time. Notably at unsaturated conditions, imbibition of practically stationary water into primary pore spaces in the rock itself becomes increasingly possible, moving a wetting front into the rock itself rather than inducing flow in the fracture. Colloids may also move between matrix and fracture, often mobile in aqueous phase, altering hydraulic behaviour over time.



(b) Non-linear Flow

Many fractured systems violate Darcy's Law, notably by being unsaturated and through being characterized by non-laminar flow. In some instances, flow is non-Darcian, implying that the relationship between flow rate and pressure drop are no longer linear. In these instances, Darcy's Law and the Cubic Law no longer apply. Forchheimer's Law can be used to describe non-linear flow despite low flow velocities or low Reynolds Numbers.

Causes of non-linearity are attributed to surface roughness (asperities), aperture variations, and obstructions or contact areas between fracture walls. Inertial effects can also be due to fluid bending at the entrance to the fracture, thereby contributing to non-linearity

$$-\nabla P = AQ + BQ^2$$
$$A = \frac{\mu}{kA_h} = \frac{12\mu}{we_h^3}$$
$$B = \frac{\beta\rho}{A_h^2} = \frac{\beta\rho}{w^2 e_h^2}$$

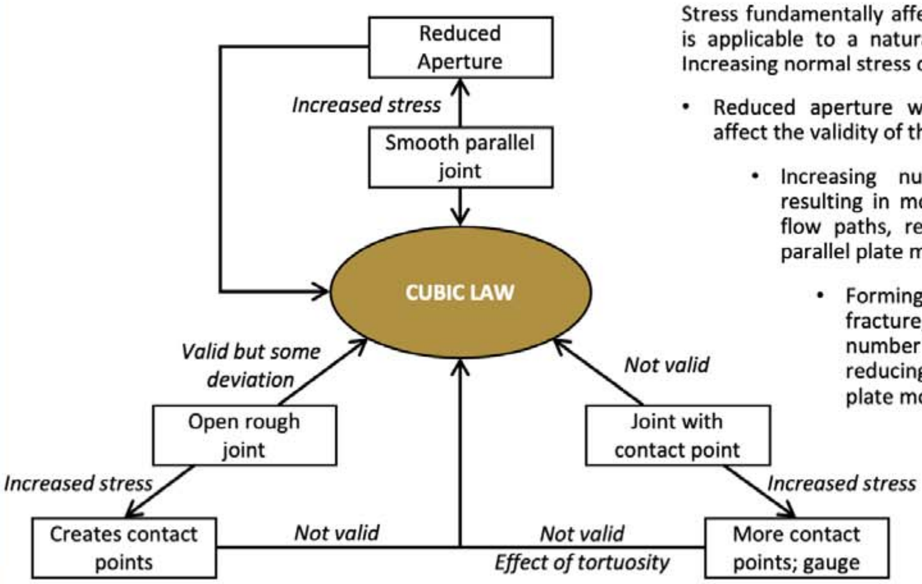
Where ∇P = pressure gradient [$ML^{-1}T^{-2}$]

A = linear coefficient

B = non-linear coefficient

β = Non-Darcy flow coefficient/ Forchheimer coefficient [L^{-1}]

(c) Changing Stress



Stress fundamentally affects whether the Cubic Law is applicable to a natural rock defect or fracture. Increasing normal stress can result in:

- Reduced aperture which very likely does not affect the validity of the parallel plate model
  - Increasing number of contact points resulting in more interruptions along the flow paths, reducing the validity of the parallel plate model
    - Forming gouge infilling parts of the fracture, coupled with increasing number of contact points, both reducing the validity of the parallel plate model.

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(a) Dippenaar and Van Rooy 2016; Bagalkot & Kumar 2018; Indraratna & Ranjith 2001; (b) Jones et al. 2020; Konzuk and Kueper, 2004; (c) Indraratna & Ranjith 2001

8.2. Geometrical Influences

Aperture generates open space for flow to occur. With increasing aperture, gravitational forces start dominating over capillary forces as there is proportionally less surface area available. Water also manages to only wet a single fracture wall under increasing aperture. Aperture itself does not affect the applicability of the cubic law, however, as roughness and contact obstacles dictate deviations from the parallel plate model through retarding flow through increased inertia and friction (Dippenaar et al. 2020; Segole and Van Rooy 2017).

This aperture behaves in a certain manner, reducing shear strength while promoting hydraulic connectivity. When completely open with large aperture, these consequences are more pronounced than when only slightly open with small lengths of persistence. The aperture of the also behaves differently to the pore space in the rock matrix, the latter behaving like the intergranular or primary porosity of a soil system. The same applies to infill cement, precipitates or clays that clogs the fracture aperture (secondary porosity) with intergranular (primary porosity) materials.

Roughness refers to the waviness on the fracture wall, and contact points specifically where these rough surfaces are in contact. Occasionally such contact points represent intact rock where the rock is continuous across the aperture, in which instance it is referred to as bridging. These lengthen (increase) the flow path, result in channelled flow, and contribute to changes in surface area available for wetting. Very importantly, under shearing, these can be sheared off and form gouge, effectively reducing the hydraulic aperture through clogging (Dippenaar et al. 2020; Li et al. 2019).

Changing of orientations and intersections determine the relationship between adhesion (wetting of side walls) and cohesion (attraction of water molecules to each other, resulting in gravitation). Hydraulic gradients still dictate flow under high enough water or moisture contents, but at low values, orientations of fracture walls may dictate the direction of water movement rather than solely gravity vertically downwards (e.g. Jones et al. 2017; Noffz et al. 2019).

SECTION D: IN THE VADOSE ZONE

9. THE VADOSE ZONE

9.1. Hydrostratigraphy

A hydrostratigraphical classification is crucial in understanding the interaction of different hydrological units in the subsurface. Hydrogeology is not solely subject to understanding of isolated aquifers for the water supply. Rather, understanding of an aquifer system requires intricate understanding of the water cycle superimposed on an area with input from a variety of long-term stable and short-term fluctuating data.

Geology, long-term climate, and geomorphology dictate the relationship between runoff and recharge. Furthermore, the properties of the entire subsurface result from this, including the different aquifers, as well as the aquitards, aquicludes, and the extent and properties of the vadose zone. Aquifers interact with each other and with water from the surface, implying that while the aquifers are often the unit of most imminent importance, its properties are dictated by its accessibility, implying the confining layers and the vadose zone.

South African diversity offers a vast range of hydrostratigraphical variation through, for instance:

- Very old geology spanning almost four billion years of the planet's history
- Substantial erosion and denudation stripping the surface of most young surface deposits and thick soil horizons following the break-up of Gondwanaland
- High climatic variability from human eastern coastlines to deserts in the north-western portions.

Hydrostratigraphical classification is equally variable, with occasional differences in data requirements for different purposes in different parts of the country. This is well explained by Diamond et al. (2019) and is shown in *Box 26*.

Overlying the hydraulic properties of different strata or horizons in the subsurface allows one to judge the cumulative effect of the system. Rather than averaging out a parameter in a complex zone such as the vadose zone, it is helpful to understand the storage and permeability properties of different materials. In unsaturated state this is already complex given variation in moisture content. However, it is further complicated by near-surface processes (such as crusting, biological processes, tillage, reworking, evaporation, and transpiration to mention a few) that make the REV of the shallow vadose zone extremely small and localised. This additional complexity causes for more variability, more bias, higher likelihoods of overlooking certain important changes to the hydrological conditions, and oversimplification of a very complex system.

As such, overlying the hydrological cycle on the ground profile requires proper understanding of both the ground profile and how water moves into, though, and out of the system.

9.2. Ground Profile

Ground profiles vary substantially based on composition (rock type, chemical and mineralogical composition, structure, texture), weathering (induced by historical and present-day climate and period of exposure to weathering agents), and present-day hydrometeorological and geomorphological conditions.

Different earth materials behave differently with respect to water (*Figure 9-1*). In understanding the lithological and pedological variation, one can start to see the vadose zone not merely as a black box, but as a highly heterogeneous and anisotropic medium with highly variable properties.

Box 26. *Hydrostratigraphy*

BOX 26. Hydrostratigraphy

(a) Classifying the Subsurface

Hydrostratigraphy is the classification of the subsurface into distinct hydrogeological units, each with defined areal extent, thickness and hydraulic parameters (Poehls & Smith 2009, p.188). Different hydrostratigraphical units may therefore possibly overlap with geological units such as formations, or may occur within single units, or may comprise multiple different geological units.

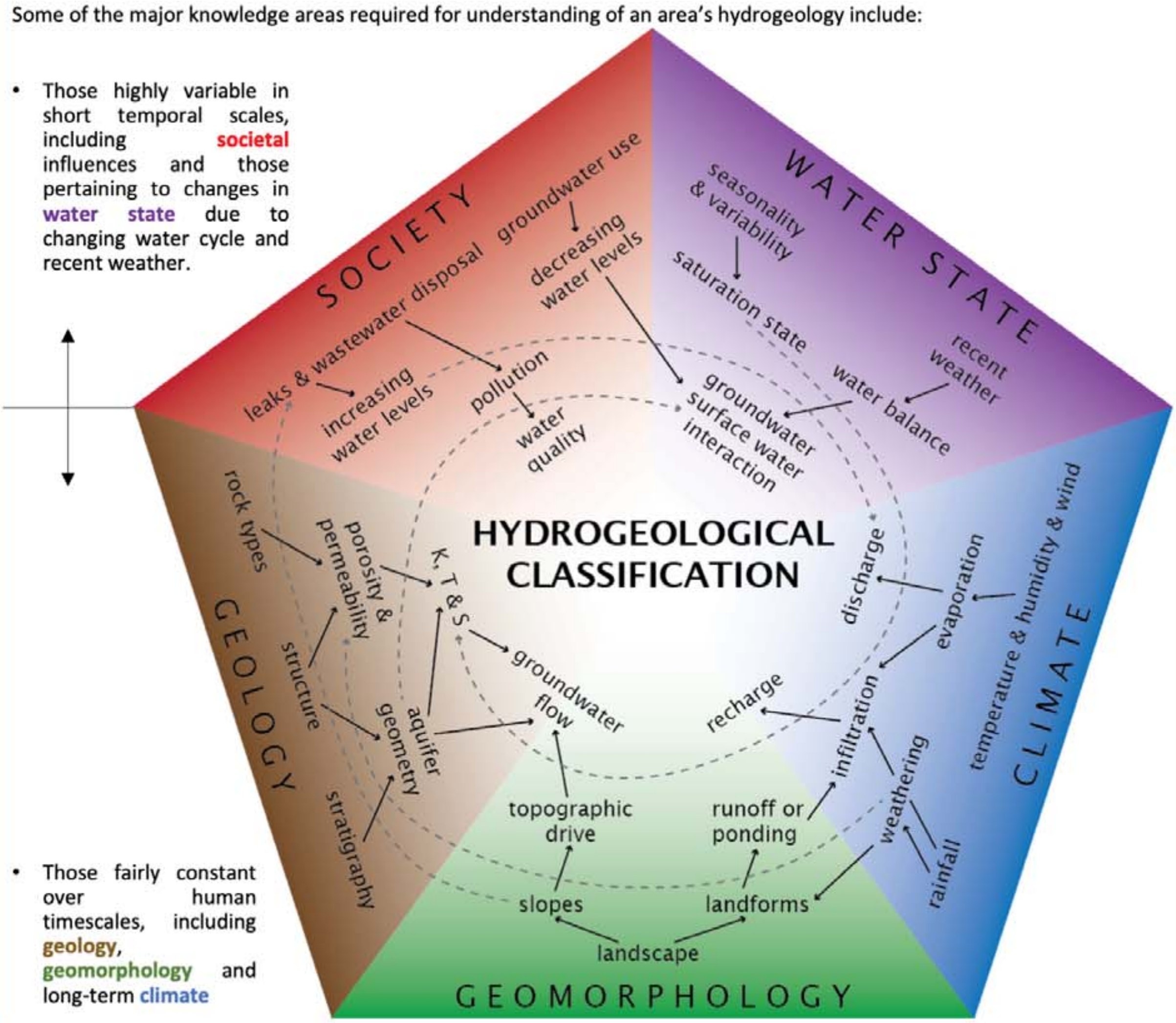
Hydrostratigraphical classification requires the obvious hydraulic parameters related to permeability and storage, the hydrogeological nature of the rock such as porosity type and distribution, andthe connectivity between different aquifers and units. In classifying hydrostratigraphy, individual aquifers only form part, and the vadose zone, aquitards and aquicludes, and even broader water cycle need to be incorporated. Aquifer classification is often based on the importance of the aquifer for supply, and include (1) aquifer flow class potential, (2) geological setting, (3) groundwater quality, and (4) depth to groundwater and connection between groundwater and surface water resources.

(b) Hydrostratigraphical Classification Framework

All these parameters interact and relate to each other, and changing one aspect will impact another. Some of these interactions are shown, for instance with weathering both resulting from climate and affecting geomorphology.

Some of the major knowledge areas required for understanding of an area's hydrogeology include:

- Those highly variable in short temporal scales, including **societal** influences and those pertaining to changes in **water state** due to changing water cycle and recent weather.



- Those fairly constant over human timescales, including **geology**, **geomorphology** and long-term **climate**

READ MORE:
ADAPTED FROM: (a) Diamond et al. 2019; detail from Chesnaux et al. 2012; Payne & Woessner 2010; Poehls & Smith 2009; (b) Diamond et al. 2019

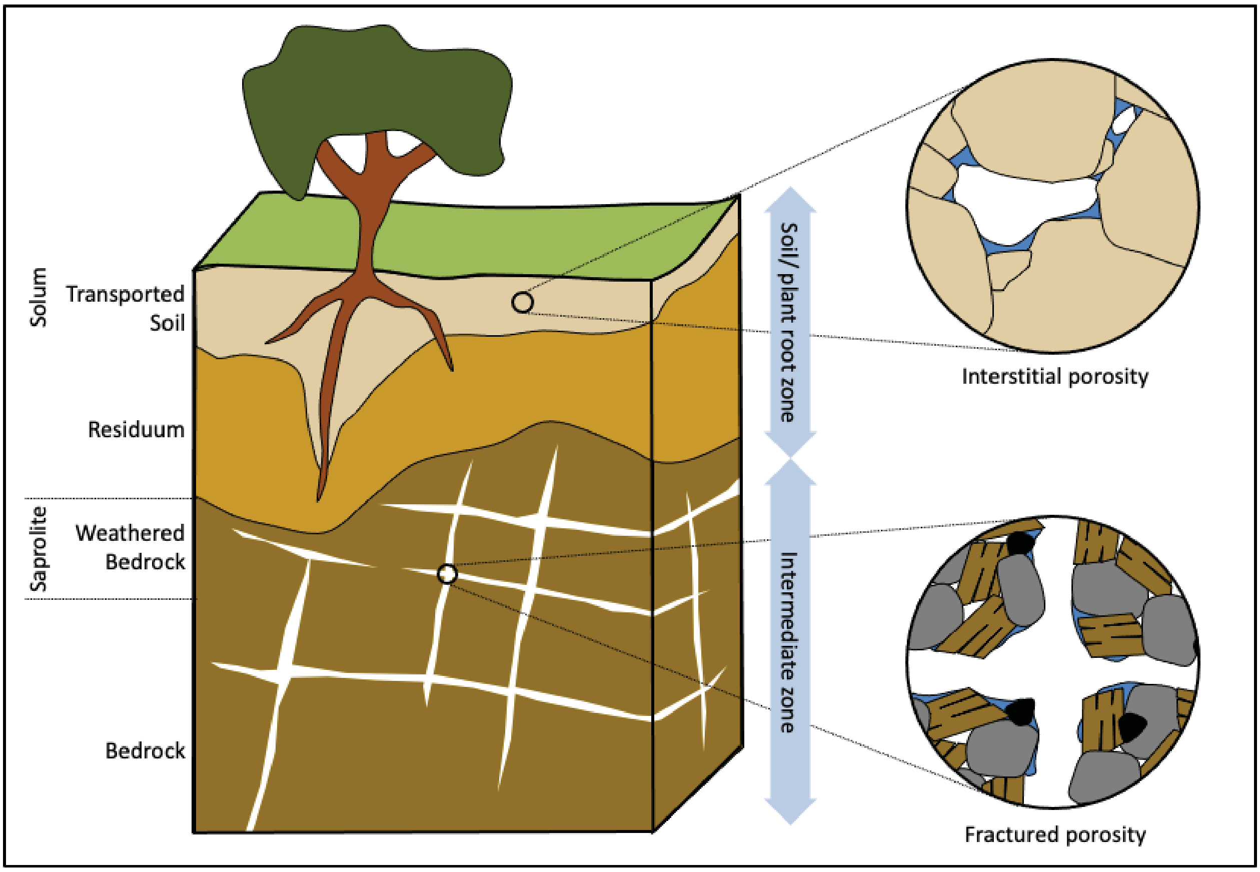


Figure 9-1. Partial saturation of soil and fractured rock.

Earth material successions are very often described, but it becomes increasingly important to describe it in a manner where the profile description can be seen as field data open for interpretation by other audiences. While an engineering geologist may describe a profile, the pedologist should be able to infer the hydropedological character based on understanding the overlap and differences between different classification systems. Different professional earth scientific disciplines can best interact here: through the proper description of a detailed ground profile that is adaptable to various and non-generic applications. In understanding this succession of material, one can deduce the historical and present-day influences that formed the vertical succession and the spatial distribution of materials. But, one can also subsequently pre-empt better what the consequence will be when removing, replacing, or altering the properties of any part of the succession.

These ground profiles form the upper layer, highly discretized with very small representative elementary volumes and high variability over small spatial scales. This is the point of immediate exchange in moisture between the surface and subsurface, and therefore fundamentally dictate the regional hydrological cycle. It is also likely the most sensitive to anthropogenic change, as it is most likely the material to be tilled, removed, replaced, sealed, or affected in any other manner. Altering the hydrological properties of these shallow soils have long-term consequences for the greater water cycle.

Proper understanding of the shallow ground profile should always be seen as the first required data, and should be followed by further tests for verification. Descriptions should be compliant to required terminology and classification systems (e.g. soil classes; lithostratigraphical units).

Some such examples showing the variability of typical South African soil and rock successions are shown in *Box 27* to *Box 29*. Note the distinct variability in profiles derived in similar climates, and/ or from similar geology.

Box 27. Intrusive Igneous Profiles from SA

BOX 27. Intrusive Igneous Profiles from SA

Nebo Granite
(KwaMhlanga; footslope)

Nebo Granite
(Dennilton; crest)

Gouplaats-Hout River
Gneiss
(Giyani)

Johannesburg Dome
Granite
(Midrand)

Rustenburg Suite
Gabbro-norite
(Bapong, Brits)

Rustenburg Suite
Gabbro-norite
(Northam)

Rustenburg Suite
Gabbro-norite
(Rooiwal)

Rustenburg Suite
Gabbro-norite
(Wonderboom Pta)

Approximate contact between soil and saprolite

Horizons subjected to distinct pedogenesis (varying degrees)

Seepage/ perched water

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Box 28. Volcano-Sedimentary Profiles from SA

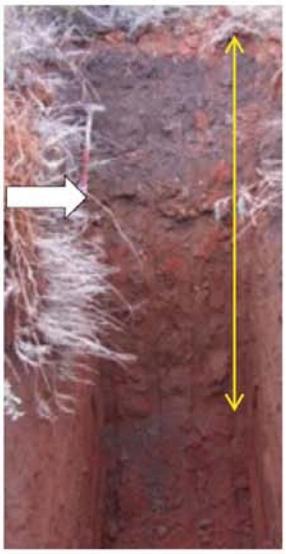
BOX 28. Volcano-Sedimentary Profiles from SA

Machadodorp Basalt (Machadodorp)

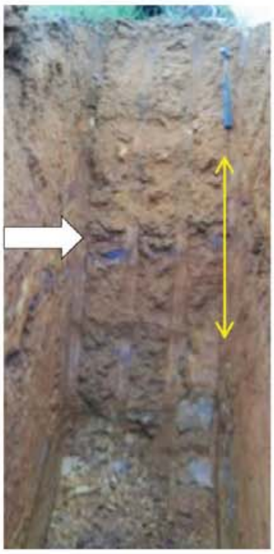
Ghaap Group Dolomite (Taung)

Chuniespoort Dolomite (Sabie)

Chuniespoort Dolomite (Vosloorus)



Silverton Shale (Proclamation Hill Pta)



Karoo Supegroup 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

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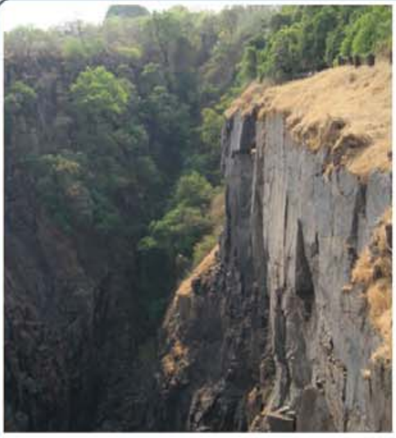
Box 29. Variability in Rock

BOX 29. Variability in Rock


Columnar jointing in Batoka Basalt (Zambia)

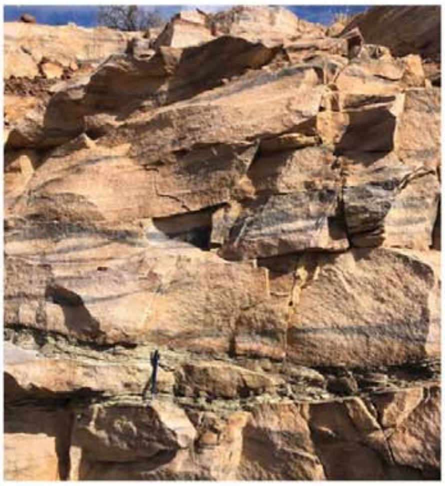

Close horizontal jointing in Table Mountain Group Sandstone (Chapman's Peak SA)


Freeze-thaw jointing in Drakensberg Basalt (Lesotho)


Dolerite dykes in Basement Granite-gneiss (Pontdrif, SA)


Contact Daspoort Quartzite over Hekpoort Andesite (Pretoria, SA)


Closely jointed Barberton Supergroup Shale (Barberton, SA)


Waterberg Group Sandstone with intercalated Mudrock (South Africa)


Spheriodal weathering in Jurassic Dolerite (Van Stadensrus, SA)


Fractured Olifantshoek Supergroup Quartzite (Tswalu, SA)

READ MORE: * SA – South Africa

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9.3. Hydraulic and Mechanical Behaviour of Ground

When all these media - soil and rock - are overlain in a vertical succession, mechanical and hydraulic behaviour become increasingly complex. As we develop the surface and shallow subsurface, we infringe not only on the mechanical properties of these materials, but also on how water moves into, through and out of the subsurface. The occurrence of moisture varies substantially between interstitial pore space and rock fractures, with further complexity arising where these systems interact and coexist.

Typical ranges of hydraulic conductivity for materials are freely available (§19.1). Similarly, specific yield values have been superimposed on the soil texture diagram (*Box 16*a) making it possible to estimate typical values based solely on soil grading or soil type description. While it is understood that such values are oversimplifying the complexity of soil and rock in the subsurface, it still provides sensible initial estimates or rules-of-thumb.

Hydraulic behaviour is dictated by the mechanical properties of ground, as well as how it changes. Whereas water may be stored or moved in one material, a change of properties may induce other behaviour. This often occurs in the residual horizon overlying weathered bedrock where - due to chemical weathering and leaching - the remnants of bedrock become so decomposed that it collapses into itself as predominantly secondary minerals. This results in a densification of the soil structure that typically goes together with a reduction in both the porosity and the permeability (or hydraulic conductivity).

Clearly this behaviour of the ground is a function of the properties of the soil and rock, as well as the interfaces between. Abrupt or smooth or undulating or gradual weathering and bedrock interfaces will all behave very differently as can probably best be described by comparing karst systems with uniform sand deposits. In karst in particular, epikarstic and pinnacle systems behave vastly different, with the latter having an actual residue (residual dolomite or wad) despite the substantial chemical dissolution of soluble rock. This behaves different to thick transported soils, and also different to typical weathering successions comprising residual soil underlying thin transported soil cover. *Box 30* provides some generalized soil profiles successions with typical variations in some important mechanical and hydraulic properties.

Rock in itself is variable, with different sedimentary beds or different lava flows often behaving different. Adding to this metamorphic foliation (such as slaty cleavage, phyllic lustre, schistosity, gneissic banding, etc.), influences of intrusions (changing grain sizes, cooling fracturing, etc.) and tectonic effects (jointing, faulting, folding, etc.), it also becomes almost impossible to simplify the rock model to a single parameter.

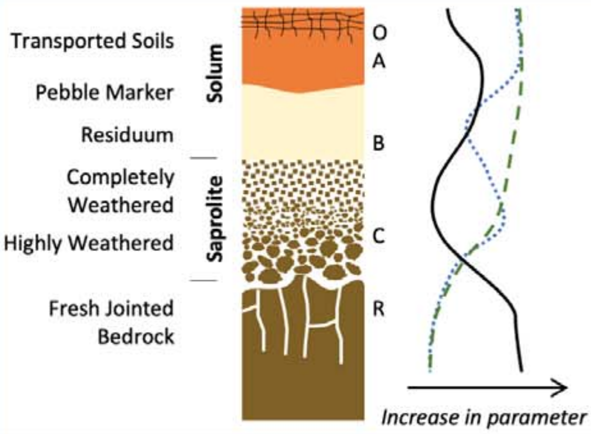
So what we end up doing, is we superimpose:

- … an already complex soil zone (where we see evaporation and transpiration happening, and where burrowing animals and plants and microbes alter the distribution and behaviour of the ground)…
- … on top of a weathering profile grading into fractured bedrock, from residual to fresh rock at depth…
- … while possible having different lithologies, or irregular degrees of fracturing and weathering at depth…
- … while not always anticipating how complex the final addition of the water cycle at highly variable saturation will make the processes occurring in the vadose zone

Box 30. Vertical Successions and Vertical Variability

BOX 30. Vertical Successions and Vertical Variability

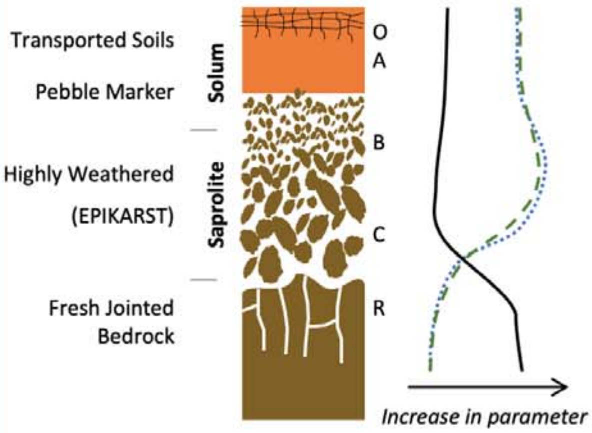
(a) Shallow Non-karstic Successions

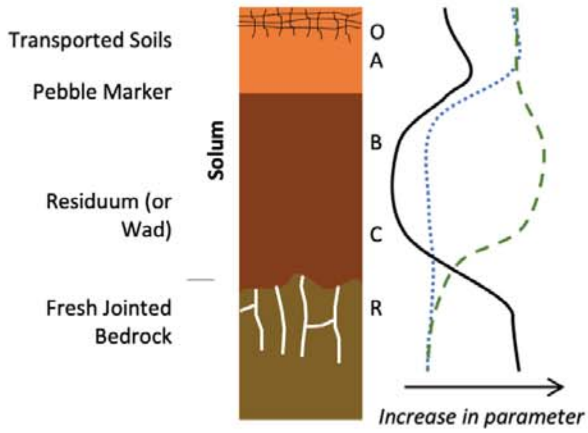


Insoluble rock comprises essentially all igneous rocks, As well as majority of the sedimentary and metamorphic rocks not formed through precipitation of water-soluble minerals. These weather progressively from a fresher (less weathered to essentially completely unweathered) state at depth to a soil representing only a residue of the original rock.

