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Assessment of vadose zone hydrology: concepts, methods, applications and guidelines

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(option: Hydrogeology)

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ABSTRACT

Vadose zone hydrology is a developing science influenced by earth scientists (soil scientists, pedologists, hydrogeologists, engineering geologists and geomorphologists) and engineers (geotechnical). However, problems faced are associated with lack of agreement between basic concepts, different approaches and definitions, and difficulty in communicating findings to other technical or non-technical audiences. The need for better cross-disciplinary dialogue and understanding subsequently becomes increasingly important, notably given the sensitivity of investigation related to ephemeral wetlands, contamination and water impacting infrastructure development. This thesis therefore aims to address basic concepts, accepted methodologies and highly variable and sensitive case studies in order to minimise risk in the assessment of the vadose zone. Terminologies, quantification, methods and existing guidelines are critically appraised and validated based on three case studies. Findings are reported in order to improve investigation techniques and to minimise risk. Final recommendations are made regarding a proposed vadose zone assessment protocol to ensure compliance to a set of minimum requirements for vadose zone assessment. It is hoped that such a methodology will be implemented towards protection of the natural environment, notably in urban areas, as well as to prevent damage to infrastructure.

DECLARATION

I, the undersigned, declare that:

1. I understand what plagiarism is and am aware of the University's policy in this regard
2. This thesis is my own original work and where other people's work has been used (either from a printed source, Internet or any other source), this has been properly acknowledged and referenced in accordance with University's requirements
3. I have not used work previously produced by another student or any other person to hand in as my own.

Signed on this 15th day of July 2014

Matthys Alois Dippenaar

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1. INTRODUCTION

1.1. Rationale

The hydrological cycle represents a very complex, yet often oversimplified, interaction between atmospheric, surface and subsurface waters. From meteoric waters, that portion reaching land surface becomes subjected to the process of *surface runoff* whereby it remains on land surface, eventually forming streams and rivers, or alternatively *infiltration* introduces this water into the subsurface. Once infiltrated into the subsurface, subsurface hydrology becomes relevant in terms of the well-defined field of *hydrogeology*, *geohydrology* or *groundwater science* and the lesser-established field of *vadose zone hydrology*.

The vadose zone comprises (i) a *soil zone* or *plant root zone* which is fairly well-studied in terms of plant water availability, nutrient cycling and hillslope and riparian hydrological processes, (ii) an *intermediate zone* which, in turn, is very poorly studied due to the lack of evaporation and transpiration influences, as well as its often fractured nature, and (iii) a *capillary fringe* which is understood in context of why and how it occurs. Yet, cross-disciplinary dialogue and a lack of a well-defined understanding of the implications and applications of vadose zone hydrology considering all zones within the vadose zone are still absent.

Standard terminology and definitions lack. Given that soils scientists, hydrogeologists, engineering geologists, hydrologists, civil engineers and so forth are all in some way studying the vadose zone, terminologies are often inconsistent. Examples of this include, for instance, the broad definition of *soil*, the differences between *recharge* (to groundwater for the hydrogeologist) and *recharge* (potential into the intermediate vadose zone for the soil scientist), as well as the interchanging of mathematical denotations for parameters such as permeability and conductivity (k and K for the scientist, and K and k for the engineer).

Basic concepts are available, but are often scattered as subsections in topical textbooks of soil science or hydrogeology. Given the increased importance of proper understanding of the vadose zone influencing the environment, urban development and the hydrological cycle, the basic concepts become increasingly important.

Quantification of hydrological and hydraulic parameters relevant to the unsaturated zone is also discipline-specific and often results in loss of knowledge due to the inability to transfer knowledge from other disciplines. The need for elaboration on the most important parameters and methods, as well as reference to state-of-the-art and best practice guidelines, are initial steps towards a unified understanding in South Africa. Subsequently, the importance of cross-disciplinary understanding, determination of and recent advances in the quantification of parameters, conceptual modelling and applications require special attention.

1.2. Objectives

The main objectives of this research are to:

1. Address vadose zone hydrology as a function of all disciplines interested in studying the unsaturated subsurface with the notable inclusion of hydrogeology, engineering geology, civil engineering and soil science, and to refine vadose zone conceptual models with the inclusion of data from all these disciplines
2. Evaluate a range of high risk and high sensitivity scenarios in notably urban settings and in which the vadose zone play the controlling role such as protection of ephemeral inland wetlands, sanitary influences of peri-urban cemeteries, water-induced geotechnical constraints for development and changing land use influences on surface water and groundwater interaction and quality
3. Reconcile methods employed in various disciplines to ensure transfer of knowledge between investigation for various purposes
4. Outline guidelines based on scope and anticipated importance of the vadose zone for a wide range of investigations and achieve unity in vadose zone hydrology without compromising individual disciplines.

1.3. Research Outcomes and Publications

1.3.1. Published papers, full length conference proceedings and research reports

Bulk of the contents of this thesis has been published. Published international peer-reviewed papers, full length peer reviewed conference papers and published research reports forming part and emanating from this thesis include:

- Dippenaar, M. A. (2012). How we lose ground when earth scientists become territorial: defining "soil". Natural Resources Research. 21(1):137-142.
- Dippenaar, M. A. (2014a). Porosity reviewed: quantitative multi-disciplinary understanding, recent advances and applications in vadose zone hydrology. Geotechnical and Geological Engineering. 32:1-19.
- Dippenaar, M. A. (2014b). Towards hydrological and geochemical understanding of an ephemeral palustrine perched water table “wetland” (Lanseria Gneiss, Midrand, South Africa). Environmental Earth Science. DOI 10.1007/s12665-014-3153-5.
- Dippenaar, M. A. (2014c). Part 1: Principles of Vadose Zone Hydrology. In: Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, N. S. and Mulders, J. A. (2014). Vadose Zone Hydrology: Concepts and Techniques. Water Research Commission report TT 584/13, project K5/2052. Pretoria.
- Dippenaar, M. A. (2014d). Part 2: Methods and Guidelines. In: Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, N. S. and Mulders, J. A. (2014). Vadose Zone Hydrology: Concepts and Techniques. Water Research Commission report TT 584/13, project K5/2052. Pretoria.

- Dippenaar, M. A. (2014e). Towards a multi-faceted vadose zone assessment protocol: cemetery guidelines and application to a burial site located near a seasonal wetland (Pretoria, South Africa). Bulletin of Engineering Geology and the Environment. DOI DOI 10.1007/s10064-014-0635-3.
- Dippenaar, M. A. and Van Rooy, J. L. (2014). Review of engineering, hydrogeological and vadose zone hydrological aspects of the Lanseria Gneiss, Goudplaats-Hout River Gneiss and Nelspruit Suite Granite (South Africa). Journal of African Earth Sciences. 91:12-31.
- Dippenaar, M. A. and Van Rooy, J