In this last residual state, mineralogy has changed fundamentally to stable forms under near-surface conditions. This is coupled by a densification of the material under collapse of its own weight with the reduced strength accompanying the weathering. Clogging through illuviation and authigenic precipitation commonly occur in this horizon, and as such the residual horizon tend to govern soil hydrology by often having high storage and low hydraulic conductivity compared to the rest of the profile.

(b) Shallow Karstic Successions





For ***epikarstic systems***, the weathered soluble rock forms a very well-drained, coarse-grained horizon that behaves essentially in an opposite manner to normal residual horizons. Here, residual dolomite and wad tend to be absent, and a gravelly horizon above fresher bedrock supply a high-storage gravelly layer from where slow release of diffuse flow can result in deeper percolation into the bedrock.

Some karstic systems do not form epikarst, but are ***pinnacled karst systems***. Here, residual dolomite or wad tend to form and it is associated with highly variable bedrock topography comprising of deeply weathered grykes and pinnacles. The residuum usually has high specific retention, often coupled with very high porosity and low density despite low hydraulic conductivity. Water can be stored in these residual horizons for very long periods.

(c) Complex Bedrock Successions

Lithological, mineralogical, and structural variation in bedrock can also result in vertical variation of profiles. The soil profile is of fundamental importance in dictating the infiltration into the subsurface and shallow interflow. However, variability in bedrock condition affect deeper throughflow and deep percolation to eventual recharge, and are of fundamental importance in the intermediate vadose zone

LEGEND

Relative matrix permeability
Relative intergranular porosity
Relative bulk dry density

LEFT: A road cutting in the Table Mountain Group sandstone showing distinct variability in rock mass and material (Cape Town 2019 © MA Dippenaar)

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10. MOVEMENT OF WATER IN THE VADOSE ZONE

In the hydrological cycle, precipitation events supply water to the land surface. 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). The wetting front of this infiltrating water is typically characterised by a fingering effect rather than a discrete line of wetting. This fingering effect is ascribed to two processes, namely (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).

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. Water movement in the vadose zone is no longer only governed by gravity where water will aim to move vertically downwards. Rather, water can be held under suction, above capillary barrier, or be mobile under hydraulic gradients. These ***flow scenarios*** address the variable moisture contents and associated occurrence in the ground (*Box 31*; Dippenaar and Van Rooy 2019). These are very helpful in anticipating how altering ground (through for instance excavations or bringing in manmade materials) or altering the water cycle (through for instance increasing or decreasing moisture content below ground) will redistribute the subsurface water cycle.

10.1. Wetting and Drying of Soils

Flow (***seepage***), ***wetting*** (***imbibition***) and ***drying*** (***drainage***) in unsaturated media become increasingly complex as explained in *Box 32*. ***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 (e.g. 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?

10.2. Wetting and Drying of Fractured Rock

Studies show that less than 15% of fracture openings transmitted 100% of percolating water at one site, and less than 20% of fracture openings have been found to transmit more than 70% of the percolating water elsewhere (Dahan et al. 1998, 1999, 2000 in Berkowitz 2002). Individual fractures therefore dominate, and identification of which fracture this is, is nearly impossible.

Due to mechanical properties of rock defects or fractures (such as aperture, continuity or persistence, roughness, and orientation), flow regimes and flow mechanisms in open fractures differ from those anticipated in soils. Air–water flow is governed by the wetting behaviour of water and the water saturation, resulting in various different flow phases, although mostly simplified to single vertical fractures with low water saturation where water will flow as droplets or films, either as laminar or turbulent flow, on the discontinuity surfaces (*Box 33*a). The possibility of different mechanisms (e.g. drop flow on fracture walls of vertical fractures at low water saturation), and influences of discontinuity intersections and orientations (e.g. vertical versus horizontal) should also be considered.

Box 31. Water Movement in the Vadose Zone

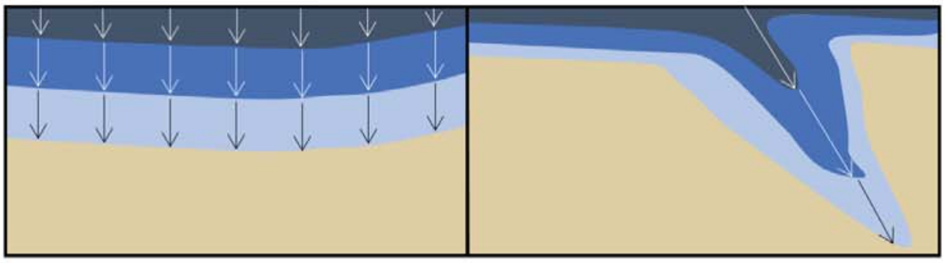
BOX 31. Water Movement in the Vadose Zone

(a) Piston Flow and Preferential Flow

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

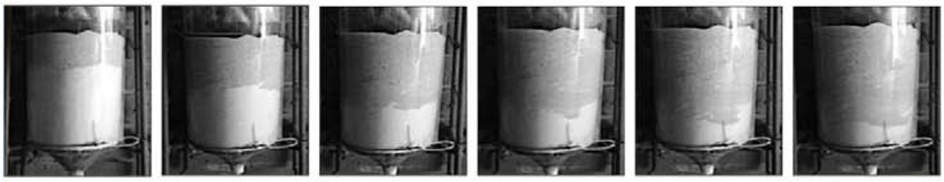
Piston, translatory, episodic, intermittent, pulsating or **threshold-like flow** entails precipitation stored in the vadose zone to be displaced vertically following infiltration of a subsequent precipitation event, thereby not affecting the distribution of moisture, but only the depth. The terms piston, 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.



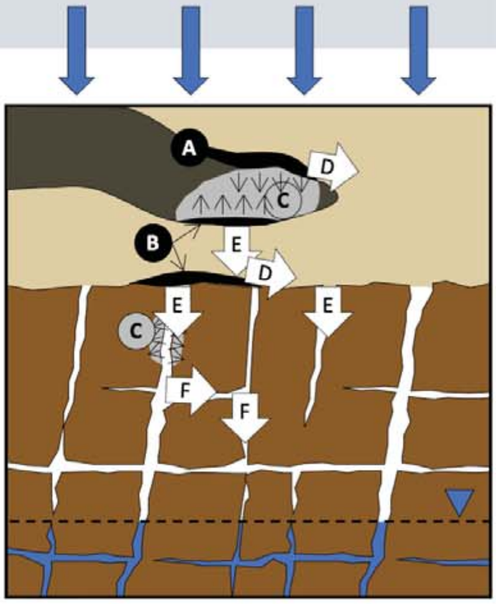
TOP: Three subsequent translatory flow events, progressively pushing the wetting front downwards

BOTTOM: Preferential flow in the form of fingering through macropores/ structures.



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

(b) Vadose Zone Flow Scenarios



- **A. Normal perching**: moisture can perch and disperse on lower permeability horizons due to the high suctions in small void spaces and the effort required to breach those suctions for water entry.
- **B. Capillary-barriered perching**: moisture can perch and disperse on higher permeability horizons due to excessive adhesion and suction in fine-grained materials retaining moisture above larger voids or fractures, thus not allowing water entry.
- **C. Imbibition**: moisture can imbibe laterally or vertically into finer-grained lower-permeability materials (soil or primary porosity of rock) due to suction, especially at fairly low moisture contents.
- **D. Shallow interflow**: perched water can be mobilised as cohesion (water-water attraction) dominates and interflow ensues on lower permeability materials.
- **E. Percolation**: perched water at high or total saturation in the vadose zone can mobilise as cohesion dominates, and gravity-driven percolation or drainage results.
- **F. Unsaturated fracture flow**: seepage at partial saturation through fracture intersections and networks.

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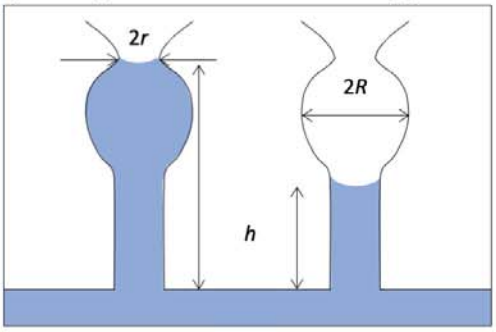
(a) Beekman & Xu 2003, Glass et al. 1988, Podgorney & Fairly 2008
(b) Dippenaar and Van Rooy 2019; Dippenaar et al. 2019c

BOX 32. Characteristic Curves and Hysteresis

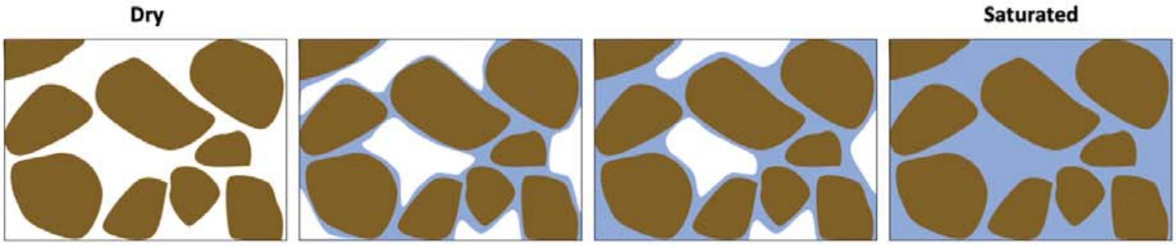
(a) Hysteresis

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. This is referred to as **hysteresis**.



Hysteresis can be ascribed to:

- Geometric non-uniformity of individual pores (irregular shapes of voids and smaller throats connecting these voids; ink-bottle effect
- Contact angle resulting in greater curvature with an advancing meniscus than in receding one causing greater 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.



(b) Characteristic Curves

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.

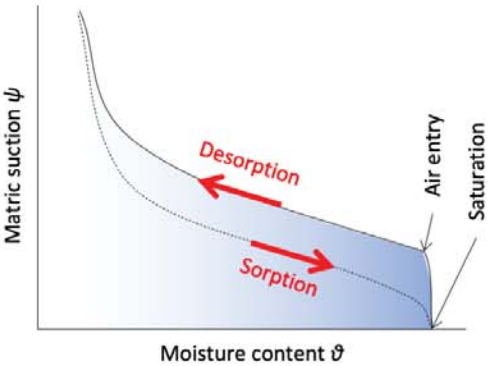
Characteristic curves are not constant and depend on the soil texture, as well as whether the soil is being wetted or dried. In terms of soil texture, clays will always have higher moisture content at the same matric suction due to the greater surface area and its porosity. At the same moisture content,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

Characteristic curves or **retention 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 curves** or **wetting curves** depend on the maximum diameter of the large pores. The process of sorption or rewetting requires greater suction for smaller pores.

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.



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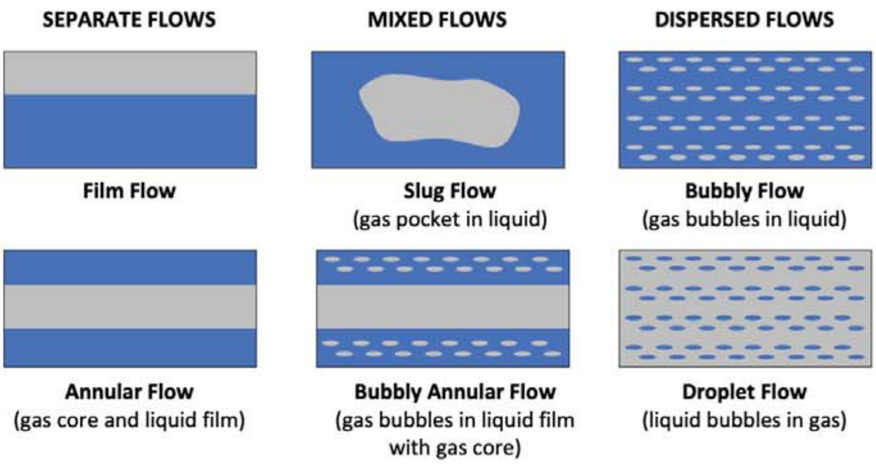
Das et al. 2005; Dexter 2004; Fitts 2002; Hillel 2003; Martin and Koerner 1984a; Schaetzl and Anderson 2005; Van Genuchten 1980

Box 33. Fracture Flow Mechanisms

BOX 33. Fracture Flow Mechanisms

(a) Flow Mechanisms

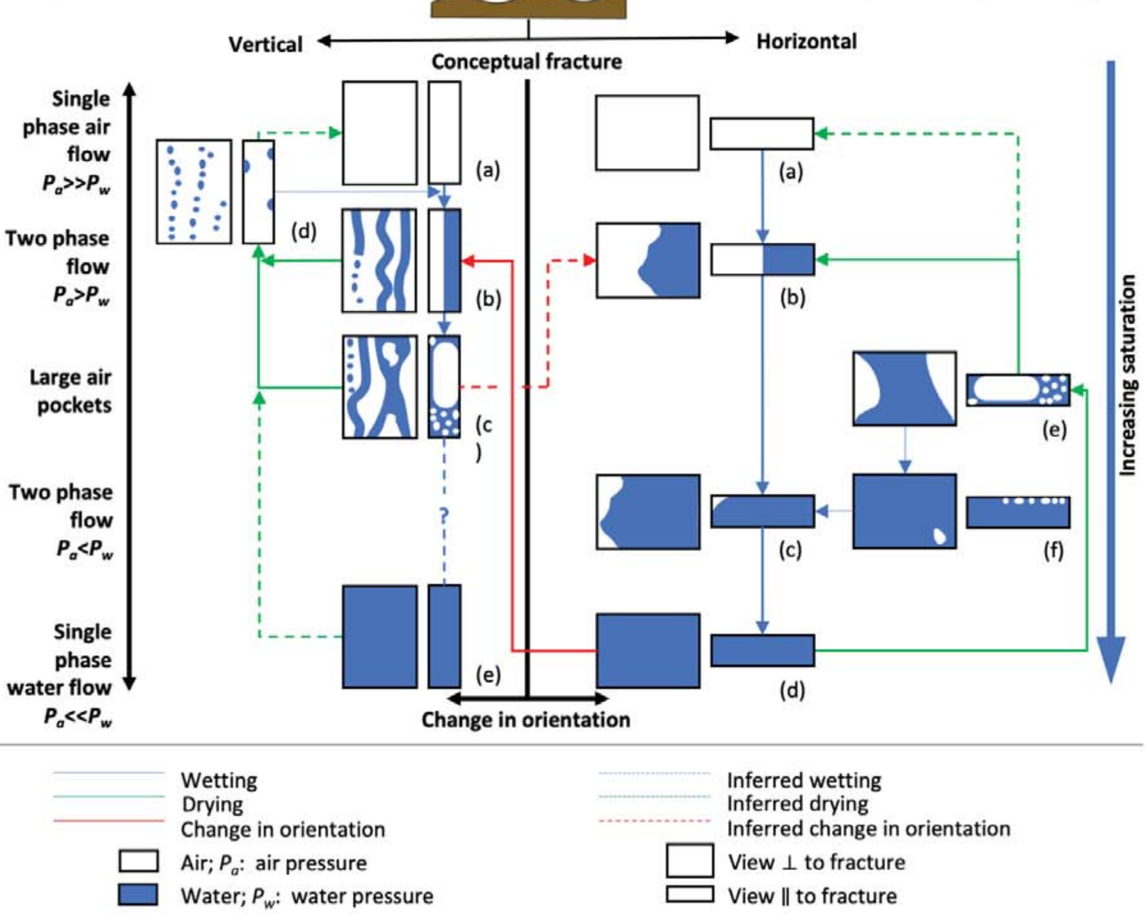
Different fluids, such as water and air, occur and move under different mechanisms with one fluid being the one most prone to wetting the rock surface, and/ or one being more likely to be dispersed or mixed into another. This is dictated by the properties of the fluids and the likelihood that they will behave as wetting fluid to a solid surface. Based on moisture content, these mechanisms can interchange, or become even more complex to include films, droplets, rivulets, etc.



(b) Changing Orientation and Moisture Content

Flow mechanisms can change when changing moisture content or fracture orientation as when two fractures intersect.

Moisture content is not constant under unsaturated flow, and is further complicated by fracture intersections and free-draining vertical defects.



READ MORE:
ADAPTED FROM: (a) Indraratna & Ranjith 2001; (b) Jones et al 2018
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This is shown by results from Jones et al. (2016) for vertical defects whereby (*Box 33*b):

- Full saturation is not ever truly achieved, regardless of their respective experimental designs entailing centrifugal acceleration or variable water supply.
- Flow remains as oscillating rivulets and, occasionally, as localised sheets with substantial air pockets.
- Flow achieved is neither uniform, laminar nor saturated.

For the horizontal counterparts, Jones et al. (2016) did occasionally observe full saturation. However, it appears to be compromised when inflow conditions are intermittent (i.e. not constant uniform water supply), with partial saturation observed in the models tested at increased gravitational acceleration aimed to mimic vertical thicknesses equivalent to the experimental gravitational acceleration. Even in instances where the horizontal fracture is fully saturated, this saturation is lost as the fluid exits at the vertical wall. Here the flow regime is observed as exiting at discrete points of the fracture as non-uniform separate rivulets or droplets.

Once in the rock, flow can occur based on geometry, connectivity and orientation of the fracture network. At partial saturation, individual defects tend to dictate flow rather than the bulk-effect of the network. The same joint set can transfer moisture laterally for vast distances at very low moisture contents through adhesion onto fracture roofs, whereas single vertical joints can rapidly move large volumes of water down under vertical percolation. Moisture content changes are therefore pivotal in understanding low-saturation fracture networks. Mineralogical, small-scale textural and structural, and weathering effects all play a part in this complexity of flow through rock (*Box 34*).

10.3. Flow across the Soil-rock Interface

Water entering the subsurface will infiltrate and percolate under gravity as long as the moisture content is adequate to promote gravitational drainage. On reaching a soil horizon of differing properties, entry into the subsequent horizon will depend on whether air in the lesser-saturated deeper horizon can be displaced. The same applies to entry of water from soil into fractured rock. Water will ˇend to pond above the bedrock interface, forming a capillary barrier above an open vertical or subvertical fracture. This results in a bell-shaped dispersion plume forming in the soil above the rock, implying vast lateral displacement of moisture from a single point source on surface. Sufficient pressures need to build up in the overlying soil before water entry can occur in the fracture. Only once this entry has occurred can fracture flow commence at partial saturation (*Box 34*a; Brouwers 2017; Brouwers and Dippenaar 2019).

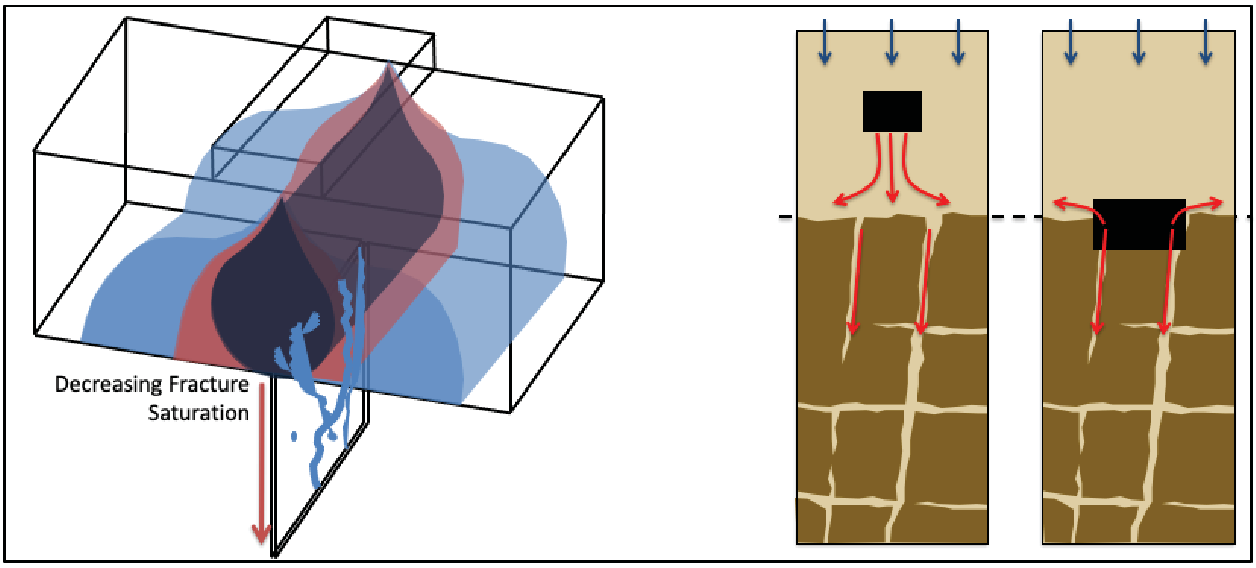


Figure 10-1. Flow along the soil-rock showing the development of a dispersion plume above a fracture (left; Brouwers and Dippenaar 2019), and a scenario where this may occur (right; Dippenaar et al. 2019c).

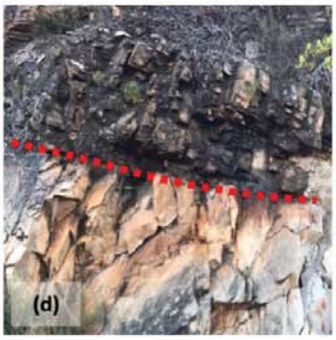
Box 34. Flow Into and Through Rock

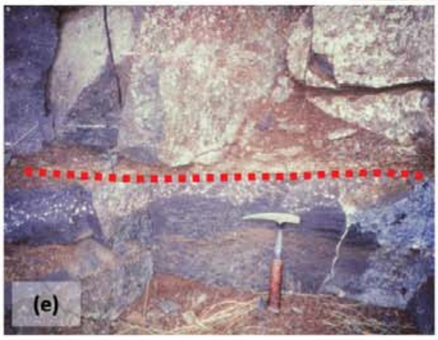
BOX 34. Flow Into and Through Rock:

(b) Road cutting in Jurassic dolerite at Gariep Dam (South Africa, 2019). Note the preferential seepage from a single vertical fracture. Brownish staying supports the notion of having preferential flow from this particular fracture or fracture set.

(a) Road cutting in Jurassic dolerite at Gariep Dam (South Africa, 2019). Note the distinct variability in weathering across the horizontal joint, likely limiting further vertical percolation by forcing infiltrated water to flow laterally along the horizontal fracture. This enhances decomposition of the upper part due to increased wetness.

(c) Road cutting showing the contact between the Daspoort Formation Quartzite (above) and the underlying Hekpoort Formation Andesite (Pretoria, South Africa, 2019). Note the decomposition of the mafic andesite compared to the lack of break-down of the chemically inert quartzite. Flow is forced to flow in the fractured quartzite, with the weathered andesite likely limiting significant deeper percolation due to low permeability.





(d) Road cutting in the Table Mountain Group Sandstone showing distinct variability in rock mass and material (Cape Town, South Africa, 2019).
Note the completely different mass properties above and below the horizontal defect (red line). Also note, due to moisture from surface very likely being prevented from passing across this defect, the distinctly different expressions of weathering. The upper part of the outcrop appears to be more densely fractured than the bottom part.

(e) Quarry in Karoo Basalt showing distinctly different discolouration for different defects above and below the horizontal clay-infilled joint (Silolo, Zambia, 1998).
The bedrock below the horizontal joint (red line) is much fresher, with much more weathering evident in the bedrock overlying. Similar to the example in Cape Town, a single horizontal defect is removing bulk of the moisture, limiting deep percolation and thereby inducing large distances of lateral offset interflow as opposed to possible vertical percolation. Also note the different colours staining on the different orientations.

(f) Quarry in Silverton Shale Formation (baked to slate by Machadodorp Member), showing distinctly different discolouration for different defects (Machadodorp, South Africa, 2012).
The precipitates may represent different ages of fluids and/ or different ages of deformation. However, vertical joints are distinctly more oxidized compared to the less-red horizontal joint sets.
The premise of a small proportion of the fracture network being responsible for bulk of the flow is very likely at least partially responsible. This can be supported by the lack of infill in the persistent well-defined vertical and horizontal joint sets.

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10.4. Spatiotemporal Processes in the Vadose Zone

Ground properties can be altered over time both due to natural and anthropogenic processes. The mechanical and hydraulic properties affect each other and altering either will inevitably have a change in the other as consequence.

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.

10.4.1. Translocation and pedogenesis

Translocation of colloids or fine particles through a soil profile alters the properties of both the horizon from which leaching occurs, as well as the horizon in which these fine grains are eventually trapped or the dissolved ions precipitated. This cementation may – at different stages of pedocrete behaviour – result in either more or lesser porous horizons. This can result in clay leaching through a profile (from an eluvial to an illuvial zone, as described in pedology, or similarly down-gradient as in catenal settings) or pedogenesis (the in situ cementing of a soil through absolute enrichment or authigenic mineralisation). These are shown in *Box 35* and *Box 36*.

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.

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 35* (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.

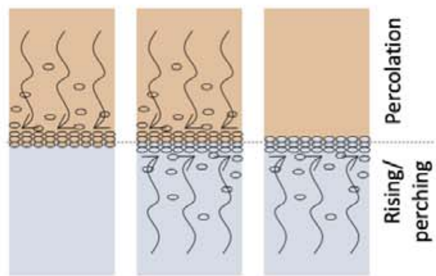
Box 35. Pedogenesis

BOX 35. Pedogenesis

(a) Pedogenesis

Pedogenesis refers to the induration of soil through the precipitation of authigenic minerals within an existing material. The stages 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)



(b) Ferricrete

Pedocretes can form from infiltrating water as pedogenetic pedocretes, or from fluctuating groundwater as groundwater pedocretes. Interflow can also result in pedocretes, mostly as a pedogenetic result rather than a groundwater process.

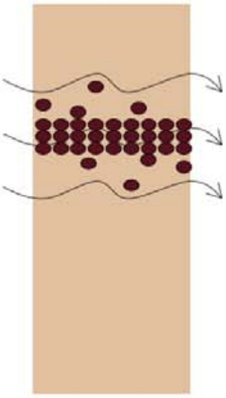
Examples of the same Lanseria Tonalite Gneiss from the Johannesburg Granite Dome in Johannesburg show two distinctly different profiles in terms of pedogenesis.

The above show an interflow system with maximum induration (hardening) in the middle, separating transported soils above from the weathered bedrock below. this likely formed in the residual granite.

The below show a gradual enrichment in iron precipitation with depth. As water infiltrates, mottling and/ or discolouration progressively increases until the stage where no further percolation takes place. This, likely due to a basal barrier to further vertical seepage, is where lateral interflow is forced to commence, hence the removal of the water.

In both instances, there is practically no connection to the actual phreatic surface or groundwater system.

Both instances show different stages of ferricrete as goethite is the predominant authigenic mineral.

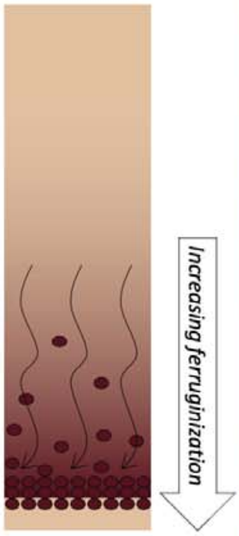


Dry dark greyish brown loose open silty sand. Colluvium

Hardpan ferricrete (likely formed in residual granite)

Dry light greyish brown completely weathered granite

Progressively grading into weathered granite



Dry, light greyish brown, very loose, intact, slightly clayey silty SAND. Topsoil.

0.40 Slightly moist, light greyish brown, loose, pinholed, slightly clayey silty SAND with occasional Fe and Mn concretions and scattered sub-rounded gravel and pebbles. Colluvium (ferruginized).

0.90 Moist, yellowish brown mottled orange and red and streaked black, loose, pinholed and voided, slightly clayey silty SAND with Fe and Mn concretions. Residual Granite (powder ferricrete).

Very moist, reddish brown mottled grey, medium dense to dense, pinholed and voided, clayey silty SAND. Completely Weathered Granite (powder ferricrete).

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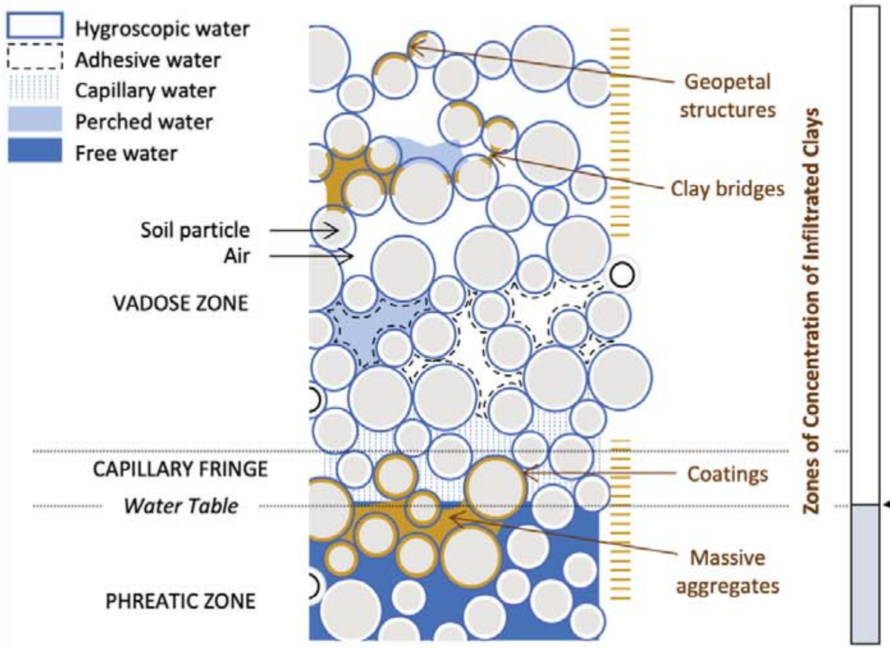
Box 36. *Translocation*

BOX 36. Translocation

(a) Translocation



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.

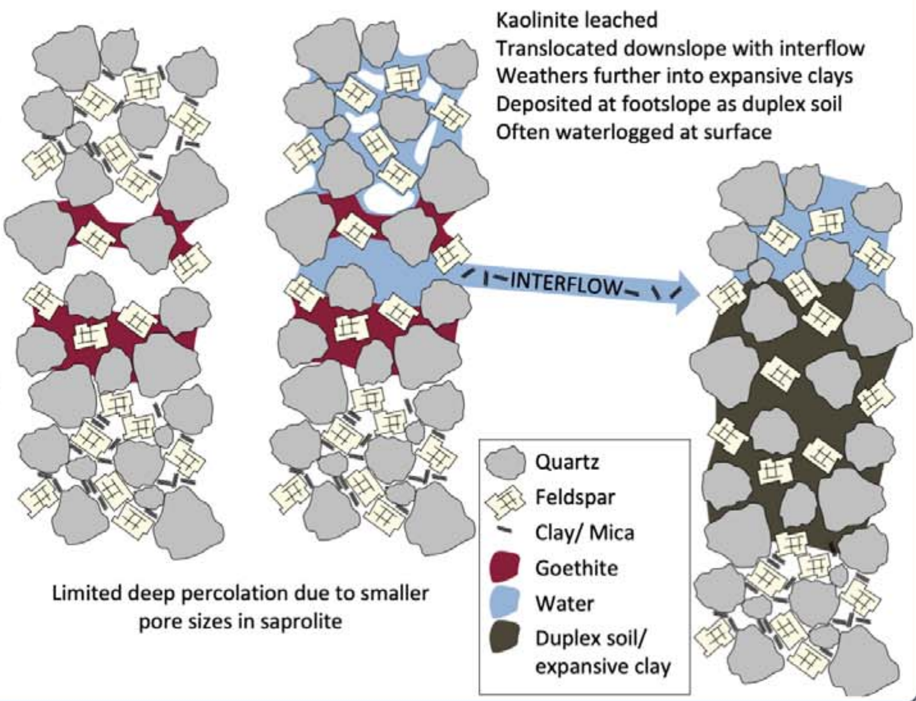
Leaching of clay minerals from a generally coarse-grained soil with percolating water can furthermore lead to a change in soil structure.

In general, leaching is from an eluvial horizon into an illuvial horizon.

(b) Interflow and Associated Translocation and Pedogenesis

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

Porosity may be lower in the indurated horizon, but due to better connectivity and larger pore sizes, interflow may in fact be preferred through this horizon. Through movement of colloids with interflow, progressive weathering may form secondary clay minerals, resulting in downslope waterlogging.



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(a) Moraes and de Ros 1990, Shaw 1994, Skolasinska 2006;

(b) Dippenaar 2014b,c

10.4.2. *Changing moisture content*

Moisture content is not a constant value. This changes spatially and temporally based on present-day climate (dictating the water input into the system) and present-day geomorphology (dictating the most likely flow paths and relationship between infiltration and runoff).

As moisture content changes, the profile may visually look different. In, for instance, the MCCSSO soil description system, the moisture parameter is placed first in order to pre-empt that colour and consistency, for instance, may appear distinctly different. Similar soils will have different colour, with increasing moisture enhancing tones suggesting oxidation or gleying, while drier soils may overall have a more monotonous tone with less distinct variability.

Some examples are presented in *Box 37*. Each of these three examples show soils that are chemically and mechanically exactly the same. Mineralogical and grading analyses verify that these soils should behave the same, but that field investigation may have had an initial different outcome. Moulding wetter soils may result in the soil likely being classified as more cohesive and clayey, whereas drier soils tend to feel more granular. Taking these soils to the same moisture content during field investigation would have identified the similarity and reduced the bias.

10.4.3. *Soil volume change*

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. 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, e.g. (1) swelling/ shrinking, (2) settlement or (3) differential movements associated with these (*Box 38*).

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.

Subsidence relates to the vertical downward movement of a structure's foundation due to loss of support beneath its foundation. This is typical of undermined ground and karst where underground cavities serve as receptacles for the downward migration of overlying strata.

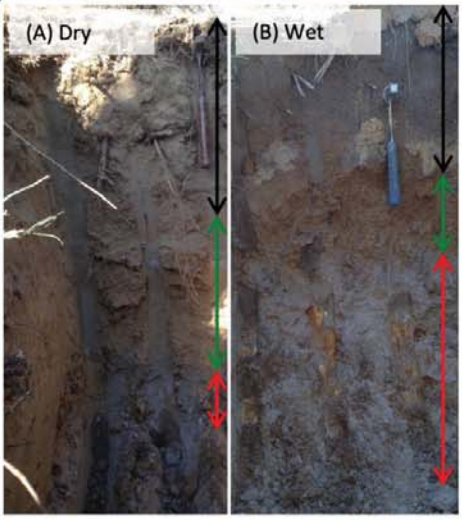
Clay mineralogy influences its ability to heave (expand) and shrink, requiring a 2:1 clay mineral. Consolidation or compaction is a readjustment of soil particles into a denser state, whereas collapse is a sudden further reduction due to loss of cohesion between sand grains.

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 (National Department of Housing 2002; SABS 2009b) 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.

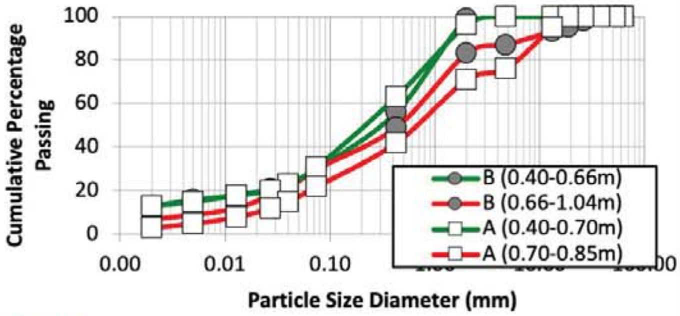
Box 37. Changing Moisture Content Soils

BOX 37. Changing Moisture Content in Soils

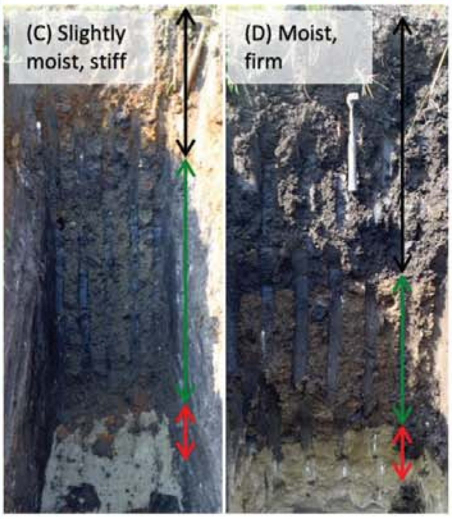


LEFT: Lanseria Gneiss (Johannesburg, South Africa)

These two profiles are located approximately 50 m apart with only the in situ moisture content being different. Grading analyses show that the mechanical properties are essentially the same. As such, the behaviour will be similar if the moisture contents are similar, as may occur from any development altering the vertical succession or the moisture movement through the succession.

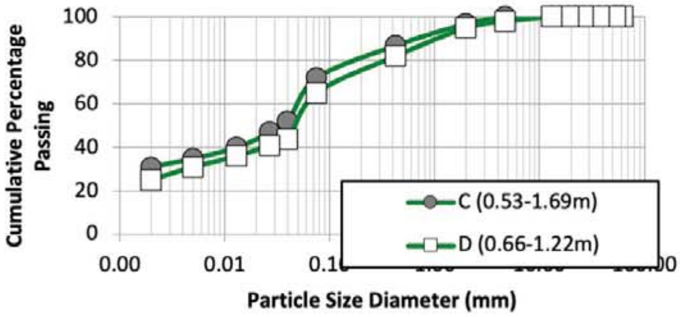


Transported *Residuum* *Completely Weathered Bedrock*

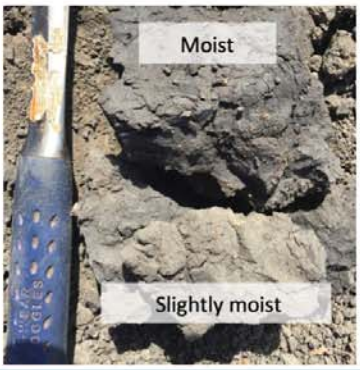


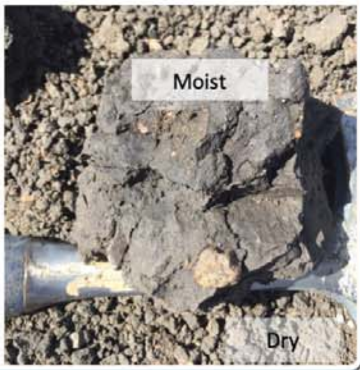
LEFT: Rustenburg Layered Suite (Marikana, South Africa)

These profiles are located less than 100 m apart, also with only in situ moisture content being different. Despite this, the mechanical behaviour is similar, as is evident by the grading and the similar mineralogy. Both profiles will therefore behave similar should the project life hydrological conditions be similar



BELOW: Karoo Basalt (Nata, Botswana) - The same soil on the same property occurs, from left to right, with desiccated structure under shrinkage in dry state; slickensided under heave in slightly moist state; structureless and intact under further heaving obscuring the slickensides.





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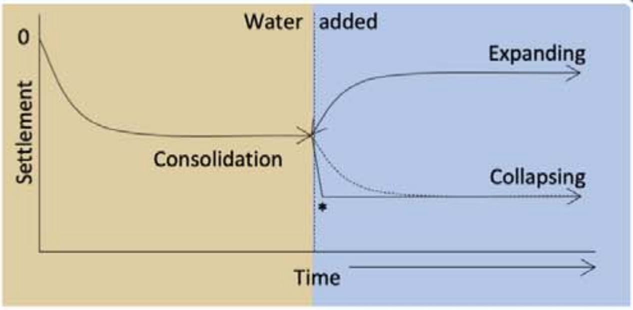
Box 38. Volume Change in Soils

BOX 38. Volume Change in Soils

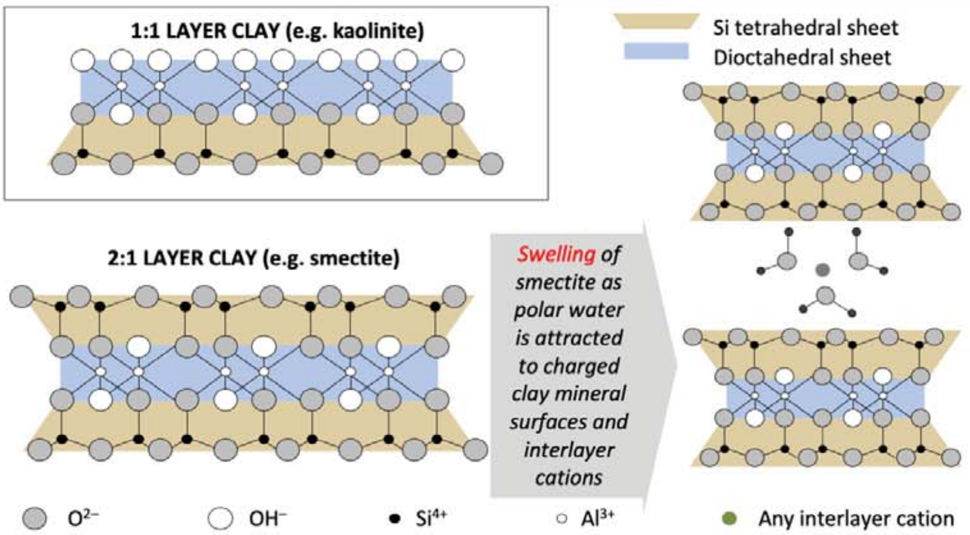
(a) Mechanisms of Volume Change

A soil occur sin equilibrium with environmental conditions. Volume change is induced over increasing load and/ or increasing moisture content. Some processes are permanent (such as settlement), whereas others such as heave (expansion) can be reversed (shrinkage).



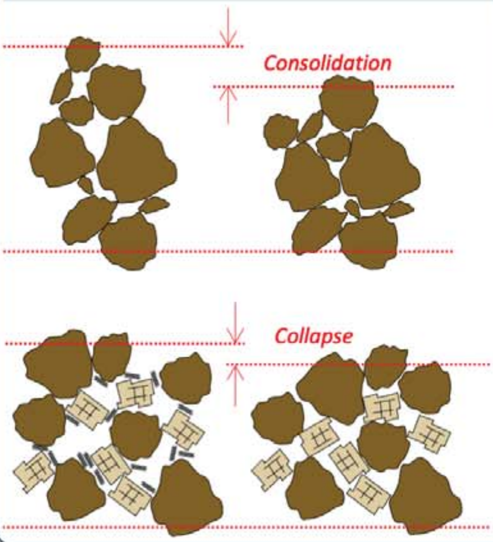
(b) Expansive (Heaving; Active) Soils

2:1 layer clays (e.g. smectite) are prone to heave, expansion or swell on wetting, and shrinkage on drying. This results in lower porosity as volume increases, or increased porosity, likely as desiccation cracking, on drying. 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.



Right: collapsible residual granite (Johannesburg)
Far right: desiccated clayey alluvium (Pretoria)

(c) Soils prone to Settlement



Settlement refers to the downward vertical movement of a structure following distribution and redistribution of stresses and loads on the soil. The volume change is permanent, unlike for expansive soils that can shrink again, and distinction is on the rate of volume change.

Compression and **consolidation settlement** (albeit somewhat different) refer to those soils experiencing gradual settlement due to volume decrease following an increase in applied load, 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.

Collapse, on the other hand, entails soils with collapsible fabric. Clay bridges maintain the soil's open structure, but on loading and wetting, are washed out and the soil grains readjust into a dense packing, thereby decreasing volume and porosity.

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Das 2008; Knappett and Craig 2012; Mathewson 1981; National Department of Housing 2002; SANS 634:2009; Schaetzl and Anderson 2005

11. HYDROPEDOLOGY

Hydropedology aims to link traditional pedology, soil physics, and hydrology to better describe the soil-water relationship. Substantial developments have been made in the application of hydropedology to South Arica. It forms a fundamental component in the understanding of water resources in general, providing a very crucial link between surface water and groundwater. In itself a part of vadose zone hydrology, the strength lies in the classification of soil types as predominantly recharge, interflow, responsive, or stagnating soils that mostly promote deeper percolation, lateral interflow, or discharge zones on surface.

While contributing to the exchange of moisture between surface and subsurface, it is also imperative for contaminant transport studies, a key requirement for wetland delineation, and important input requirements for hydrological modelling.

Hydropedology is well described in South African context (Le Roux et al. 2011; Van Tol et al. 2013) with a recent review by Van Tol (2020), stating that the link between the hydropedological system and the deeper intermediate vadose zone poses a crucial component for future work.

Hydropedological processes broadly includes all soil processes where "… flowing or stagnant water acts as the environment or agent or vehicle of transport" (Matula 2011). This is key in the scientific approach of hydropedology that emphasizes "… the central importance of water for a variety of processes in complex soil systems and the fundamental control of soil structure on diverse soil functions across scales…" (Vogel et al. 2013). Soil controls the connection between atmosphere and bedrock, and water links these two zones by being a fundamental transport agent, implying that integrating pedological and hydrological processes into hydropedology can provide new perspectives in understanding the critical zone (Lin et al. 2015).

Water drains through the soil profile and under gravity, and is redistributed by the permeabilities of the soil and rock layers it moves through. The different soil types along the hillslope becomes imperative in understanding this moisture distribution and movement. The diagnostic horizon is deemed useable as it defines all the possible stratifications of soil profiles in South Africa, implying that specified ***soil forms*** can be used that incorporate specific soil horizons, at specific positions, in specific soil classes (Le Roux et al. 2011).

Based on this, in hydropedology, soils can be classified as (Le Roux et al. 2011; Van Tol and Le Roux 2019):

- ***Recharge soils*** are soils without morphological indication of saturation where flow is mainly in a vertical direction into underlying bedrock. These flowpaths can be long and uncertain given the contribution of bedrock. Recharge soils are imperative in generating baseflow and its contribution to catchment hydrology ceases when evapotranspiration exceeds precipitation.
- ***Interflow soils*** are soils where interflow dominates either at the A/B horizon interface, or at the soil/bedrock interface. The prior is typically associated with duplex soils where water builds up in the topsoil due to textural controls, and the latter where freely drained soils are found overlying fairly impermeable bedrock. A lower permeability (e.g. clayey B horizon or bedrock) typically results in the formation of interflow soils.
- ***Responsive soils*** typically generate overland flow and can be shallow overlying relatively impermeable bedrock, or they morphologically indicate prolonged periods of saturation.
- ***Stagnating soils*** are characterized by limited or restricted water outflow and recharge and interflow are limited. Infiltration can occur, but water movement is upward, driven mostly by evapotranspiration. Flow is limited typically due to accumulations or cementation by carbonate, silica, or iron.

The storage and movement of water in and through hillslopes are complex. Hillslope water in the vadose zone is explained through two storage mechanisms (Le Roux et al. 2011), namely transient and perennial groundwater (*Table 11-1*).

Table 11-1. Transient and perennial groundwater in hillslopes (Le Roux et al. 2011).

Nature	Transient Groundwater	Perennial Groundwater
Position	Solum	Solum; rock cracks
Evapotranspiration	Within reach	Beyond reach except for deep tree roots
Pathway	Water is released to lower-lying polypedons; may be perched	Water is released to regional groundwater table, G horizons, wetland soils
Periodicity	Seasonally event-driven; peak rainy season if arid	Seasonal to permanent; around springs only in arid regions
Soil types	Sandy A, B or E horizons	G or uw horizons
Flow type	Piston action vertical and lateral through sand layers; preferential through dry soil cracks	Preferential flow most important
Permeability	Vertical ≪ lateral; controlled by clay content and bulk density; movement by near-surface macropore flow	Vertical high in soil and saprolite; reduces in cracks with depth
Response time	Quick to rain events; primary	Slow to rain events; secondary
Residence time	Short (weeks to months	Month and longer
Interaction with other water tables	Little if any	Feed regional water table; can result in overflow
Source	Water from recharge; interflow soils	Water from recharge soils mostly
Response type	Like a permeable medium on an aquitard	More steady state

As hydropedology highlights in situ soils in the landscape, with characteristic pedogenic features such as aggregation, as well as soil-landscape features such as catenae or soil distribution patterns), it can contribute to the interaction between pedological and hydrological processes. As summarised by Lin (2010), hydropedology emphasizes soil architecture (solids, pores, and their interfaces), soil sin relation to landscapes, soil morphology and pedogenesis, and the delineation of functional soil units as fundamental scientific issues related to hydropedology.

Natural soils comprise horizons with differing solid components (texture, microfabric, aggregation), pore space (morphology, distribution, connectivity) and interfaces between solids and pores (coatings, soil-root, microbe-aggregate, etc.). This is furthermore affected by, for instance, pedogenic processes, as well as the distribution of soils in the landscape. Soils are therefore naturally very heterogeneous, implying preferential flow occurs widespread (Lin 2010) and at various scales, described by Clothier et al. (2008) and summarised in *Table 11-2*.

Table 11-2. Spatial and temporal scales of preferential flow (Clothier et al. 2008 from Lin 2010).

Spatial scale	Temporal scale
Pore scale (10^{-3} m)	
Core scale (10^{-1} m)	Fluid flows in order of 10^{0}-10^{1} seconds
In pedons (10^{0} m)	Hydrological events of 10^{0}-10^{2} hours
Down hillslopes (10^{1}-10^{3} m)	Seasonal changes 10^{0} years
Through catchments (10^{4}-10^{5} m)	Across inter-annual variations of 10^{1} years
Across large regions (≥ 10^{6} m)	

All in all, hydropedology offers an in-depth appreciation of the interaction between soil, water and the landscape, at all spatial and temporal scales, proving to be very beneficial in better understanding the movement of water through the landscape.

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SECTION E: APPLICATIONS

12. HYDROLOGICAL AND ENVIRONMENTAL APPLICATIONS

12.1. Wetland Delineation

Wetlands occur at most places where the upper horizons are waterlogged frequently enough to advance the growth of aquatic plants. These are broadly defined as wetlands and are pivotal in facilitating exchange between surface water and groundwater while also acting as sensitive ecosystems As such, wetlands often occur in the vadose zone where ground is periodically, seasonally or ephemerally waterlogged or wet. 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 39*.

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 12-1*, which highlights the likelihood of periodical unsaturated conditions in these environments.

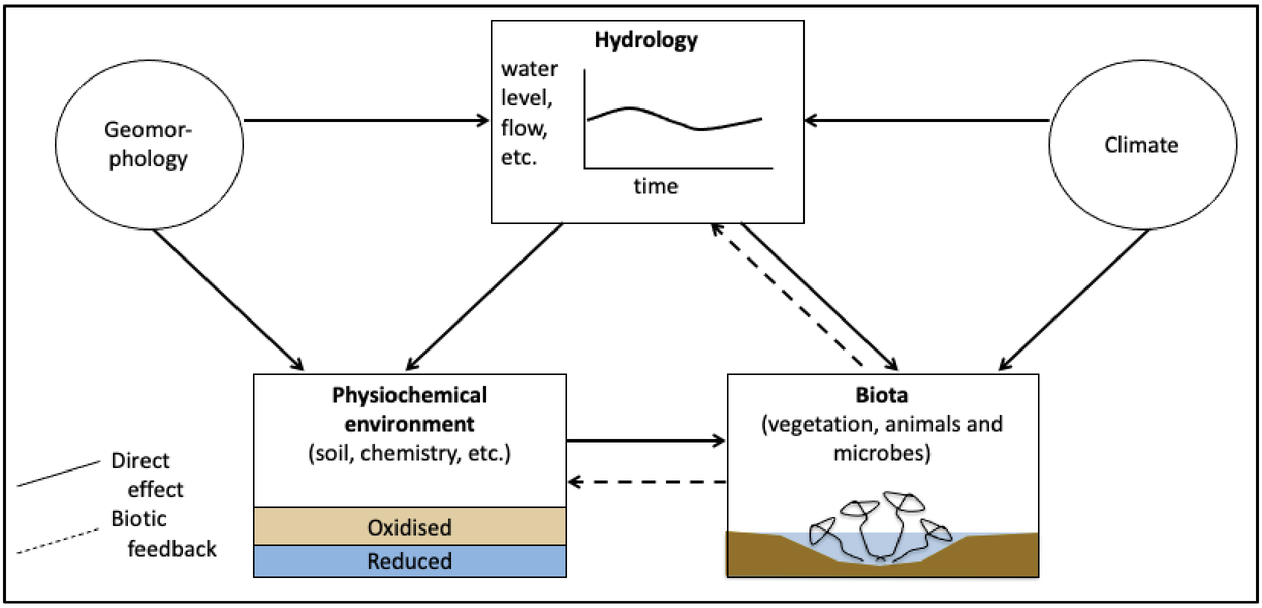

Figure 12-1. Defining wetlands based on hydrology, the physiochemical environment and biota (adapted from Mitsch and Gosselink 2000).

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
- To identify classification systems for inventory and mapping
- To provide evenness in concepts and nomenclature.

Box 39. Applications: Wetlands

BOX 39. Applications: Wetlands

(a) 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).

(b) Types of Wetlands

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)

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

(c) Wetland Classification and Delineation

Hydrogeomorphic Wetland Classification (HGM) System

	DISCIMINATORS		*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; Geology
Secondary discriminators	Dominant cover type	LEVEL 4: STRUCTURAL UNIT	Soils
Tertiary discriminators	Dominant life-form/ vegetation	LEVEL 5: HABITAT UNIT	Natural and artificial influences

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 cues and clues:

- Hydromorphic soils exhibiting characteristics due to prolonged saturation
- Hydrophytes (water-loving plants) present occasionally or more frequently
- High water table, causing saturation of the surface or shallow subsurface and anaerobic conditions in the upper 0.50 m of the soil
- Shallow clay or impervious layer in upper 0.50 m
- 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.

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Day et al. 2010; DWA 2005; Ewart-Smith et al. 2006; NWA 1998; RAMSAR 2006; SANBI 2009; Semeniuk and Semeniuk 1995; (b)

Some approaches to wetland delineation and classification are discussed in *Box 39*. 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.

Distinction is recommended between three types of systems based on:

- Level 1: 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); inland systems (permanently or periodically inundated or saturated; with no existing connection to the ocean)
- Level 2: the level of drainage and applies only to estuarine systems (permanently open or temporarily closed) and inland systems (non-isolated or isolated)
- Level 3: the landform and tidal discriminators
- Level 4: substratum, surface/ subsurface vegetation and/ or emergent vegetation, non-vegetated areas
- Level 5: 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, midslopes and footslopes as per *Figure 12-2* (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.

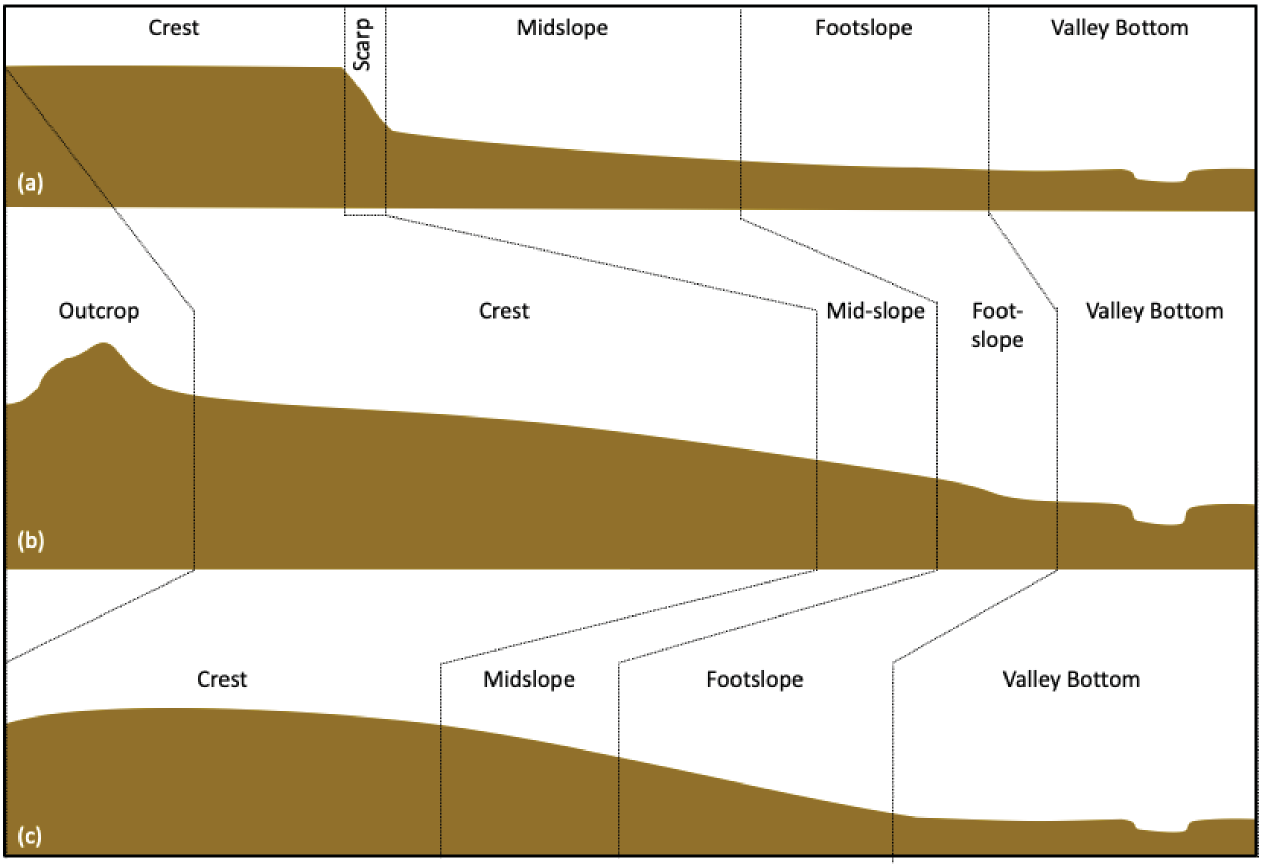


Figure 12-2. ***(a) Typical terrain units of wetlands (after DWA 2005) correlated to typical alternative landform units used in South Africa and based on the (b) southern and (c) central Kruger National Park (Venter 1986).***

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).

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. Given 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).

These indicators link closely to hydropedology, emphasising the importance of proper hydropedological assessments. Wetlands commonly pose important geotechnical issues for development and land use changes (e.g. Breedt 2014; Dippenaar 2014b,d), necessitating the need for proper delineation and understanding - even in unsaturated state.

12.2. Contaminant Transport and Aquifer Vulnerability

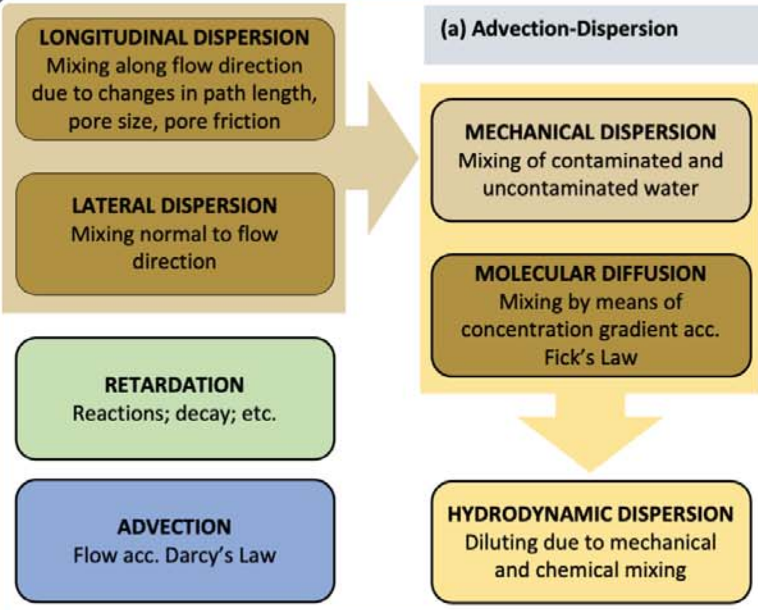
Contaminants refer to any compounds in concentrations above what is deemed natural, whereas pollution specifically imply levels of contamination with adverse effects to some receptor. As such, contaminant transport refers to the movement of any such contaminants through a variety of processes (*Box 40*). These contaminants can be released as single once-off sources (such as a spill), or gradually over prolonged periods (such as leaking pipes). They can furthermore be ***point sources*** where all the contamination is released at one position, or ***diffuse sources*** where the source of contamination is over a large area. Typical factors affecting water quality are shown in *Figure 12-3* and *Figure 12-4*.

When released on land surface or in the shallow subsurface, these contaminants have the ability to migrate to the groundwater through the vadose zone. The term ***aquifer vulnerability*** refers applied here, implying the protection offered by the vadose to the groundwater by contaminants released from surface. The thicker the vadose zone, the lower its hydraulic conductivity, and similar factors - all intrinsic properties of the vadose zone - are therefore imperative in protection groundwater while offering opportunity for natural attenuation (*Box 40*).

Box 40. Applications: Contaminant Transport and Vulnerability

BOX 40. Applications: Contaminant Transport and Vulnerability

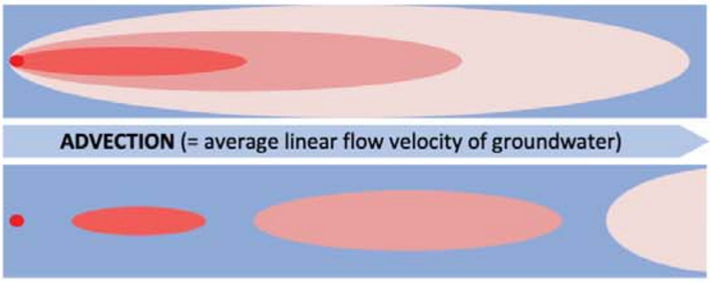
(a) Advection-Dispersion



Contaminants in groundwater move according to the average linear flow velocity of the groundwater. This is referred to as **advection** in contaminant transport. However, concentrations of contaminants can be mixed mechanically due to interruptions in the flow path **(dispersion)**, or chemically through balancing of concentration differences **(diffusion).** These cannot always be distinguished and are referred to as **hydrodynamic dispersion**. Various process, such as decay and sorption, can reduce concentrations of contaminants.

In the vadose zone, these processes still apply, albeit slightly differently. Advection may be slower at unsaturated hydraulic conductivities, and retardation may be higher due to natural attenuation processes such as bioaccumulation.

(b) Sources of Contaminants



Understanding the transport pathway depend on understanding the source.

Disposition of contaminants can be continuously or as a once-off release. The prior clearly pose higher risk as concentrations of contaminants do not dissipate with moving water as rapidly as with once-off sources.

Furthermore, sources can be point sources (typically leaks from pipes and tanks) or diffuse (such as pesticides or large land fills).

(c) Aquifer Vulnerability

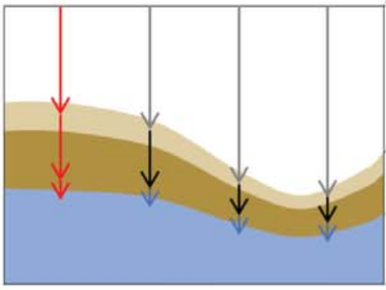
Protection of the aquifer depend on the ability of contaminants to be transported to the phreatic surface. It is, therefore, very important to be able to address these parameters.

Contaminants enter 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.).

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

READ MORE:
ADAPTED FROM: (b) Foster et al. 2002; Saaiman et al. 2007; Sililo et al. 2001

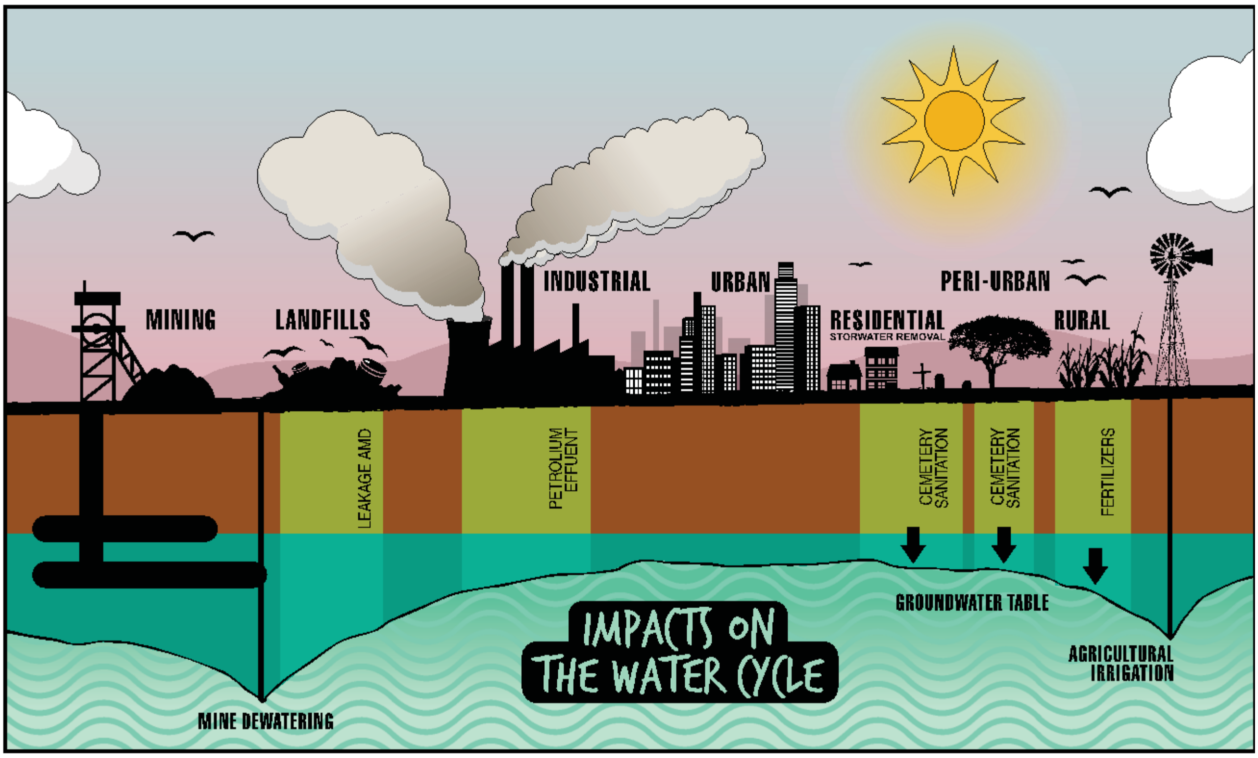


Figure 12-3. Anthropogenic Impacts on the water cycle (Dippenaar 2015).

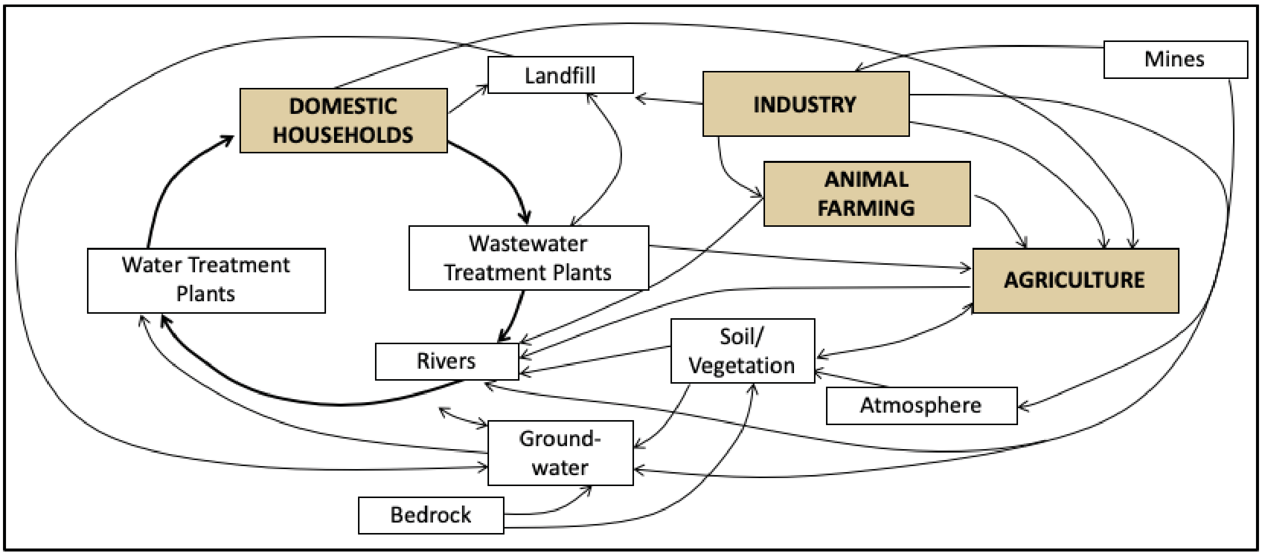


Figure 12-4. Influences on the water cycle and water quality (Balderacchi et al. 2013).

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. Advances in vulnerability assessments on karst terrain in South Africa are described by Leyland et al. (2006), Leyland and Witthüser (2010) and Van Rooy and Witthüser (2008), building on the method of Vías et al. (2003).

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 (load and the likelihood of contaminants entering the subsurface
- Aquifer protection through confining layers.

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

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.

13. Construction and Engineering Applications

13.1. Effects of Water in Construction and Engineering

Water affects all geotechnical and engineering applications. Some of the main purposes of these investigations are to identify the mechanical and geotechnical properties of the ground, and to infer likelihood and quantity of possible volume change. It is imperative that the influence of changing moisture contents on the engineering properties of the ground is identified during investigation. Some examples of water damage to infrastructure, as well as the impact of water on backfill and excavations, are shown in *Box 41*.

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.

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 causing 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 changing 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.

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).

SANS 634 (SABS 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.

Box 41. Applications: Geotechnics and Engineering

BOX 41. Applications: Geotechnics and Engineering

(a) Water Damage to Buildings

Increased Infiltration and Interflow 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.

Leaking Upslope Water Pipeline resulting in Failure of Retaining Wall
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, and water damage to paint and mortar in basement.



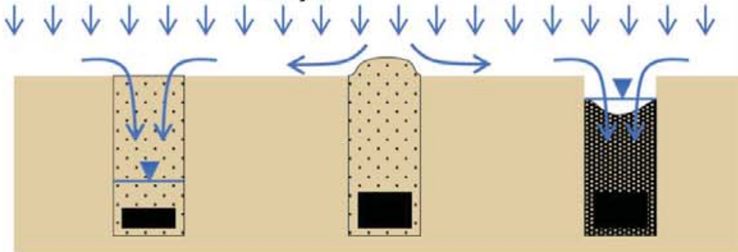

(b) Excavations and Backfill

RIGHT: Backfill compaction dictates infiltration into the ground. During and following construction or, in this instance, burial, backfill will affect the relationship between surface runoff and infiltration.

BELOW: Excavations can also fail due to weaker material underlying stronger material, an entire profile of low-strength cohesionless soil, and/ or reducing shear strength of soil due to wetting. These all should be duly identified during investigation so that appropriate solutions can be provided.

(left) Karoo Mudrocks (Middelburg Mpumalanga, 2016); mounded backfill

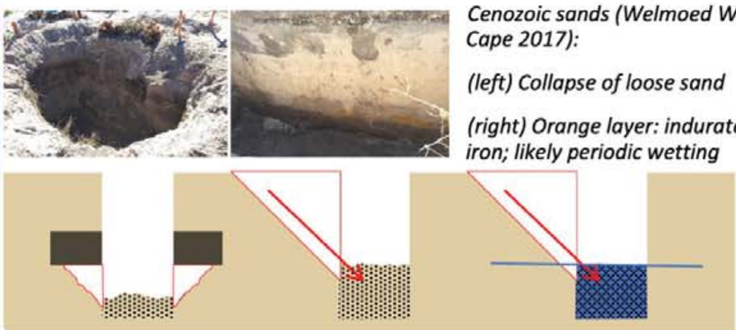
(right) Cenozoic Sands (Delft Western Cape, 2016); depressed backfill

Cenozoic sands (Welmoed Western Cape 2017):

(left) Collapse of loose sand

(right) Orange layer: indurated by iron; likely periodic wetting



Low-cohesion loose soil
Displaced dry soil
High-cohesion stiff soil
Displaced wet soil
Perched water table
Water movement
Soil movement

READ MORE:
ADAPTED FROM: (b) Dippenaar et al. 2019c
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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 (SABS 2009a;b).

Engineering geologists and geotechnical engineers relate soil moisture content to soil consistency (*Figure 13-1*). Referred to as ***Atterberg Limits***, these relationships are mostly applied to cohesive (clayey and silty) soils. 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 (Craig 1999; Das 2008; González de Vallejo & Ferrer 2011; Knappett and Craig 2012).

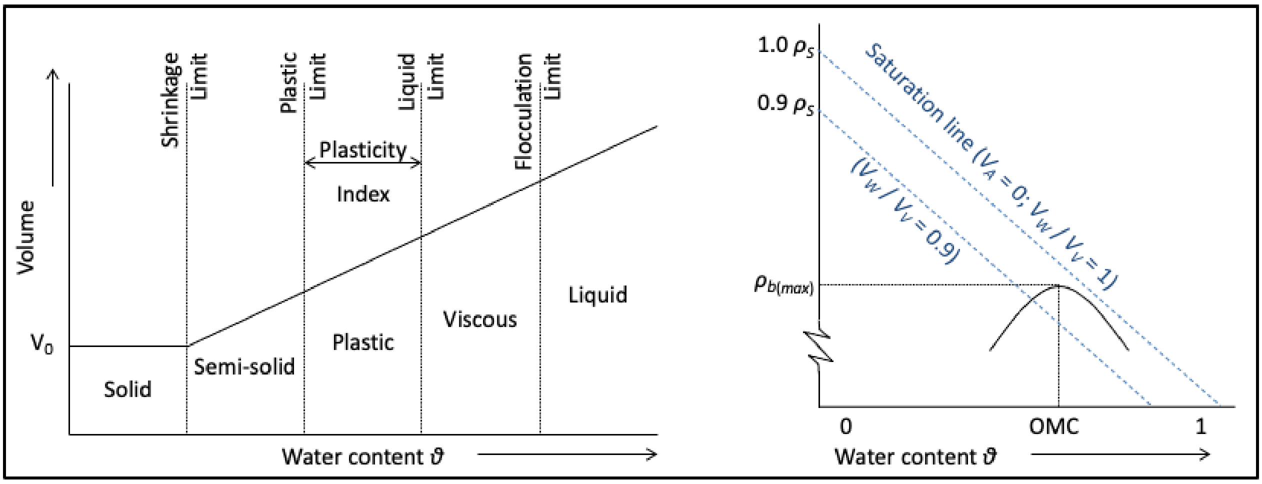


Figure 13-1. Important geotechnical parameters related to moisture content: Atterberg limits (left) and optimal moisture content (right).

The ***optimal moisture content*** (OMC) is also an important design parameter, and is that moisture content at which the soil has a maximum bulk density under constant compaction. It 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.

13.2. Problem Soils and Karst

Construction may involve problem soils (*Box 38*) where the soil may undergo volume change on changing load and/ or moisture content. Further problems may include, for instance, subsidence and sinkhole formation in soluble ground (Dippenaar et al. 2019a;b) and dispersive or erodible behaviour. The prior, subsidence and sinkholes, occur due to water ingress, groundwater lowering, or a combination of both (*Figure 13-2*), and is subject to investigation in accordance with SANS 1936 (SABS 2012a,b).

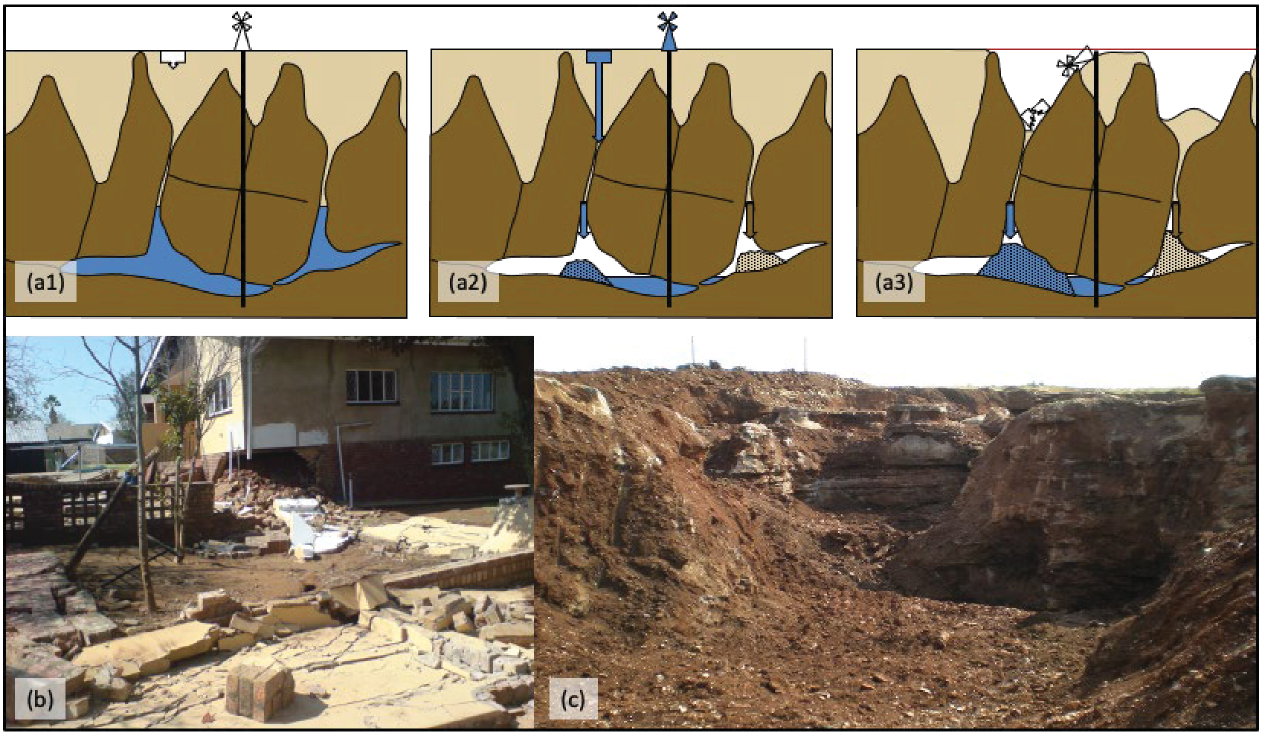


Figure 13-2. ***(a) Mechanisms of karst-related failure due (Dippenaar et al. 2019a;b); (b) damage to house due to sinkhole (in City of Tshwane in 2012; © MA Dippenaar; (c) sinkhole in Khutsong in shallow dolomite interlayered with chert (3 May 2018; © I Kleinhans).***

13.3. Excavations and Backfills

Excavations described during engineering geological or geotechnical investigations can supply substantial insight into how water will possibly affect the development, and what the stability of excavations will be. Recording of wetness and sidewall stability indicators during field investigation will already supply valuable insight for interpretation of results (*Table 13-1*). Coupled with this, the soil profile should be described to clearly identify discolouration (e.g. mottling), as well as whether the discolouration suggests good drainage, interflow, waterlogging, or other possible hydrological scenarios in the shallow subsurface (e.g. Box 31, Box 34, Box 35, Box 36, Box 38).

Table 13-1. ***Wetness indicators during engineering geological investigations (Dippenaar et al. 2019c).***

ID	Wetness (1)	Water Seepage (2)		Standing Water (3)		Stability (4)	
	Depth	Depth	Rate	Depth	Time	(Un-)Stable	Time
NOTES	(1) Depth from which the moisture content is very moist to wet, according to MCCSSO						
	(2) Depth of seepage, and estimation of seepage rate (slow, medium, fast, very fast)						
	(3) Depth of standing water in excavation, as well as time taken to fill to stated level (else immediate)						
	(4) Sidewalls stable or unstable, and time since excavation instability						

13.4. 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.

13.5. 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.

13.6. Construction Impacts on the Water Budget

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

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

14. Other Urban Applications

14.1. Urban Hydrology and Changing Land Use

Some distinct considerations related to development, 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 (interruption 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 addressing deteriorating urban water quality.

The role of subsurface water in urban development and urban water management is becoming increasingly important, highlighting the influences of changing groundwater levels and gradient under pumping, diversion or urban recharge, as well as important changes to groundwater quality (e.g. Seyler et al. 2019). Examples of relevance are shown in *Figure 14-1*.

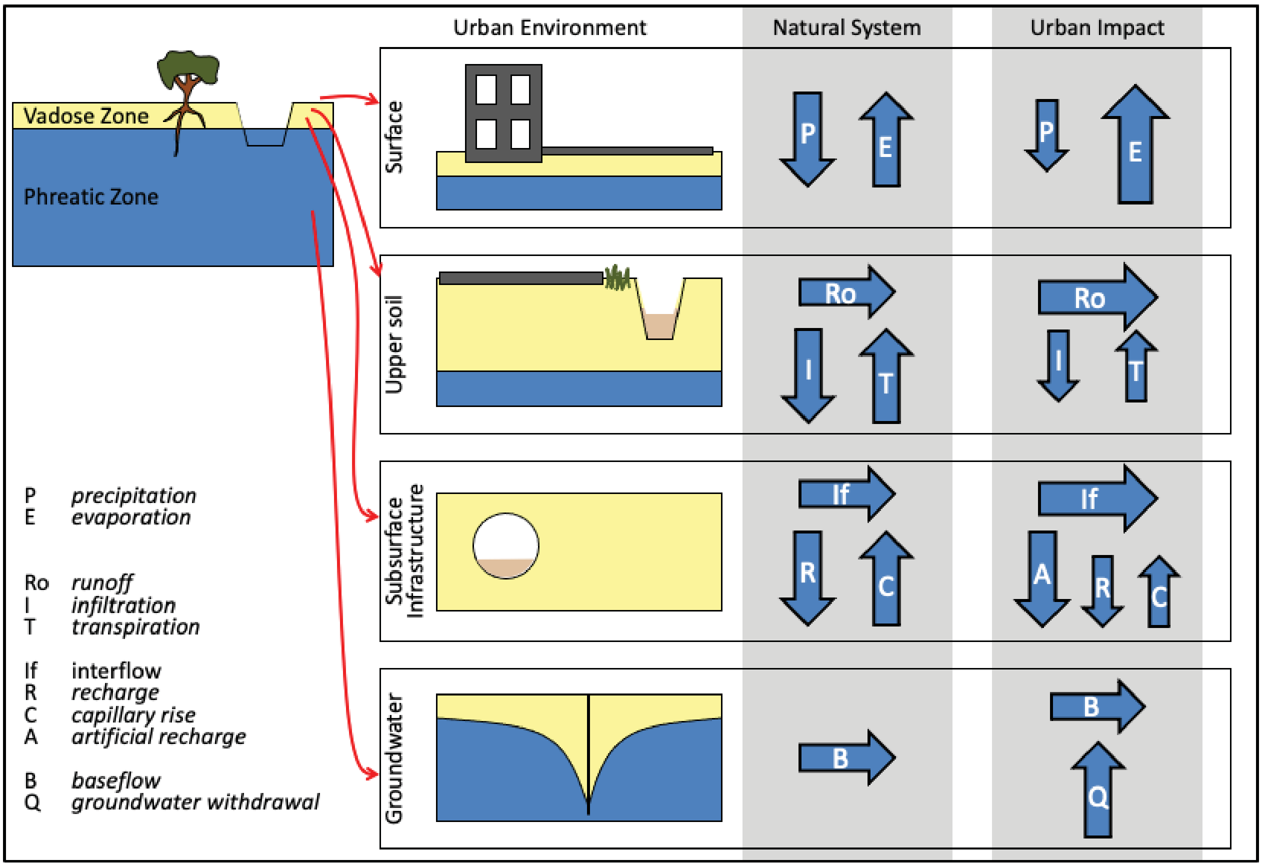


Figure 14-1. Impacts of the urban environment on water balance (arrows indicate modified or newly introduced water flows) (adapted from Schirmer et al. 2013).

14.2. Changing Vadose Zone Storage and Subsurface Water Budgets

Surface sealing reduces infiltration whereas water imports, leaking pipes and irrigation induces excess water on the surface and the subsurface. This implies that developments intrinsically affects the moisture budget of the subsurface during project life cycle (*Figure 14-2*). Further to this, urban water budgets are substantially altered by pumping of water from basements and tunnels, leaking pipelines, artificial groundwater recharge, and so forth.

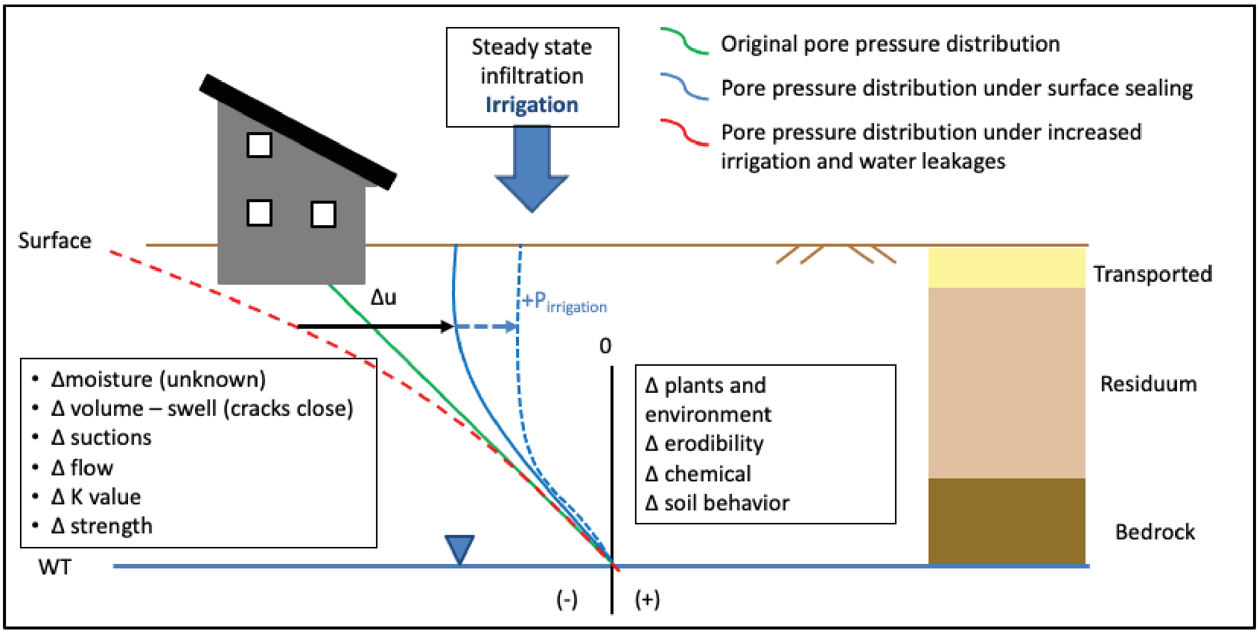


Figure 14-2. Hypothesised influence on subsurface pore water pressure distributions under developments entailing surface sealing and/ or increased water input.

14.3. Cemeteries

Burial occurs in the vadose zone, ideally only in areas where groundwater is deeper than 4 m. These are fairly low-risk developments in terms of water pollution given the likelihood of much more significant urban, industrial and agricultural sources of contamination in close proximity of burial space. Risks posed by cemeteries are described in extensive detail by Dippenaar et al. (2019c) and include the following:

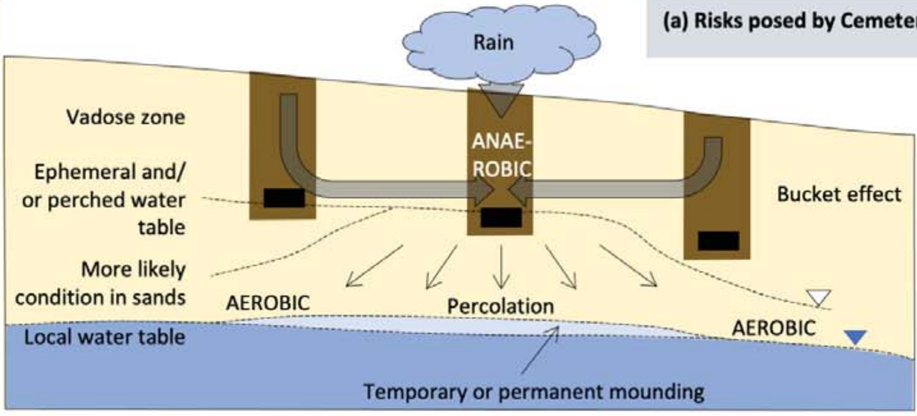
- Backfill of graves can generate hydraulic access through forming depressions on collapse of the coffin and settlement of the backfill material. This promotes water ingress and the flooding of the collapsed coffin, from where contaminants can mobilise for slow release deeper into the subsurface.
- Backfill of graves can induce surface runoff through forming mounds diverting surface water. This results in erosion and alters the subsurface water cycle.
- Contamination can result, although the body itself breaks down to water, carbon dioxide and calcium phosphates with very low risk of adverse effects. Main sources of contaminants are through medical implants such as pacemakers, jewellery, and cosmetics. More recently, endocrine disruptors, compounds from medicines, and pathogens associated with cause of death are becoming increasingly important.

Guidelines are present (Dippenaar 2014d; Dippenaar 2019c) to mitigate these risks and to allow adequate opportunity for on-site attenuation of contaminants. An overview of investigation for cemetery sites based on these guidelines are supplied in *Box 42*. Siting is, however, a concern, as excavation depth and residential encroachment are inevitable.

There exists the perception that cemeteries are low-risk compared to adjacent land uses, and they don't generally tend to be located near drinking water sources. Apart from contamination, cemeteries are easily overlooked as for the substantial manner in which they alter the interface between land surface and the shallow subsurface. Often these impacts are detected through altered subsurface flow not always anticipated prior to development.

Box 42. Applications: Cemeteries

BOX 42. Applications: Cemeteries



(a) Risks posed by Cemeteries

Risks mostly pertain around possible contamination and safety issues associated with the stability of the excavations. These risks are typically exacerbated by developing cemeteries on unsuitable land, or through not anticipating the impact of the cemetery development on the subsurface hydrological regime.

(b)	Contaminant	Mobility and Rate of Leaching	Persistence in Vadose Zone	Toxicity
M	Metals	Corrosion of interred materials Leaches out in months to years	Stored in vadose zone Years or more	Variable; chronic Occasionally carcinogenic
N	Nutrients	Source variable and not solely due to interment	Stored/ attenuated Months to years	Variable; chronic Organoleptic; non-carcinogenic
O	Organics	Embalming agents: days Lacquers, etc.: days to months	Days Highly variable	Variable Often carcinogenic
P	Pathogens	Interred body and environment Leaches in days to weeks	Variable: days to years *E.coli* days	Variable; acute to chronic Infectious disease

(c) Risk Assessment

Ranking is typically based on a scoring system to eventually supply an indication of site suitability. This is based on the following criteria:

Engineering Geological/ Geotechnical
Excavatability ease to 1.80 m
Stability sidewalls stable for prolonged periods
Workability material to be used as compacted backfill
Sanitary/ Environmental/ Hydrogeological
Water table thickness of protective vadose zone
Subsoil permeability preventing ponding and rapid infiltration
Backfill permeability preventing ponding and rapid infiltration

(d) Investigation Requirements per Site Area (hectares)

Summarized proposed requirement for the geotechnical and hydrogeological investigations are supplied based on size of proposed cemetery sites, in order to address the environmental impact assessment and water use license application requirements.

Geotechnical	≤ 5	≤ 10	≤ 20	≤ 50	≤100	>100
Test Pits; Profile (*/ha)	4-10 (2)	4-10 (1)	5-15 (0.5)	10-25 (0.5)	25-50 (0.5)	35-70 (0.35)
Foundation Indicators	4	4	6	10	15	20
Moisture-Density	4	4	4	5	6	10
Other	2	3	4	5	6	10
pH/ EC	4	4	4	5	6	10
Mineralogy	4	4	4	5	6	10

Hydrogeological	≤ 5	≤ 10	≤ 20	≤ 50	≤100	>100
Infiltration/ Percolation (*/ha)	4 (1.25)	4-8 (0.5)	4-10 (0.5)	8-15 (0.33)	10-20 (0.20)	10-40 (0.20)
Water Quality	1 upstream; 1 downstream; 1 other; within 2 km radius					
Hydraulic Tests	Preferably more than 1 appropriate phreatic test					

* See the latest guidelines by Dippenaar et al. for full requirements and explanations on the different data requirements.

READ MORE: Latest Guidelines: Dippenaar et al. 2019c

ADAPTED FROM: (© www.wrc.org.za) (a) Dent and Knight 1998; (a),(b) Dippenaar et al. 2014; Dippenaar 2014; (c) Hall and Hanbury 1990

14.4. Ground-based Sanitation

Ground-based sanitation options are numerous and generally fall within two broad types, namely:

- Pit latrines (such as the ventilated improved pit latrine or VIP) which are dry systems
- 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 10252-2 (SABS 1993) as per *Box 49*. The main considerations for such on-site ground-based 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.

14.5. Corrosion

Site materials affect the aggressiveness or corrosivity of the environment to different materials such as metals and cement (*Figure 14-3*). Improved understanding of the influences of different environmental factors on the corrosivity of different metals and cement can aid in better inferring which contaminants may likely mobilise, from which sources, and what rates. Additionally, knowledge about the corrosiveness of the site materials can aid in preventing damage to the integrity of manmade construction materials. Of importance is that many of these parameters work in a synergetic relationship, implying that the cumulative effect of more than one may exceed the effect of the sums of the individual parameters. Similarly, certain parameters can also cancel each other out to some extent, e.g. high alkalinity which should be corrosive to steel, but $CaCO_3$ that effectively slows down corrosion (e.g. Bhattaria 2013; Dippenaar et al. 2019; Van Allemann 2017; Van Allemann et al. 2019).

Parameter	**→ Increasing Corrosivity or Aggressiveness of Soils →**					
EC (S/m)	<0.0050: Essentially non-corrosive	<0.0100: Mildly corrosive	<0.0200: Moderately corrosive	<0.0333: Corrosive	<0.1000: Highly corrosive	>0.1000: Extremely corrosive
Soil type	Sand and gravel generally have lower EC: Generally less corrosive			Clay generally has higher EC: Generally more corrosive		
Saturation	<40% or 100%: Generally not aggressive to mildly corrosive				60-85%: Maximum expected corrosion rates	
pH	Soils with neutral pH are generally not very corrosive			Very acidic or alkaline: corrosive to steel Acidic (pH < 5.5): likely corrosive to concrete		

Figure 14-3. Influences on corrosivity of soils (Dippenaar et al. 2019c; adapted from Bhattaria 2013).

14.6. Permeable Pavements

With urbanisation, changes in precipitation intensity, ageing and leaking infrastructure, increased imports of water for increasing demands, and so forth come an increase in stormwater generated for already strained infrastructure. As such, more and more municipalities require for stormwater to be attenuated on-site in new developments. Apart from this, on-site storage of stormwater for irrigation and other uses is also increasing as part of efforts to reduce the use of treated water for non-domestic purposes.

This drive towards ***sustainable drainage solutions*** and ***water sensitive design*** has as one possible solution resulted in the increased use of permeable paving systems. Interlocking bricks are mostly used where the packing configuration dictates the percentage opening of the surface for infiltration. Recent results by Van Vuuren (2020) and Van Vuuren and Dippenaar (2021) are shown in *Box 43*.

15. LEAKAGE AND SEEPAGE

Preliminary work indicate that pressure testing in unsaturated state poses some substantial issues related to injection pressures and flow rates in fractures. Recent studies (Jones et al. 2019a,b,c) show that flow rates in unsaturated experiments mimicking Lugeon tests are not proportional to the cube of the aperture and a non-linear behaviour (in terms of the relationship between pressure and discharge) results.

Complexities in fracture geometry, coupled with highly variable fluid pressure-flux relationships under variable moisture contents caution as to the assumption of saturated state when conducting Lugeon or pressure tests, and to the implications of using test results and then altering saturation states after testing.

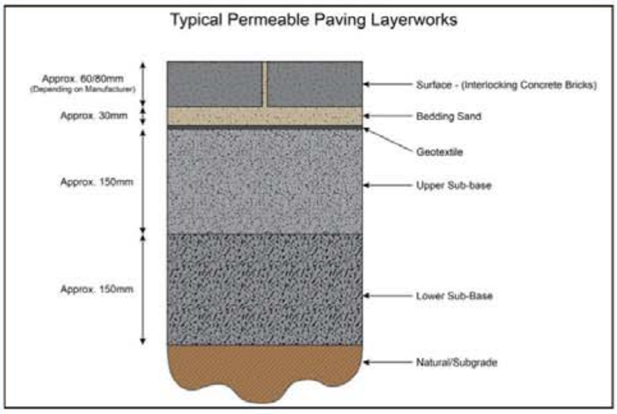
Box 43. Applications: Permeable Pavements

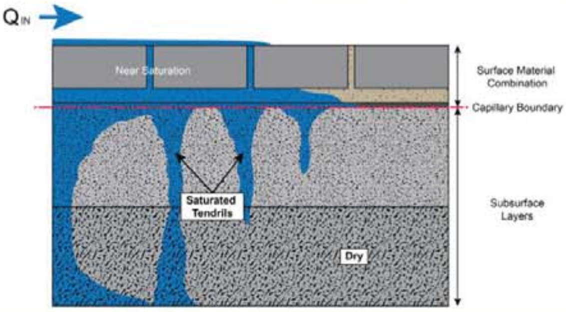
BOX 43. Applications: Permeable Pavements

(a) Permeable Pavements

Permeable pavements, including permeable interlocking concrete pavements (PICP), are used increasingly to mitigate stormwater onsite by promoting infiltration while reducing runoff. This reduces stress on urban stormwater systems while allowing groundwater replenishment or on-site storing of water in underground conservancy tanks. In the broader arena of water sensitive design.

(b) Layer Works and Flow



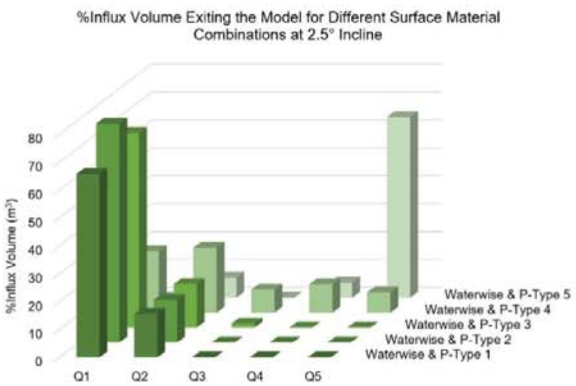


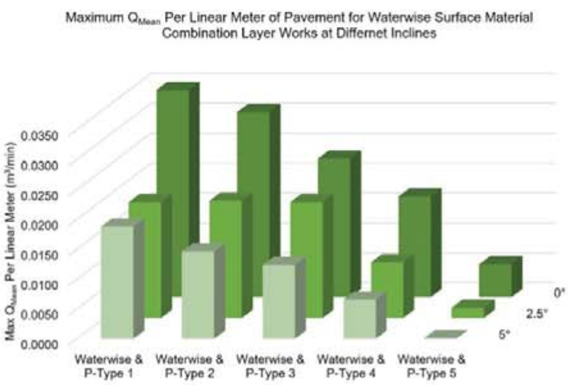
As any road pavement, PICP also has road layers to aid in distribution of the load while, in this instance, allowing drainage of infiltrated water. The natural subgrade (in situ mate will, however, dictate whether deeper percolation can occur at expense of induced lateral interflow.

(c) Performance Criteria

For the exact same configuration and incline, sand used as fill is the most important determinant in the infiltration. P-Type 1 to P-Type 5 represent sand for uniformly graded clean to well-graded sand, and Q1 to Q5 represent linear meters distance from the water source as volumes infiltrated into the pavement. The cleaner and more uniform the grading, the better the performance. Flatter gradients induce more infiltration as runoff is not induced by a sloping surface. However, once offset from horizontal, the influence of gradient is surpassed by that of the fill sand.

Interlocking orientation of the bricks do not affect infiltration. The percentage open space between the bricks, however, do, as do when the openings are clogged by, for instance, dust, precipitates, moss, and oil.





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All graphics and data: Van Vuuren 2020; Van Vuuren and Dippenaar 2020; materials from Bosun Group (Pty) Ltd; additional information: Lucke et al. 2014; USDA 2012

SECTION F: VADOSE ZONE ASSESSMENT

16. VADOSE ZONE ASSESSMENT PROTOCOL

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) is proposed, while 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.

It aims to provide an outline applicable to developments affecting the vadose zone. Through providing basic information input requirements in a logical sequence, the VZAP provides a process gradually increasing confidence and data by supplying tiers of information that consecutively increase detail and understanding.

16.1. Bias and Errors

Data obtained from the field are subject to a number of biases that can possibly affect the accuracy of the data and its applicability (*Box 44*). This can be in terms of sampling (describing materials) which are not representative of the actual material due to:

- The conditions of the exposure (e.g. selection bias), where, for instance, the sample is more weathered or disturbed due to the state of exposure, or where undisturbed soil samples are retrieved based on ease of removal rather than representation of the horizon
- The sample selection (e.g. selection bias), where different scales of measurement are employed, possibly censoring or truncating those measurements beyond the selected scale
- The limited extent of the exposure (e.g. sampling biases), where, for instance, a fracture's exposure is limited by the outcrop or borehole core length, or its spacing and frequency is misjudged.

This is exacerbated by having various possible inputs that can compound bias and error through acting in additive (1 + 1 = 2) or even cumulative (1 + 1 > 2) manner. In other words, making errors in field description, and sampling, and laboratory analyses, and modelling, and interpretation, all result in a compound bias and faulty recommendation.

16.2. 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.

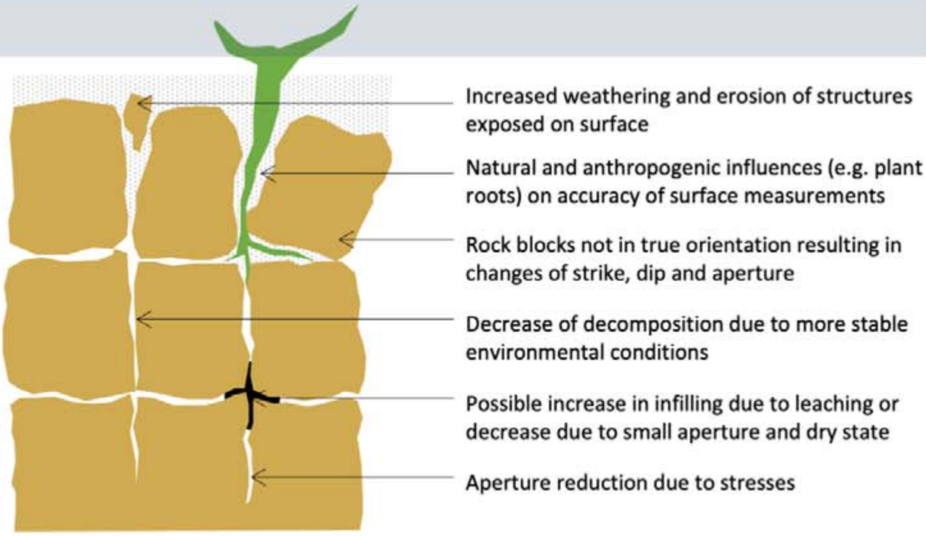
An example at hand is that urban development in karst land prone to subsidence will differ from a cemetery investigation affected by wetland conditions near surface drainage features or hillslope seeps. Even though the vadose zone critically affects both, the development and conditions will dictate the appropriate investigation techniques.

Box 44. Bias

BOX 44. Bias

(a) Bias

Sampling errors can be in terms of misrepresentation, e.g. where outcrops are disturbed and do not reflect the actual conditions, or scale, e.g. where measurements are variable based on the scale of measurement.



Different orientations of structures will be less represented than others in core. Vertical structures have a very low likelihood of being encountered, and may be completely disregarded. The same applies to structures parallel to the face of the outcrop being mapped.

(b) Sampling Bias of Scanlines

Orientation data of fractures are intrinsically biased based on collection technique. Borehole core or outcrop scanline mapping intrinsically apply a linear sampling technique, implying that statistical methods are often employed to reduce the bias. Sampling of these fractures imply describing them. This, in turn, require the fractures to be exposed and present in along the trace length.

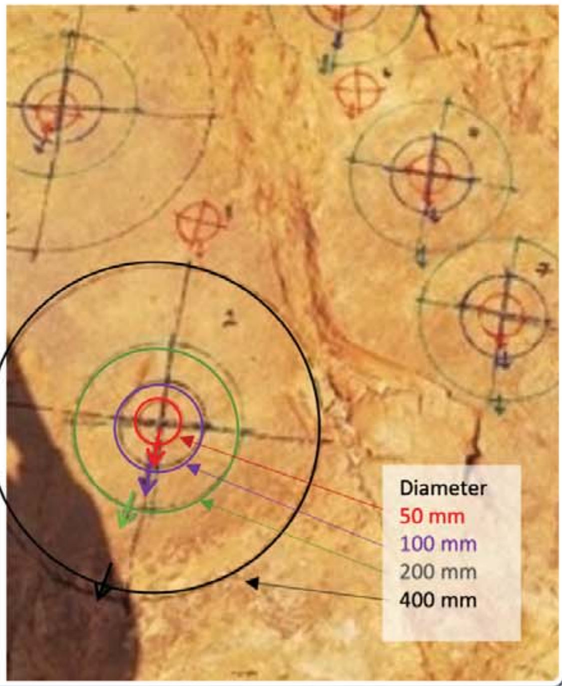
Some of the most prominent biases in the sampling of trace lengths include:

- **Orientation bias**: the relative orientation between the fracture and the outcrop dictates the probability of the fracture appearing
- **Size bias**: larger fractures and longer fracture traces are more likely to be sampled than smaller and shorter fractures.
- **Truncation bias**: short trace lengths are often difficult or impossible to measure.
- **Censoring bias**: very long fractures extend beyond the visible exposure and cannot be measured in full.

(c) Circular Scanlines

Circular scanlines, making use of circular disks with different diameters (), span roughness profiles based on the diameter and its relation to the wavelength and amplitude of the roughness profile. Differences in, for instance, dip and dip direction can be encountered due to the scale on which the defect is being described.

RIGHT: example from Daspoort Formation Quartzite in Pretoria (South Africa). Different diameters of circles were used to find the orientation of the same rough surface. Based on these sizes, different parts of the roughness profile were spanned, resulting in deviations in dip direction (indicated by arrows) and dip (not shown here) measurements. This highlights the importance of disclosing sampling methods.



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(b) Park & West 2002; Zhang & Ding 2010, from Einsten & Baecher 1983; Kutilake & Wu 1984; Priest 1993; Priest & Hudson 1981; (c) Mauldon et al. 1999; photo © MA Dippenaar

16.3. Cost-Ease-Benefit Screening

Efficacy of selected methods in quantifying hydraulic parameters can be judged by considering:

- **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.

Relative cost and effort are shown in relation to increasing data accuracy in *Figure 16-1*. 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.

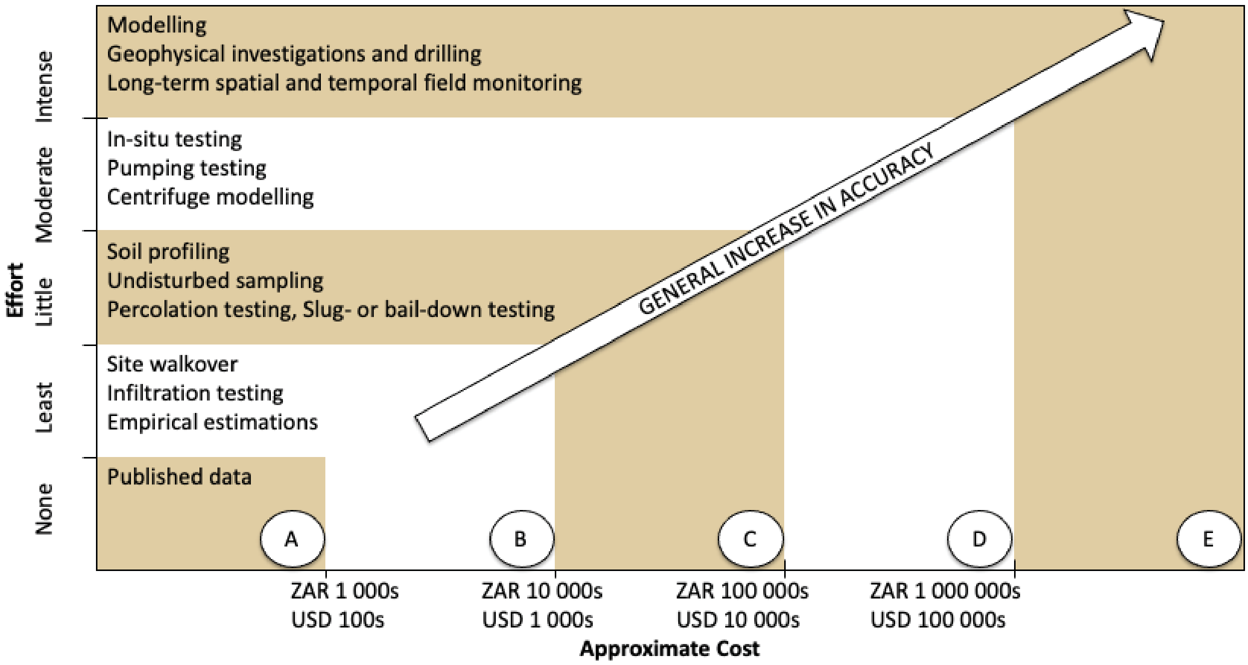


Figure 16-1. Relative cost-effort screen related to tiers of investigation.

Based on this, the tiered approach concluding this chapter 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.

16.4. 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, 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.

16.4.1. 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.

16.4.2. 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. Flow mechanisms and regimes play a part here as they fundamentally dictate if and, if so, how and where to moisture will move based on variable and changing moisture content.

16.4.3. 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.

16.5. Vadose Zone Assessment Protocol

The purpose of a Vadose Zone Assessment Protocol (VZAP) is (i) to ensure adequate data input (ii) in order to compile a conceptual earth system model that incorporates the 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 45* (with specific reference also to cemeteries and karst investigations) with elaboration in *Table 16-1*. 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.

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.

Each tier requires 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) re-evaluation 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.

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.

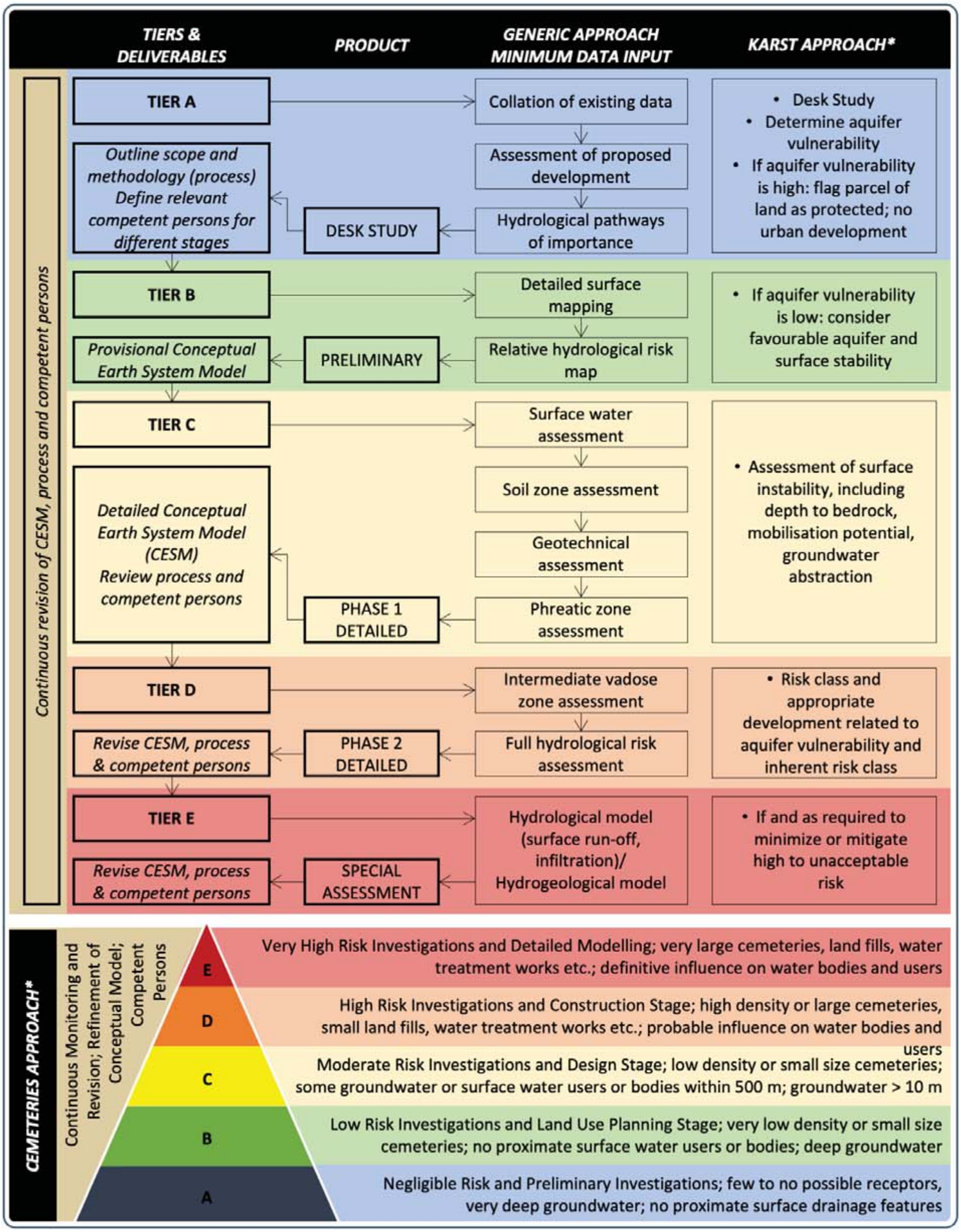
Tier C is adequate for low-risk developments or small-scale influences on the hydrological cycle. Intrusive testing, borehole testing and extensive disturbed and undisturbed sampling commence.

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.

Box 45. Vadose Zone Assessment Protocol

BOX 45. Vadose Zone Assessment Protocol



READ MORE: Generic approach: Dippenaar et al. 2014; this document

ADAPTED FROM: (© www.wrc.org.za) * Cemeteries approach Dippenaar et al. 2019c; Dippenaar 2014

Table 16-1. 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

16.6. 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.

In certain instances, special conditions exist to be considered competent, for example as a level 4 competent geo-professional in terms of SANS 1936 pertaining to dolomitic D4-classes.

16.7. 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 / www.iah.org.za)
- 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/)
- Geological Society of South Africa (www.gssa.org.za)

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

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APPENDIX A: BACKGROUND AND CASE STUDIES

17. About the Preceding Projects

The project emanated from a series of Water Research Commission funded projects related to vadose zone hydrology applied to engineering geology and hydrogeology:

- WRC K8/876 Preliminary Vadose Zone Classification Methodology (2009-2010) report K8/876
- WRC K5/2052 Vadose Zone Hydrology (2011-2014) report TT 583/13
- WRC K5/2326 Fractured Intermediate Vadose Zone (2014-2016) report in print
- WRC K5/2449 State-of-the-Art Cemetery Guidelines (2015-2018) report 2449/1/19
- WRC K5/2523 Karst Vadose Zone (2016-2019) report TT 779/19
- WRC K5/2826 Complex and Anthropogenically Altered Vadose Zone (2018-2021) this report.

The research outputs, mostly in the form of journal and conference contributions, are summarised in *Figure 17-1*.

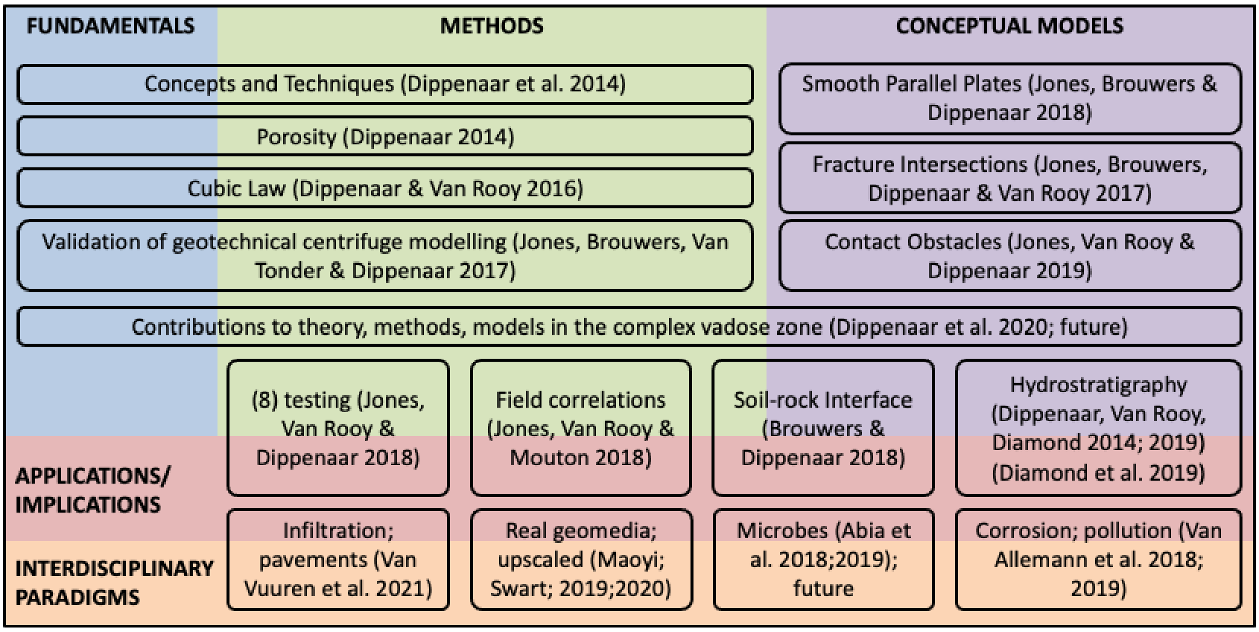


Figure 17-1. Summarised research outputs contributing to the development of the present research rationale on complexity and anthropogenic influences on the vadose zone.

18. About the Supporting Case Studies

Case studies forming part of this project and its build-up during the past ten years are summarised in *Table 18-1*. Masters and doctoral degrees are indicated as “Dissertations and Theses”, and papers published in peer-reviewed journals and proceedings are indicated as “Papers”. The “WRC No/ Report No” refers to the relevant Water Research Commission publication in which the full details of the project is presented.

This section aims to provide a glance into the experimental process, and to link the appropriate references to the work. Much of the content of this book emanates as new theory from these previous studies, and as such context to those are required. The aim is, however, not to duplicate studies already presented elsewhere in the academic literature. Findings from the case studies are presented as part of the main text of this book.

The study areas are labelled “VZSA” for “Vadose Zone Study Area”. In many instances this is arbitrary as deviation were inevitable through all these various projects.

Table 18-1. Case studies VZSA (Vadose Zone Study Area) and references to reviewed and examined data in WRC reports, UP masters dissertations ([M]), UP PhD theses ([D]), and journal papers).

No.	Title	WRC No/ Report No	Dissertation/ Thesis	Papers
VZSA01	Ephemeral Inland Wetlands (Midrand, Gauteng)	TT 584/13	Dippenaar 2014c[D]; Breedt 2014[M]	Dippenaar 2014b
VZSA02	Platinum Tailings Storage Facility (Bushveld Complex)	TT 584/13	Huisamen 2013[M]	Huisamen and Van Rooy 2012
VZSA03	Peri-urban Cemeteries (Temba, City of Tshwane)	TT 584/13	Dippenaar 2014c[D]	Dippenaar 2014d
VZSA04	Pollution from Accessory Burial Materials	2449/1/18	Van Allemann 2017[M]	Van Allemann et al. 2018; 2019
VZSA05	Flow along the Soil-Rock Interface	2449/1/18	Brouwers 2017[M]	Brouwers and Dippenaar 2019
VZSA06	Fontein Street Cemetery, Steve Tshwete LM	2449/1/18	Aphane 2019[M]; Mahlangu 2020[M]	Mahlangu et al. 2020
VZSA07	Cape Town Cenozoic Sand Cemeteries	2449/1/18	Schmidt 2021[M]	Abia et al. 2018
VZSA08	Microbiological Studies of Selected Burial Sites	2449/1/18	-	Abia et al. 2018; 2019
VZSA09	Hydrology & Geochemistry of a Dolomite Mine	TT 779/19	Van Staden 2020 [M]	*In preparation at time of completion*
VZSA10	Dolomite Bedrock	TT 779/19	-	Dippenaar et al. 2019a
VZSA11	Residual Dolomite and Wad	TT 779/19	Swart 2020[M]	Swart et al. 2019; Swart 2019
VZSA12	Facilitated Karst Dialogues	TT 779/19	-	-
VZSA13	Variably Saturated Fracture Flow	K5/2326	Jones 2019c[D], Segole 2017[M]; Maoyi 2019[M]	Jones et al. 2017; 2018; 2019a; 2019b; 2020; Segole and Van Rooy 2017
VZSA14	Lugeon Testing at De Hoop Dam	K5/2326	Jones 2019c[D]	Jones et al.
VZSA15	Permeable Pavements	K5/2826	Van Vuuren 2020[M]	Van Vuuren et al. 2021
VZSA16	Urban Karst Systems (Natalspruit)	K5/2826	-	*In preparation at time of completion*
VZSA17	Saprolite and Residuum	K5/2826	-	*In preparation at time of completion*
VZSA18	Microbial Tracers	K5/2826	-	*In preparation at time of completion*
VZSA19	Conceptual Models	K5/2826	-	Dippenaar and Van Rooy 2014; 2015; Dippenaar et al. 2019; Diamond et al. 2019
*	Transdisciplinary Contributions	K5/2826	-	Dippenaar 2012; 2014b; 2014d; Dippenaar and Van Rooy 2019; Diamond et al. 2019; Dippenaar et al. 2020

18.1. VZSA01: Ephemeral Inland Wetlands (Midrand, Gauteng)

Contributions

WRC Report: Dippenaar et al. 2014 (TT584/13)

Publications: Dippenaar 2014b; Dippenaar and Van Rooy 2014

Qualifications: Dippenaar 2014c; Breedt 2014

Links within this report: *Box 36*; *Box 39*; *Figure 19-1*

Background

An excavated hillslope seep through Lanseria Gneiss in Johannesburg (South Africa) provided a glimpse into the workings of an interflow system in honeycomb ferricrete formed in residual tonalite. As a consequence the excavation flooded, rendering the development implausible and ceasing all earthworks. Present guidelines and geotechnical zones described as marshy identified the area as a wetland. 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.

The study conducted by the project team entailed mineralogical and chemical analyses of soil and rock that, coupled with bulk densities, could be interpreted to porosities. Coupled with detailed soil profile description and field hydraulic tests, a conceptual model was devised for the flow through the system (*Figure 18-1*).

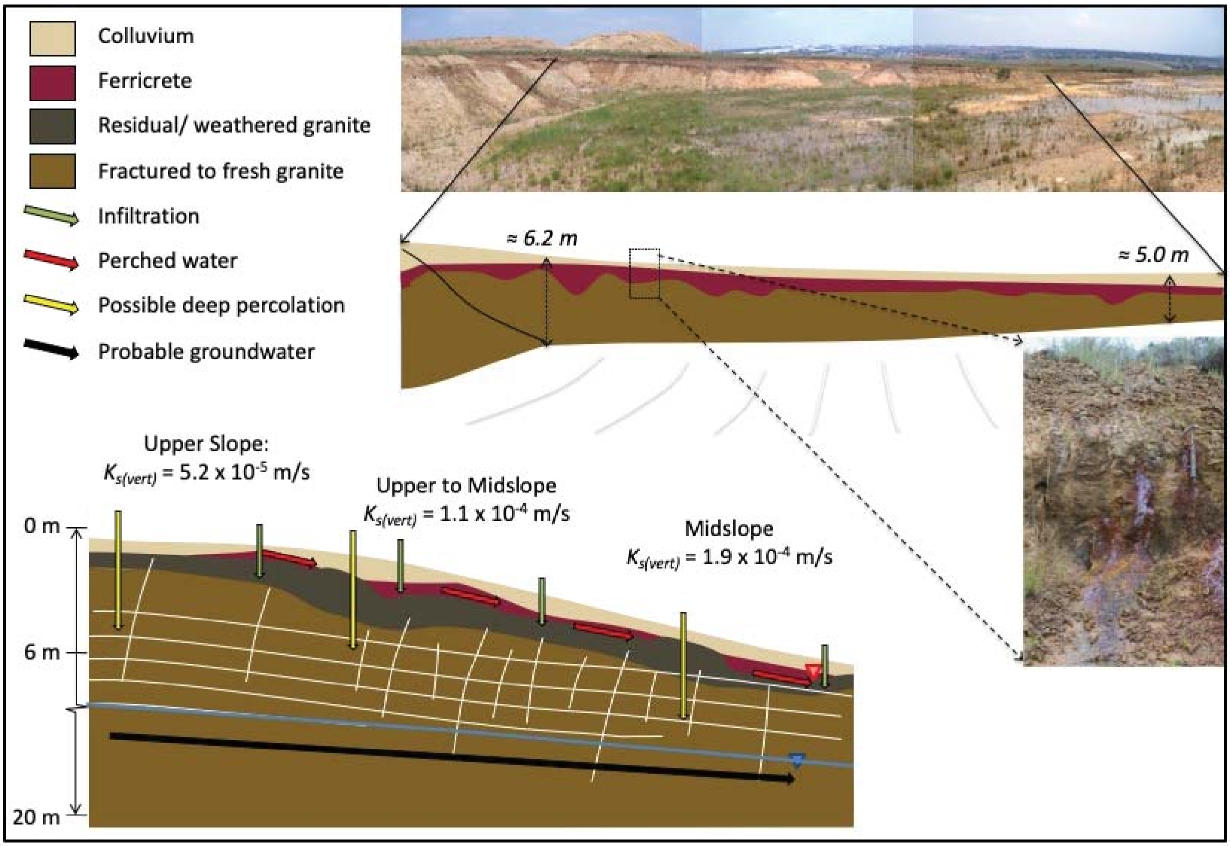


Figure 18-1. VZSA1: view and conceptual model of the Randjesfontein wetland.

Main Findings and Outcomes

- Porosity was calculated by means of Istomina's method, and through mineral and bulk density relationships. Various grading-based empirical approaches used these porosities to estimate saturated hydraulic conductivity. Empirical methods apply to very distinct ranges of materials (typically uniform sands) that 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.
- 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. Lateral dispersion of water from the test hole is inevitable.
- Chemical methods (e.g. XRD) significantly to the understanding of the chemical processes, notably pedogenesis and clay movement. This improve understanding fg weathering processes, the geological model, and hillslope hydrology. XRD, furthermore, contributed to the increased understanding of the porosity of the various materials, supplying significantly more realistic values for further use.
- It is imperative to better conceptualise the spatial movement of moisture in the vadose zone, and not solely the vertical movement thereof.

18.2. VZSA02: Platinum Tailings Storage Facility (Bushveld Complex)

Contributions

WRC Report: Dippenaar et al. 2014 (TT584/13)

Publications: Huisamen and Van Rooy 2012

Qualifications: Huisamen 2013

Links within this report: -

Background

The study involves a tailings storage facility (TSF) situated on a mine between Steelpoort and Mashishing in Mpumalanga Province. It is underlain by the Critical Zone of the Bushveld Igneous Complex and is presently developed as an active mine with large tailings storage facilities.

The TSF comprises material graded at -86 µm and of mafic to ultramafic nature. 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. A generalised hydrogeological profile were developed based on available information and was classified into two aquifer systems viz. a shallow, weathered aquifer system and a deeper, fractured rock aquifer system.

Profiles of the tailings were described and sampled by means of direct push probe sampling.

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 water samples for ICP scans.

A falling head permeameter test was conducted on the tailings material, and pumping tests were conducted.

Main Findings and Outcomes

- 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.

18.3. VZSA03: Peri-urban Cemeteries (Temba, City of Tshwane)

Contributions

WRC Report: Dippenaar et al. 2014 (TT584/13); Dippenaar et al. 2019c (2449/1/18)

Publications: Dippenaar 2014d

Qualifications: Dippenaar 2014c

*Links within this repor*t: *Box 42*

Background

The Temba Cemetery is situated in Temba, directly west of Hammanskraal, in the northern suburbs of the City of Tshwane, Gauteng. It is underlain by the Hammanskraal Formation of the Ecca Group and is composed of medium- to coarse-grained immature sandstones.

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.

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.

Soil profile descriptions and visual evidence of water seepage were collated to combine a 250-long conceptual model of the site. 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 18-2*).

Main Findings and Outcomes

- 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.

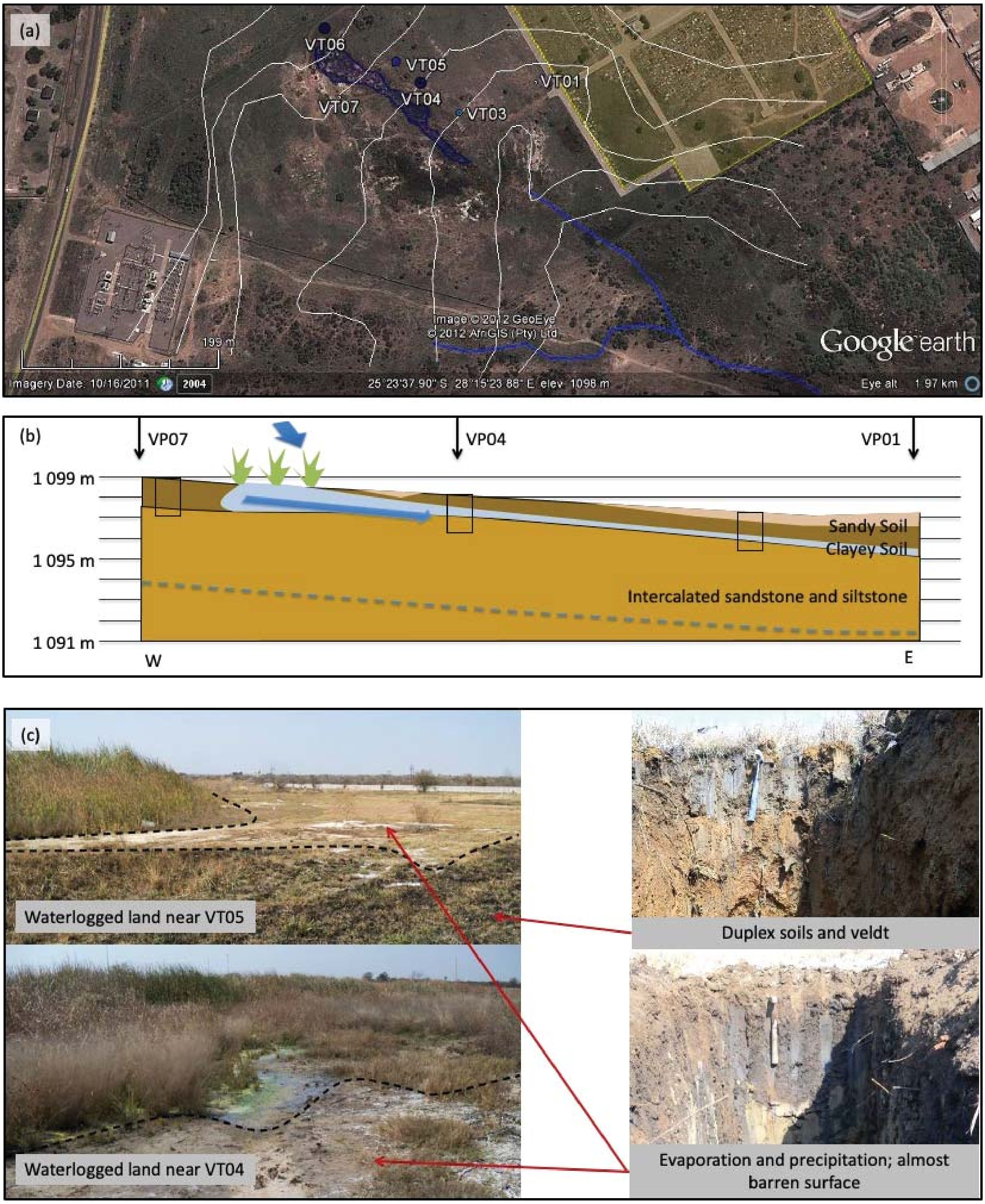


Figure 18-2. VZSA3: (a) Surface elevation, present cemetery (yellow), surface drainage (blue) and sampling positions indicated on Google Earth™ imagery (2013); (b) conceptual model; and (c) view of the site.

18.4. VZSA04: Corrosion of Accessory Burial Materials

Contributions

WRC Report: Dippenaar et al. 2019c (2449/1/18)

Publications: Van Alleman et al. 2018, 2019, 2014d

Qualifications: Van Alleman 2017

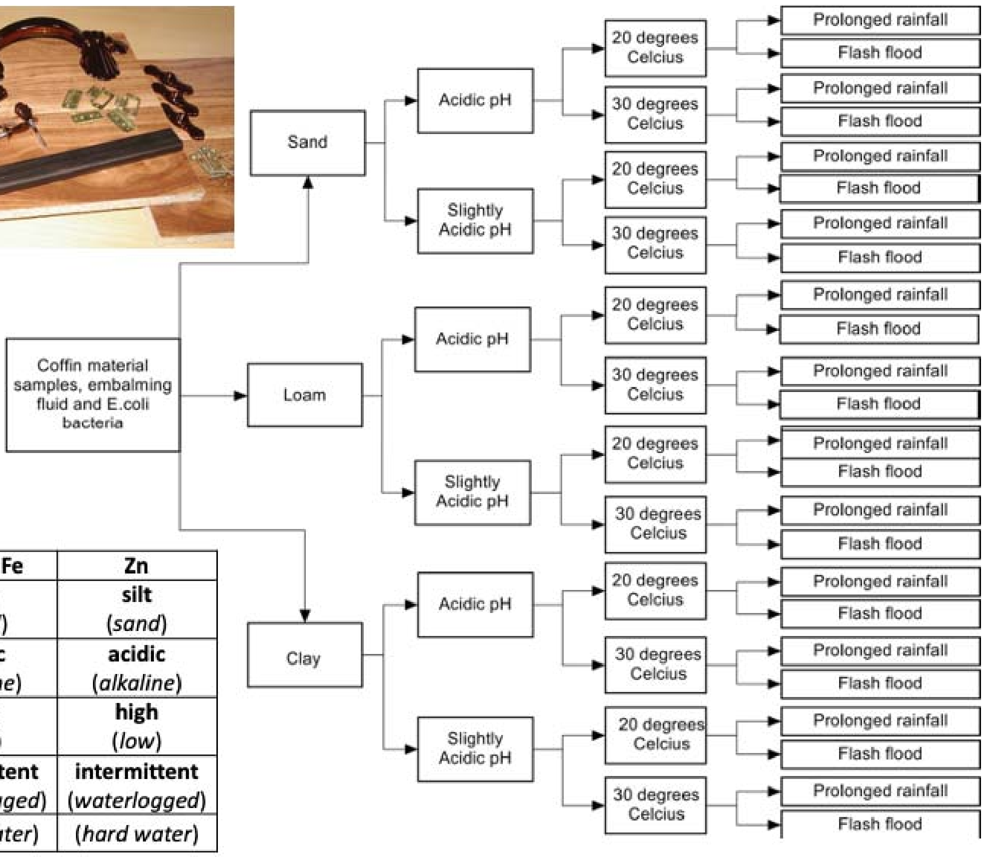
Links within this report: *Box 42*

Background

How coffin materials corrode contributes to the possibility of contamination from cemetery sites. In addressing this, the influence of variable moisture and climate on corrosion of common metals used in the fabrication of coffins is evaluated in controlled laboratory environments with materials supplied from reputable undertakers. Controlled experiments were conducted as per *Figure 18-3*.

(a)

(b)



(c)

	Al, Cu, Fe	Zn
Soil type	**clay** (*sand*)	**silt** (*sand*)
pH	**acidic** (*alkaline*)	**acidic** (*alkaline*)
Temperature	**high** (*low*)	**high** (*low*)
Wetting	**intermittent** (*waterlogged*)	**intermittent** (*waterlogged*)
Hardness	(*hard water*)	(*hard water*)

Figure 18-3. VZSA4: (a) Accessory coffin materials tested; (b) experimental planning; (c) key findings (bold - inducing; italics - retarding).

Main Findings and Outcomes

- Formaldehyde persists in soil and slowly percolates through the soil for periods of at least 14 weeks.
- In general, metal corrosion and mobility are increased by fine-textured soils, low pH, high temperature, and intermittent wetting.

18.5. VZSA05: Flow along the Soil-rock Interface

Contributions

WRC Report: Dippenaar et al. 2019c (2449/1/18)

Publications: Brouwers and Dippenaar 2019

Qualifications: Brouwers 2017

Links within this report: *Box 29*; *Box 30*; *Figure 10-1*

Background

In terms of hydrological risk, it is imperative to assess the movement of water from a soil material into fractured rock at partial water saturation. This is done in conjunction with other Water Research Commission projects, and addresses the very important hydrological processes occurring as water (possibly contaminated from, for instance, cemetery sites) passes from soil into fractured bedrock. Whether the coffin is placed above the soil-rock interface in the soil material, or on the contact itself (as excavation conditions will likely be too hard for placement within bedrock alone), will have fundamental implications on the possible flow mechanisms and directions in the subsurface.

Laboratory models were constructed using pluviated sand and acrylic sheets under geotechnical centrifugal acceleration. Visual observations qualitatively represent the various flow mechanisms as functions of time, saturation and water supply (*Figure 18-4*).

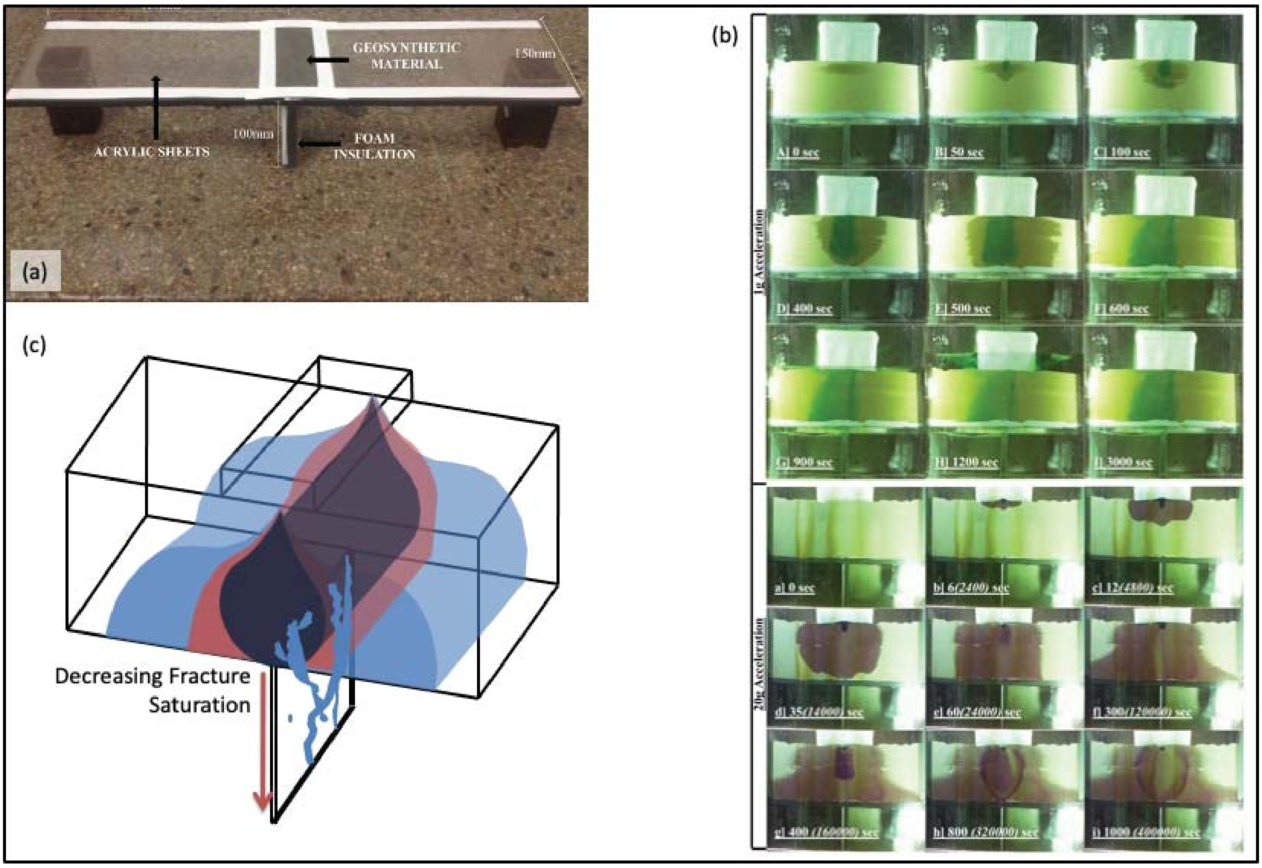


Figure 18-4. VZSA4: (a) Acrylic model of fracture; (b) experimental results showing dispersion in sand overlying single vertical fracture; (c) conceptual model of dispersion and flow mechanisms in fracture.

Main Findings and Outcomes

- Water flow from soil into a single rock fracture depicts the complex flow mechanisms occurring as water from a dispersion plume in soil enters fractured rock. Here, flow occurs in aerated state and at highly variable rates depending on the level of saturation. Progressive rewetting of the so-called dispersion plume in the soil (indicated by red and black) eventually allows a capillary barrier above the fracture to breach, allowing water entry into the fracture. Water movement in the fractured system is then intrinsically different from the soil system.
- Further complexity results in fractured systems where fracture orientations change over fracture intersections. In general, horizontal fractures are easier to saturate, whereas vertical fractures will drain more quickly at lower rates of saturation.

18.6. VZSA06: Fontein Street Cemetery (Steve Tshwete Local Municipality)

Contributions

WRC Report: Dippenaar et al. 2019c (2449/1/18)

Publications: Mahlangu et al. 2019

Qualifications: Aphane 2019; Mahlangu 2020

Links within this report: *Box 42*

Background

The Fontein Street Cemetery (henceforth Fontein St) management has noted issues related to flooding of graves and the close proximity of a drainage channel to the site. Coupled with a landfill on an adjacent property, the dense residential development around the site, and the need for additional land for burial in the municipality, access was granted for investigation of Fontein St. The first burial took place in 1959 and approximately 32 846 graves were recorded until 2015. The site is bounded by a historic landfill that is presently used as a sports ground. Residential development occurs to the east, and a drainage channel and open veldt are found to the west and north.

A number of shallow monitoring wells were installed to observe the movement of shallow water. These levels and water quality were monitored together with hydrocensus boreholes and stream water. Water samples collected were analysed for general chemical parameters as well as isotopes.

Main Findings and Outcomes

- Using absolute best-case and worst-case scenario data acquired during the site investigation, the site can be ranked as unacceptable (mostly due to engineering or mechanical constraints) to very good for development as a cemetery. The sensitivity of the existing cemetery suitability ranking systems to personal bias is highlighted.
- Shallow interflow and a proximate drainage channel contribute to possible water-related issues at the site. Understanding is improved regarding interflow systems through anthropogenically altered areas.
- Backfill material was highlighted as a problem here where cohesive soils form mounds over graves that can affect stormwater and erosion.

18.7. VZSA07: Cape Town Cenozoic Sand Cemeteries

Contributions

WRC Report: Dippenaar et al. 2019c (2449/1/18)

Publications: Schmidt and Dippenaar (under review)

Qualifications: Schmidt 2021

Links within this report: *Box 42*

Background

The Cape Town Cenozoic Sand Cemeteries is facing special issues with respect to drainage and stability of graves excavated in Cenozoic sand deposits. The Maitland, Welmoed and Delft cemeteries form part of this combined study, looking at the flow and contaminant transport through the unconsolidated sands.

The purpose of the study is to investigate the fate and transport of various contaminates within the Cape Flats Aquifer. Welmoed Cemetery was as contaminants are potentially not solely derived from the cemetery, but also possibly from proximate agricultural, industrial and animal-related industries.

Welmoed Cemetery is approximately 94 hectares in spatial extent and is located in Eerste Rivier (Western Cape) approximately 30 km east of Cape Town. A small piggery is situated directly to the north, and informal settlements are found further to the north. Agricultural land, predominantly vineyards, is found to the east, and the residential area Penhill Estate is located to the south. To the east of Welmoed Cemetery, along Van Riebeeck Road, is an industrial area comprising liquid petroleum gas storage and distribution and a vehicle transport and storage facility.

Field work entailed soil profiling, installation of monitoring wells, sampling for major chemistry and microbiology, and conducting of on-site infiltration and percolation tests.

Main Findings and Outcomes

- Using absolute best-case and worst-case scenario data acquired during the site investigation, the site can be ranked as unacceptable (mostly due to shallow water seepage and expected excavation instabilities) to satisfactory for development as a cemetery. This further highlights that site suitability ranking can be biased.
- Shallow interflow and a proximate drainage channel contribute to possible water-related issues at the site. Proximate residential and commercial developments and the old municipal landfill upslope of the site may contribute to water quality issues.
- Excavation stability was highlighted here as sidewalls tend to collapse under increasing moisture content.

18.8. VZSA08: Microbial Contamination of Selected Burial Sites

Contributions

WRC Report: Dippenaar et al. 2019c (2449/1/18)

Publications: Abia et al. 2018, 2019

Qualifications: -

Links within this report: *Box 42*

Background

Monitoring the changes in microbial communities as well as the presence or absence of pathogens in soil samples from cemeteries, can serve as an early warning system of the possible negative impacts of cemeteries on the environment, groundwater, grave diggers and cemetery workers. The microbial content of soil is a reflection of a number of parameters including land use activity, which cause subtle changes over time in microbial populations. High through put screening provides an opportunity to conduct detailed microbial community analysis of cemetery soil samples and associated water bodies to determine if the same organisms are identified in both water and soil as well as if there are relationships between sampling depth (surface and burial) and microbial composition.

The microbiological component of this work consisted in investigating if cemeteries could contribute to the pollution of groundwater. The experiments in this section consisted of culture and molecular (metagenomics). Study sites included those previously discussed, viz. Fontein Street Cemetery the Cape Town Cenozoic Sands Cemeteries study.

Main Findings and Outcomes

- *E*. *coli* was detected in water samples collected at depths of 2.3 m which is deeper than the burial depth of 1.8 m. This could imply the possible movement of microorganisms from decaying bodies down into surrounding groundwater bodies especially in areas like Maitland where water was detected at depths of 1.7 m (< 1.8 m).
- A rich microbial diversity was also found at a depth of 2 m for both cemeteries. This depth is approximately the burial depth of 1.8 m. Of importance is the fact that some of the microorganisms isolated have also been found to be of clinical importance.
- Microbial tracers could in future assist in better understanding subsurface flow and potential contamination.

18.9. VZSA09: Hydrology and Geochemistry of a Dolomite Mine

Contributions

WRC Report: Dippenaar et al. 2019b (TT 779/19)

Publications: -

Qualifications: Van Staden 2020

Links within this report: *Box 9*

Background

The Mooiplaas Dolomite Mine is situated with the northern portion of the pit underlain by Eccles Formation chert-rich dolomite and the southern portion by Lyttleton Formation chert-poor dolomite. A northwest-southeast striking syenite dyke furthermore divides the pit into a western section in the Aalwynkop Dolomite Compartment and the eastern section in the Laudium Dolomite Compartment.

Geochemistry and isotopes were employed to infer movement of water through the subsurface. This, as well as rock mechanical and structural geological field description of the dolomite mine and the geomechanical properties of the wad and bedrock at the site, will allow for a detailed geological, geomechanical and hydrogeological conceptual site model to improve understanding. Water levels were monitored, and some pumping tests, infiltration tests and percolation tests were also conducted around the pit.

Main Findings and Outcomes

- Compartmentalization by doleritic dykes affect water movement through the mine, acting as barriers to flow
- Nitrate concentrations are elevated as a consequence of blasting
- Sewage contamination was detected in surface drainages, without any noteworthy indication of elevated nitrate levels
- Interaction between the pit water and the aquifer are much more evident than interaction between the pit water and the proximate surface water.

18.10. VZSA10: Dolomite Bedrock

Contributions

WRC Report: Dippenaar et al. 2019b (TT 779/19)

Publications: Dippenaar et al. 2019a

Qualifications: -

Links within this report: *Box 9*; *Figure 13-2*

Background

The initial intention was to relate bedrock mineralogy with that of the soils and the different lithological units. Some analyses have been conducted, and is yet to be published.

18.11. VZSA11: Residual Dolomite and Wad

Contributions

WRC Report: Dippenaar et al. 2019b (TT 779/19)

Publications: Swart et al. 2019

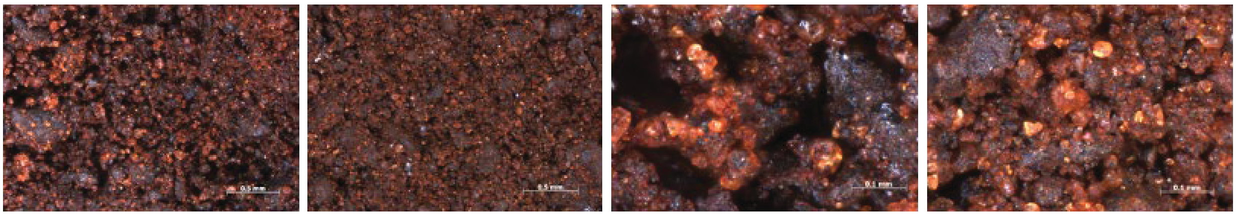
Qualifications: Swart 2019

Links within this report: *Box 9*; *Box 30*

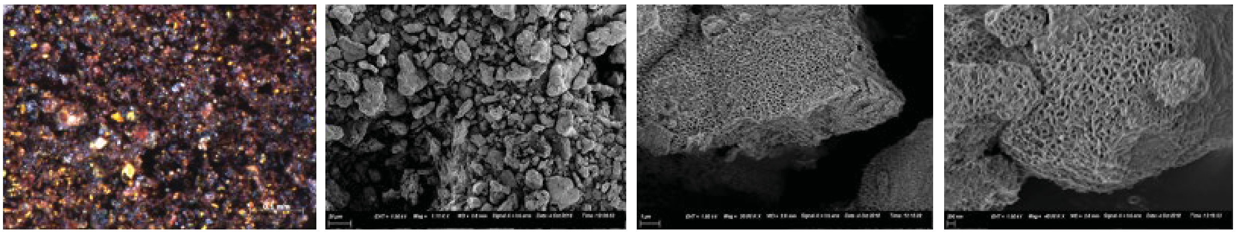
Background

This study aimed to improve understanding regarding the geomechanical and hydrological behaviour of wad in relation to the geochemical composition and the microstructure, and to determine the limits of geotechnical testing on this material. The structure and properties of wad are highly dependent on the parent material's stress history and the history of the soil itself.

Sampling entailed various undisturbed and disturbed samples of residual dolomite and wad from known formations across South Africa. A number of tests were conducted to expand the understanding of residual dolomite, including dispersion, grading, Atterberg limits, chemical analyses, triaxial shear and permeability, and field and lab permeability tests, along with photographs of the soil taken at various magnitudes (*Figure 18-5*).



Stereomicroscope images of the Mooiplaas samples pre- and post-triaxial undrained testing. Left to to right: Undisturbed sample at x20 magnification; undisturbed sample at x94 magnification; post testing at x20 magnification; post testing at x94 magnification.



Stereomicroscope image of the Doornhoek samples. Left: x94 magnification.
SEM of Doornhoek silt-size aggregates at x1000 magnification; x20000 magnification; and x40000 magnification.

Figure 18-5. VZSA11: Stereomicroscope images of residual dolomite and wad.

Main Findings and Outcomes

- Improved data pertaining to the hydraulic and mechanical behaviour of residual dolomite and wad imply that better estimates are now available for permeability, soil suction, void ratio (or porosity), dry density, grading, and Atterberg limits from various formations across South Africa.
- Terminology pertaining to residual dolomite and wad are clarified and the distinction is made clear.

18.12. VZSA12: Facilitated Karst Dialogues

Contributions

WRC Report: Dippenaar et al. 2019b (TT 779/19)

Publications: -

Qualifications: -

Links within this report: -

Background

Two facilitated dialogues formed part of the project. The first entailed a closed session with invited professionals working in the civil and government spheres with respect to water and land suitability in dolomite terrain. The second dialogue formed part of a two-day symposium jointly organised by various parties.

Main Findings and Outcomes

- Terminology, mechanisms of failure and investigation techniques were discussed in great detail by appropriate professionals from the industry

18.13. VZSA13: Intermediate Vadose Zone of Fractured Rock Mass

Contributions

WRC Report: Dippenaar et al. 2019b (TT 779/19)

Publications: Dippenaar and van Rooy 2016; Maoyi 2019a; 2020; Segole and Van Rooy 2017

Qualifications: Maoyi 2019b

Links within this report: *Box 34*

Background

A number of acrylic models were constructed, some subjected to centrifugal acceleration, to assess partially saturated flow through these systems.

The cubic law was addressed through single, smooth, parallel plates with changing aperture. Orientation were changed later on.

Moulds in acrylic followed where aperture was made to change through imposing stepped roughness profiles. Casts of real fractures followed, after which actual rocks were used at normal gravitational acceleration to verify findings.

Some experiments were conducted with intersecting fractures, all aiming to mathematically and visually describe the flow at highly variable saturation through discreet natural rock fractures.

For the actual rock fractures, laser scanners were used to acquire roughness profiles. This was correlated with field roughness data, mostly through joint roughness coefficients (JRC values), to infer the influence of different geometrical intricacies (roughness; aperture; bridging; etc.) on flow.

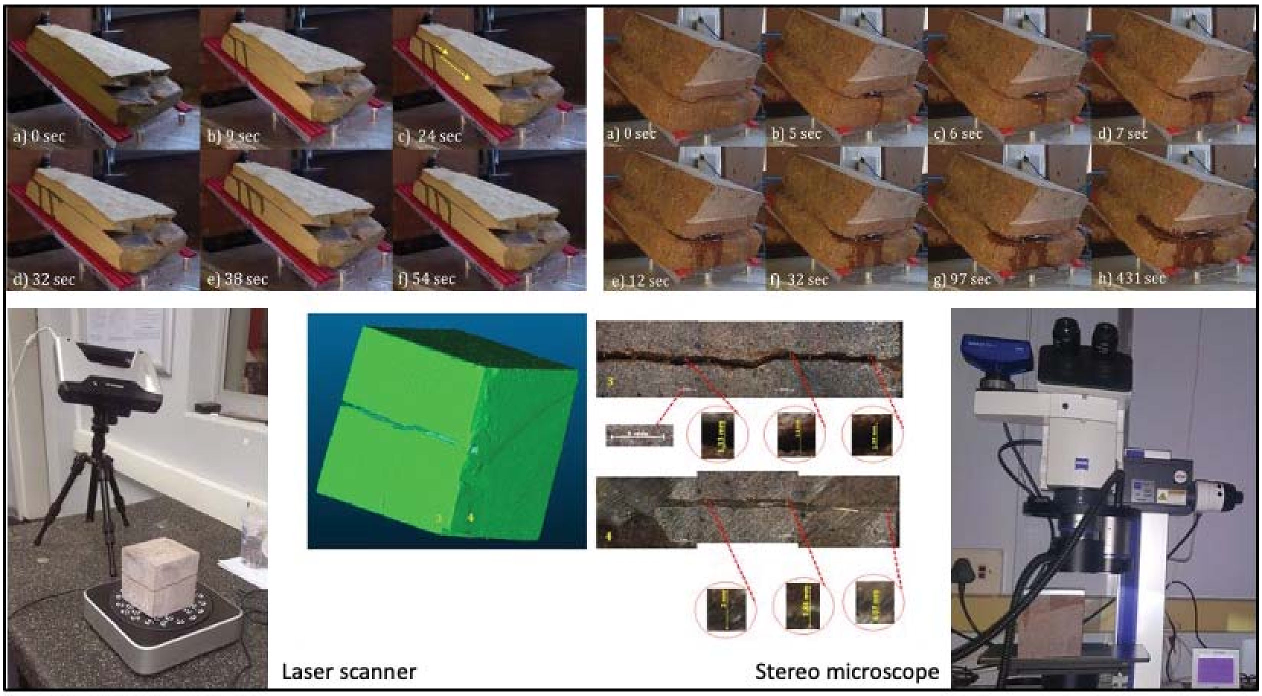


Figure 18-6. VZSA13: Rock specimens inclined at 23°; photography and scanning results to deduce roughness and aperture profiles.

Main Findings and Outcomes

- Flow regimes and flow mechanisms in rock fractures are complex. The prior - regimes - can be deduced to be laminar or turbulent, as well as rotational or irrotational. The latter - mechanisms - involve the wetting of mineral surfaces along the defect into flow phases such as droplets, films, sheets, etc.
- The complex relationship between wetting and drying vertical and horizontal fractures at fracture intersections provide valuable input into how rapid vertical percolation can occur at very low degrees of saturation, compared to slow lateral movement in near-saturated horizontal fractures.
- Spill-and-fill effects dictate the storage and movement of moisture in unsaturated state. The movement and understanding is further complicated by spill-and-fill processes, inertial versus frictional energy losses, turbulence, and changes in saturation.

18.14. VZSA14: Variably Saturated Fracture Flow

Contributions

WRC Report: Jones et al. 2016 (project K5/2326; in print)

Publications: Jones et al. 2019a,b; Maoyi et al. 2020; Dippenaar et al. 2020

Qualifications: Jones 2019c; Maoyi 2019b

Links within this report: *Figure 8-1*; *Figure 8-2*; *Box 24*; *Box 25*; *Box 29*; *Box 33*

Background

The De Hoop Dam was constructed as bulk water supply to the rapidly expanding Sekhukhune district (situated on the eastern limb of the Bushveld Igneous Complex). The dam supplies water for infrastructure, mining activities as well as 800 000 people living on the Nebo Plateau.

The dam wall is divided into three zones, namely the right flank, the river section or spillway, and the left flank. The portion chosen for the experimental site is located on the left flank, from Block 88 (Ch 600) to Block 118 (Ch 760) of the dam wall. This area was specifically chosen due to seepage that occurred after the completion of the dam wall, as well as anomalously high Lugeon values that were obtained from grout curtain borehole packer testing.

The as-built foundation maps of the exposed rock mass were used to model the pegmatite vein as it contained relatively detailed information on the geometry of the fracture.

The pegmatite vein was mathematically modelled as a 2D plane in a 3D axis system.

In order to model the flow through the pegmatite vein, it is required to know the hydraulic gradient under which the flow occurs. A confined flow net method was utilised to approximate the hydraulic head distribution throughout the plane.

A geotechnical centrifuge model was also constructed to mimic packer testing in an inclined defect (representing a possible vein) with a vertical borehole. Injection occurred into an initially dry fracture, implying wetting of an unsaturated medium (*Figure 18-7*).

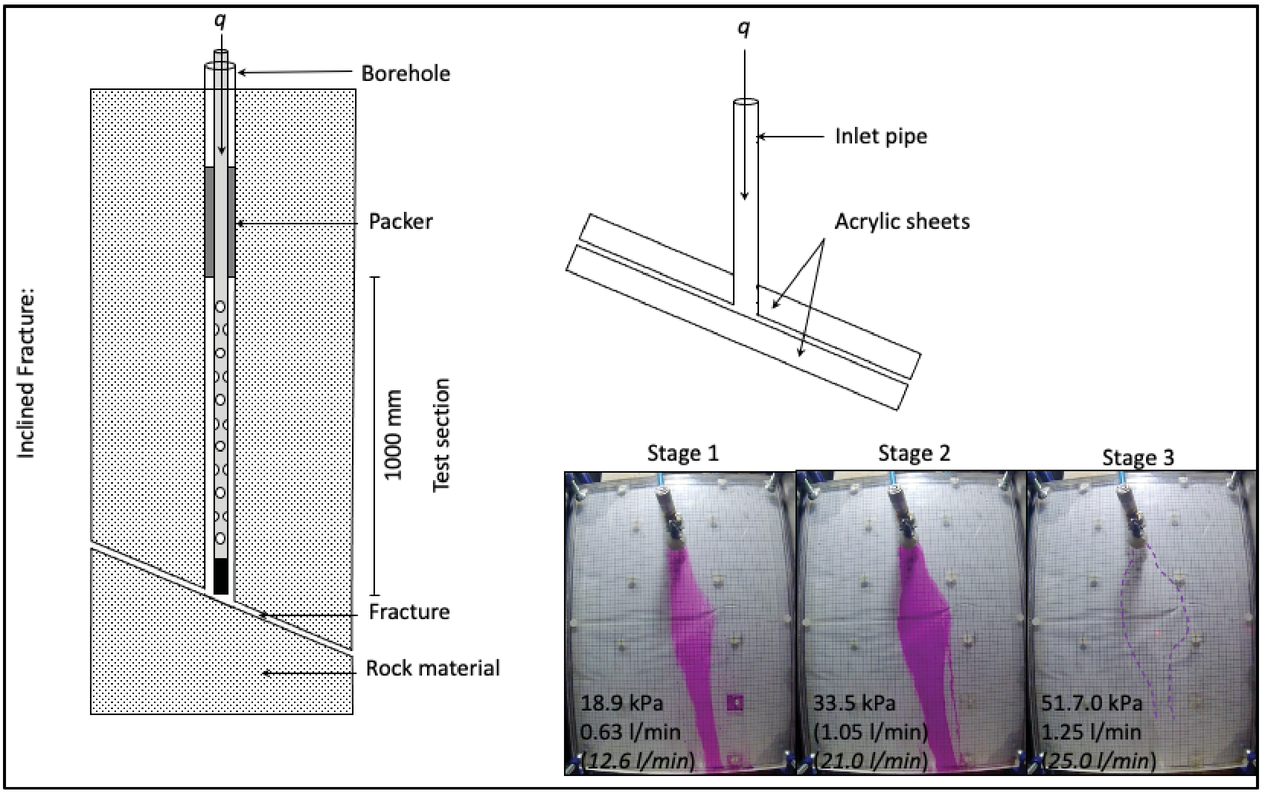


Figure 18-7. VZSA14: Acrylic model as constructed; flow over time at different pressures and fluxes (potassium permanganate used to make flow visible).

Main Findings and Outcomes

- Predicted results using the Forchheimer law compare well with the measured experimental results, when using the width of the flow path adjacent to the inlet source. The Forchheimer relationship has been used to describe non-linear flow in saturated fractures due to the effects of fracture geometry (e.g. roughness, aperture, etc.) and it is shown here that it may also be useful to better quantify flow through discrete fractures in the fractured vadose zone.
- Lugeon tests conducted in an initially unsaturated rock mass might misrepresent the hydrogeological regime, which would instead be accurately represented under saturated conditions. One can exemplify this by considering Lugeon tests conducted within an unsaturated rock mass during investigation of a dam site, which would lead to a misunderstanding of the rock mass permeability, which would only become apparent only once saturated conditions are achieved after reservoir impoundment.
- Using broad empirical correlations to define hydraulic conductivities of Lugeon test intervals from Lu-values should be cautioned. Classical volume-effective approaches do not contribute to fundamental research questions, and require a deeper understanding of the small-scale processes in the porous fractured systems that characterize the intermediate fractured vadose zone. Ultimately, finding a suitable representation of an analogous fractured rock mass is difficult, and at process scales the best one can do is to isolate individual processes.

18.15. VZSA15: Permeable Pavements

Contributions

WRC Report: This report (project K5/2826; in print)

Publications: Van Vuuren et al. 2021

Qualifications: Van Vuuren 2020

Links within this report: *Box 43*

Background

An infiltration table apparatus was constructed, supported by Bosun. The table's dimensions were 6 m in length, 2 m in width, and 1 m in depth.

Pavements were constructed successively with only bricks, bricks on sand, and so forth until the recommended specifications with appropriate base, subbase and geotextiles were in place.

Experiments entailed measuring flux into, over and through the pavement. Vertical percolation was collected every meter length, and overflow at the end at a separate gauge. Flow was interpreted for different the grade (inclination), fluxes (continuous versus intermittent), filler sand, brick packing, and other appropriate variables.

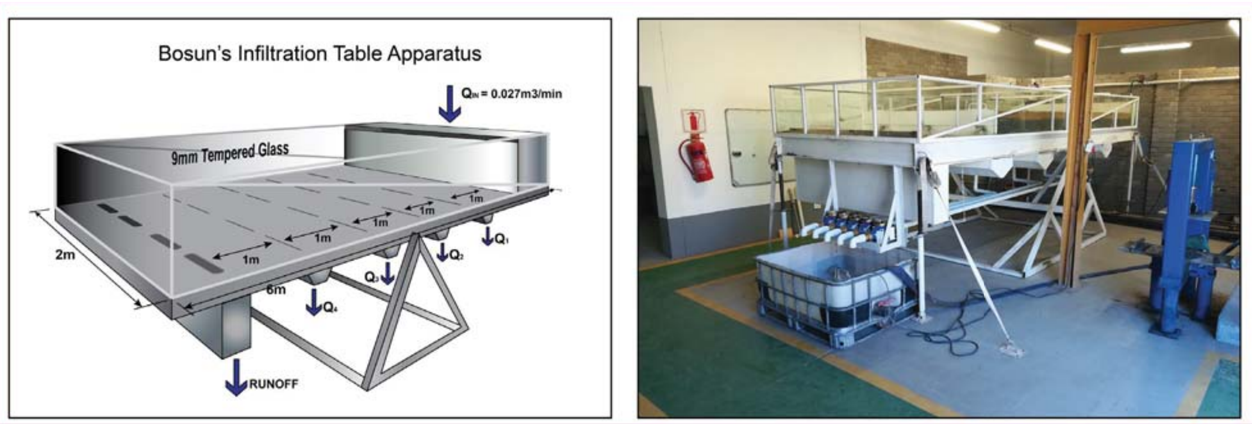


Figure 18-8. VZSA15: Schematic and photograph of the infiltration table apparatus mimicking permeable pavements (Van Vuuren 2020; Van Vuuren et al. 2021).

Main Findings and Outcomes

- Filler sand plays a predominating role together with grade and flux volume.
- Results provide helpful design parameters for urban permeable pavement system under flood conditions.

18.16. Ongoing Work

- VZSA16: Urban Karst Systems (Natalspruit)
- VZSA17: Saprolite and Residuum
- VZSA18: Microbial Tracers
- VZSA19: Further Advanced in the Intermediate Vadose Zone

APPENDIX B: HYDRAULIC PARAMETERS

19. Empirical Approaches

19.1. 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 19-1*. 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 Domenico and Schwartz 1990, Freeze and Cherry 1979, Fetter 1994, Narasimhan and Goyal 1984).

Table 19-1. 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

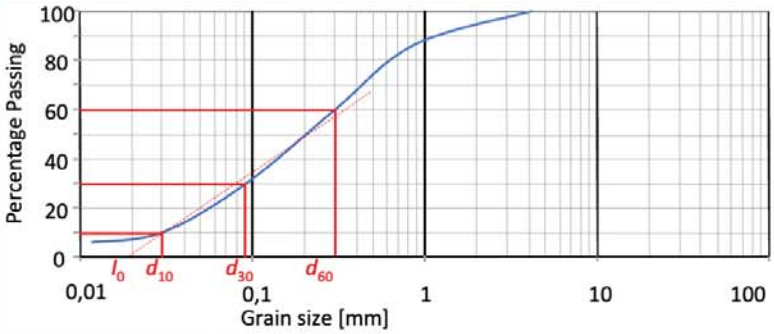
Rock Material	K_{sat} range low (m/s)	K_{sat} range high (m/s)	Average (m/s)
Crystalline rock (dense)	1.00E-13	1.00E-09	5.00E-10
Shale	1.00E-12	1.00E-08	5.00E-09
Crystalline rock (plutonic)	1.00E-09	1.00E-07	5.05E-08
Shale	1.00E-08	1.00E-07	5.50E-08
Tuff	1.00E-08	1.00E-06	5.05E-07
Lava	1.00E-08	1.00E-06	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

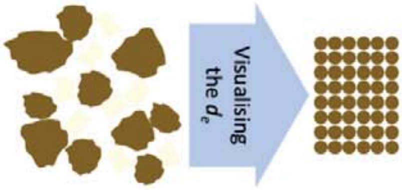
19.2. Grading-based Empirical Approaches

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 (*Box 46*). Evaluation of such methods is well published in, for instance, Cheong et al. (2008) and Odong (2008).

BOX 46. Methods: Grading-based Hydraulic Conductivity Estimation

(a) Dimensional Homogeneity





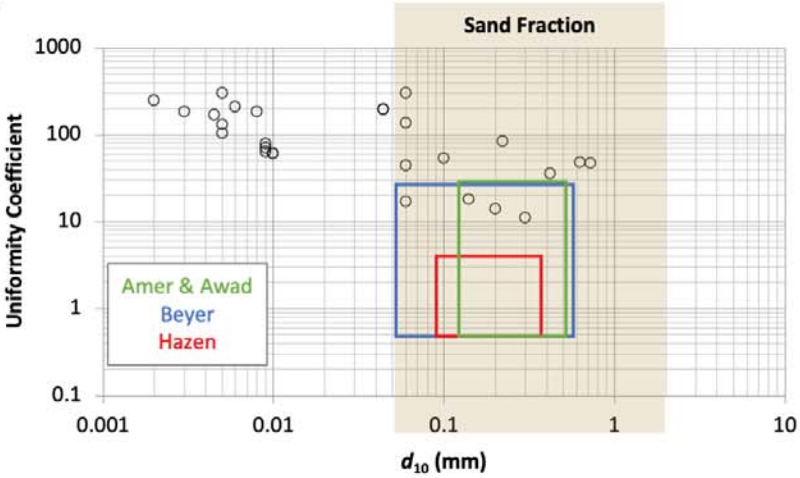
The dimensionally homogeneous form comprises:

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

(b) Empirical Methods

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, are supplied below where K is estimated by multiplying C, $f(\eta)$ and $f(d_e)$.

RIGHT: Results from granitic regolith show the small ranges of applicability of these methods, highlighting the importance of using more advanced and appropriate techniques as well.



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: ADAPTED FROM: (© www.wrc.org.za) Amer and Awad 1974; Carrier 2003; Das 2008; Fitts 2002; Hazen 1911,1930;Kenney et al. 1984; Odong 2007; Shababi et al. 1984; Van Schalkwyk and Vermaak 2000; Vukovic and Soro 1992; data Dippenaar et al. 2014

The data from an ephemeral hillslope wetland on Lanseria Gneiss (VZSA1) are shown in *Box 46*, 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. It is imperative to use empirical methods - like all other methods - cognisant of their limitations and assumptions.

The same data, for five empirical approaches and field percolation tests, are shown in *Table 19-2* and *Figure 19-1*. 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 (d10) and uniform materials, whereas field methods include for site conditions.

Table 19-2. Experimental results: correlation between empirical K-values and field percolation tests (m/s).

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

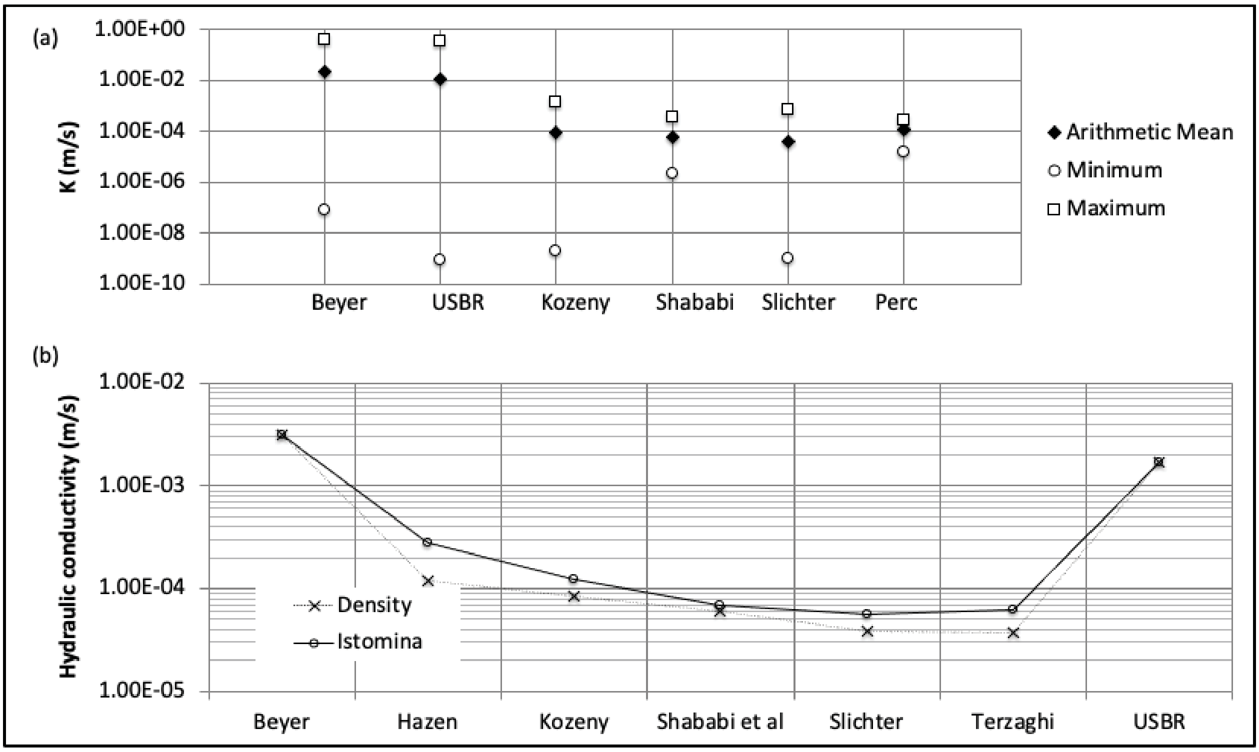


Figure 19-1. Experimental results: empirical grading-based hydraulic conductivities calculated using (a) different approaches and (b) different methods of estimating porosity (Dippenaar et al. 2014; Dippenaar 2014b).

The general consensus is that empirical methods should be employed cautiously when materials do not comply with the assumptions and ranges of applicability. 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.
- 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.

20. LABORATORY TESTS

20.1. Constant-head and Falling-head Permeability Tests

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 47*).

20.2. Geotechnical Centrifuge Modelling

Permeability tests can also be conducted under gravitational acceleration to scale certain dimensions. 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 $h_p = Nhm$. The geotechnical centrifuge of the University of Pretoria and some typical designs and results are shown in *Box 48*.

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). Van Tonder and Jacobsz (2017) since determined that the hydraulic conductivity is independent on scaling and that the hydraulic gradient is scaled.

Box 47. Methods: Constant-head and Falling-head Permeability Tests

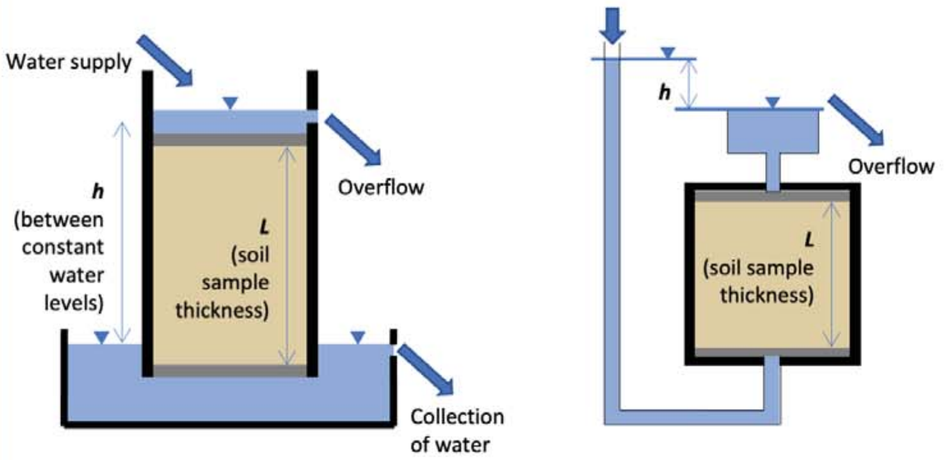
BOX 47. Methods: Constant-head and Falling-head Permeability Tests

(a) Constant-head Permeability Test

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*.

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

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



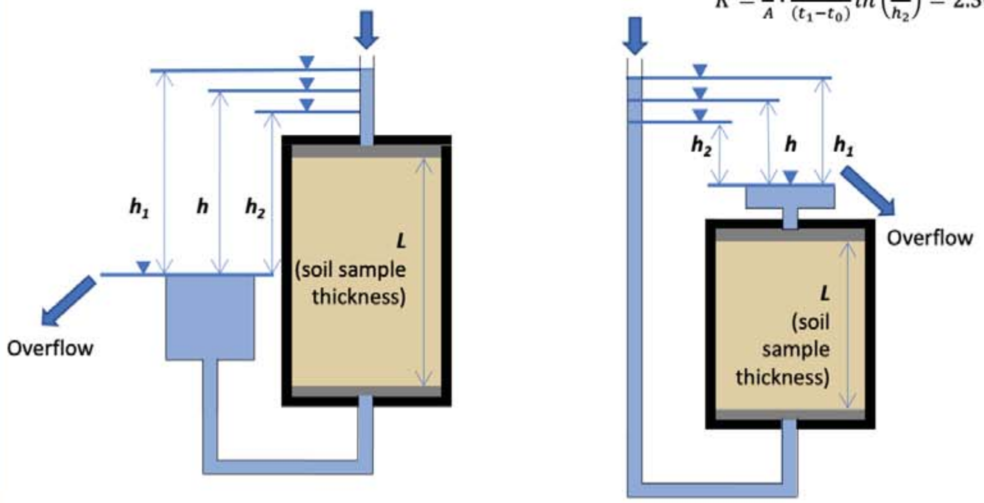
(b) Falling-head Permeability Test

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*.

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

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

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



READ MORE:
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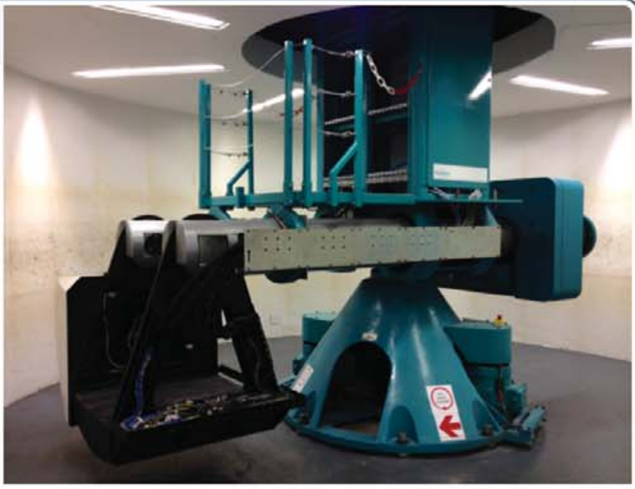
BOX 48. Methods: Geotechnical Centrifuge Modelling

(a) Equipment

The centrifuge of the University of Pretoria can accelerate almost one tonne of sample to more than 100 times Earth's gravitational acceleration. *N* relates to the amount of *g*'s (Earth's gravitational acceleration). This is done in order to scale different dimensions. The vertical distance (depth or *z*) is typically scaled *N*-times (i.e. equal to the amount of *g*'s), and/ or time is scaled N^2-times.

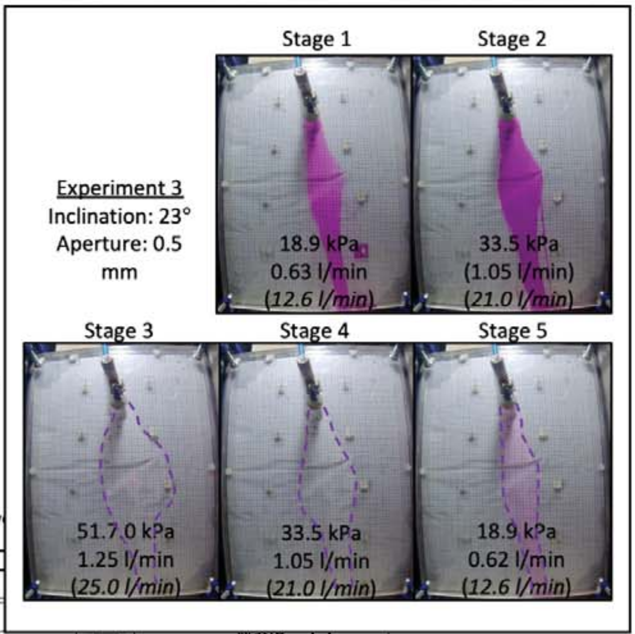
Models are built in a safe box with media representing actual stress conditions. On acceleration, data is interpreted based on the scaling laws. As such, the centrifuge can be used to conduct permeability tests under greater thicknesses at shorter times.

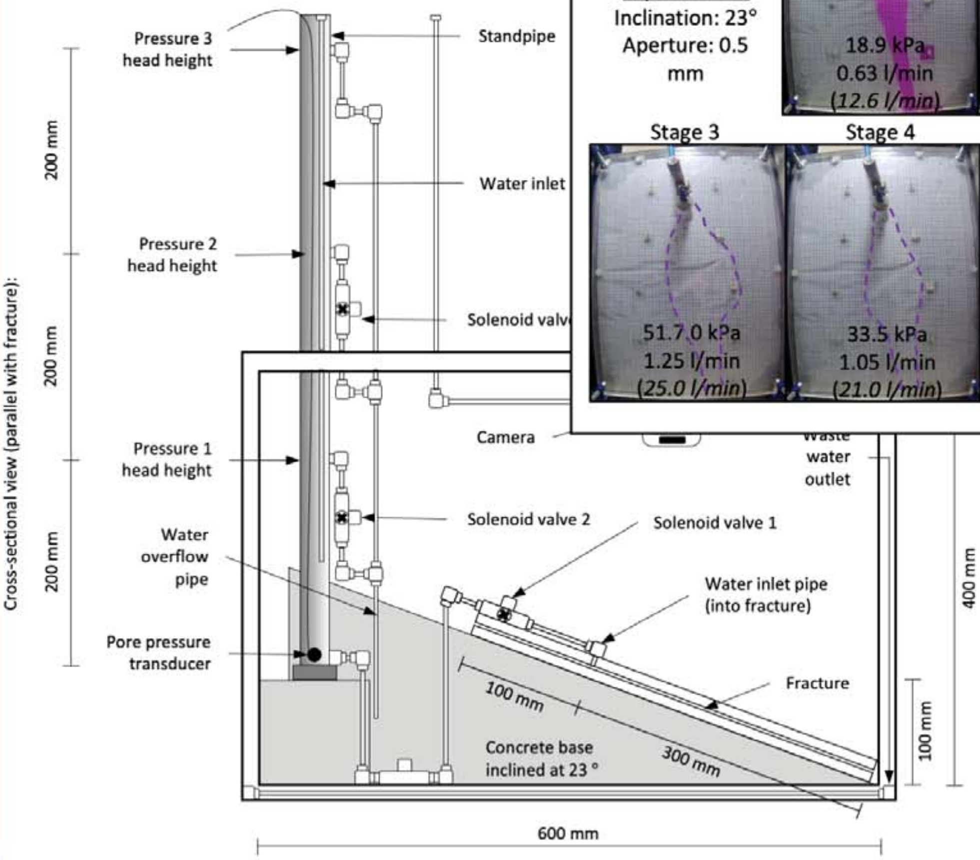


(b) Experimental Design

BELOW: The design drawings of an experiment design to mimic injection of grout into an inclined discontinuity.

RIGHT: water coloured with potassium permanganate recorded in real time with a GoPro™ camera shows the movement of water under different fluxes.





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Employed in Jones et al. 2016;2017;2018;2020 Brouwers and Dippenaar 2019; details as examples from Jones et al. 2019

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 modelled – 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)
- 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).

20.3. Infiltration Table Apparatus

Bosun (Pty) Ltd constructed an infiltration table apparatus (ITA) that was tested extensively by Van Vuuren (2020) and Van Vuuren and Dippenaar (2021). The ITA is equipped with a water supply system and can be tilted to different gradients. Road pavements can be constructed in the 10 m^2 apparatus for a variety of hydraulic tests (*Figure 20-1*).

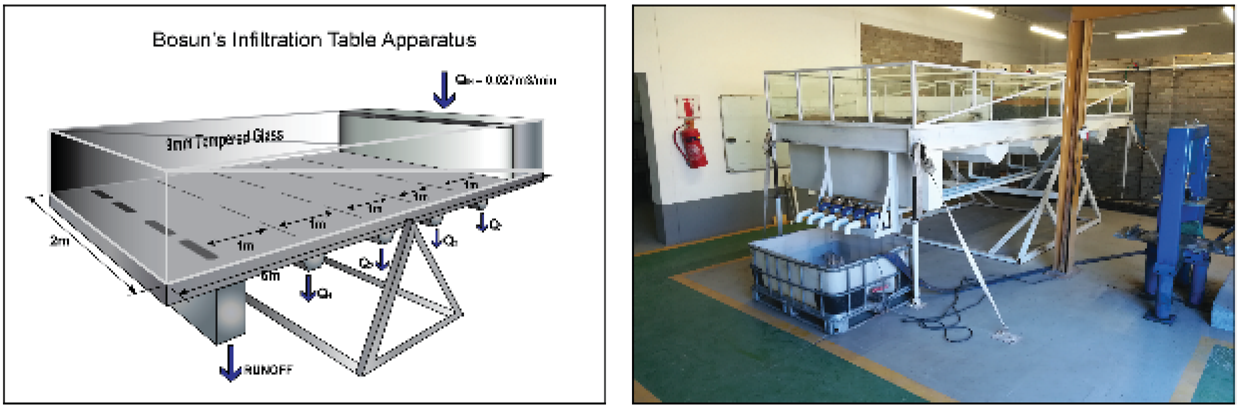


Figure 20-1. Tilting table schematic construction (left) and final equipment (right); surface area 10 m^2.

20.4. Soil Moisture Characteristic Curves

Characteristic curves are used to relate moisture content to matric suction as explained in *Box 32*. This can then be applied to estimate hydraulic conductivity for a medium at variable saturation, provided that the saturated hydraulic conductivity is known. There are different procedures available to determine suctions at different moisture conditions under drying and wetting conditions. These can then be plotted to show retention curves, possibly including effects of hysteresis, relating the moisture content to suction for soils under investigation.

21. Field Tests

21.1. Percolation Tests and Infiltration Tests

In-situ field tests are usually conducted from surface to determine infiltration, or from holes to determine percolation

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 (SABS 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 49*. 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.

21.2. 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 21-1*. Water from the measurement tube aims to equilibrate with soil moisture and the suction is detected using the pressure gauge.

Box 49. Methods: Field Infiltration and Percolation Tests

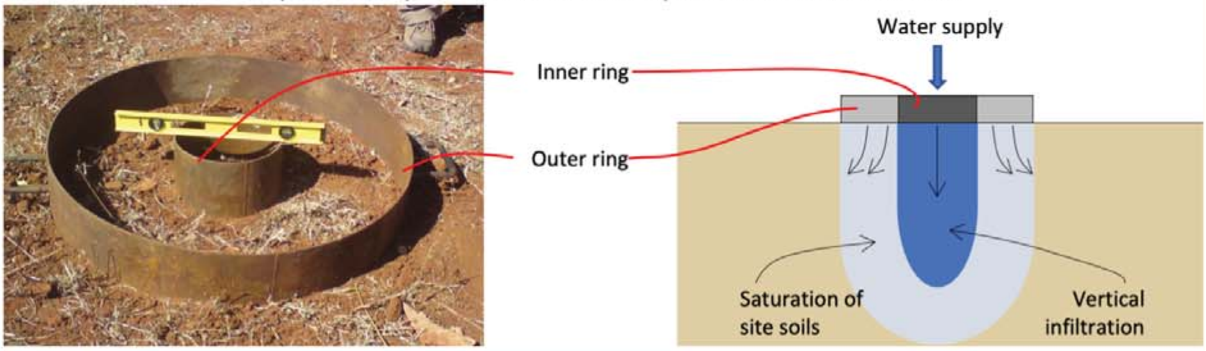
BOX 49. Methods: Field Infiltration and Percolation Tests

(a) Double Ring Infiltrometer (DRI) Test

Infiltrometers are 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.

The test assumes specifically soaked (saturated) conditions, and is most suitable for relatively uniform fine-grained soils of low plasticity. The test is most effective for hydraulic conductivities between 1×10^{-8} m/s and 5×10^{-5} m/s.

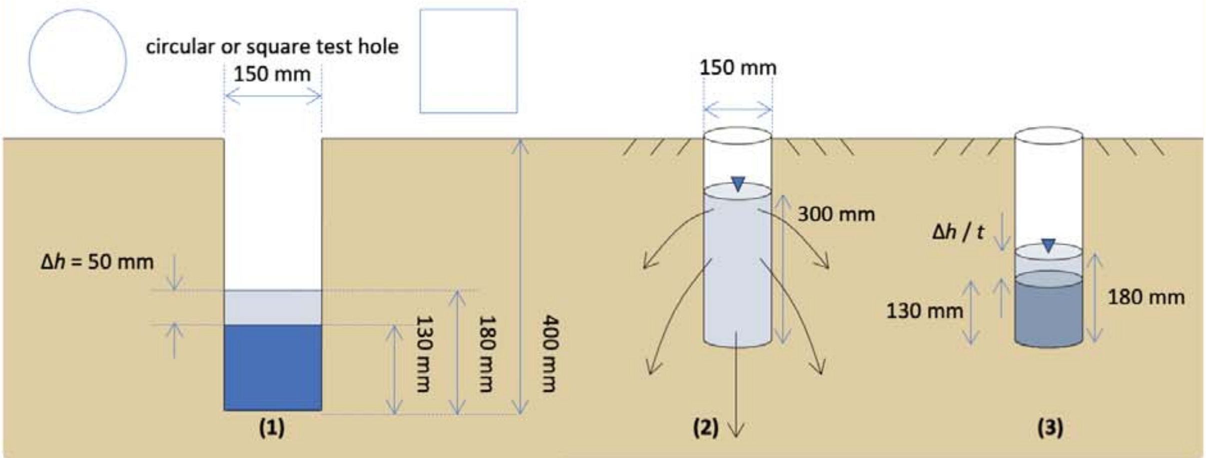
An alternative test comprising only a single ring can also be conducted. In this instance, the main additional limitation is that more water is allowed to disperse laterally and the likelihood of solely vertical infiltration is reduced.



(b) Percolation Test

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 standard set-up is as follows:

1) A trial hole is excavated with the given dimensions, the sides are scarified and gravel is placed at the bottom.
2) Water is added to 300 mm from the base and allowed to drain away completely three times or for at least 8 hours prior to conducting the test.
3) 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.



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ASTM D 3385-94; SANS 10252-2 1993; Jenn et al. 2007c; Reynolds and Elrick 1986; Dippenaar et al. 2010

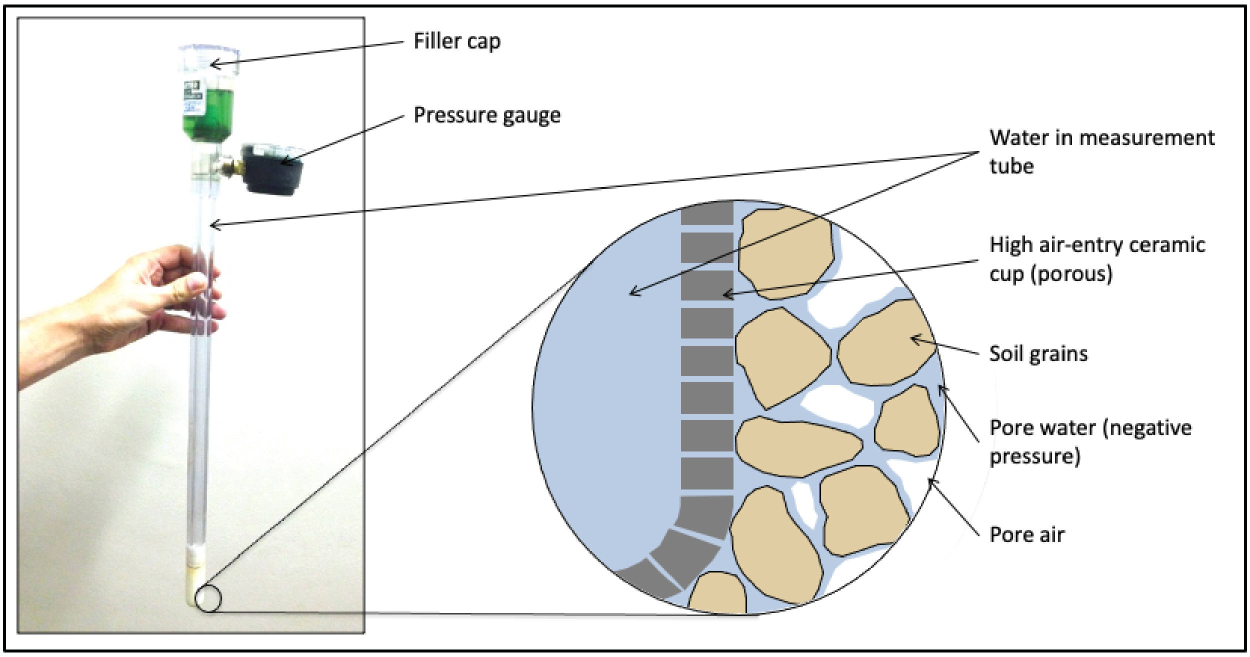

Figure 21-1. Irrometer moisture indicator (left; supplied by CalAfrica) and detail of the ceramic tip of the tensiometer (right; after Lu and Likos 2004).

22. MODELLING

Compilation of a model is dependent on a high quality initial conceptual model. The compilation of a quality conceptual model is crucial, including the acquisition of proper material descriptions to ensure validity of the conceptual model.

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.

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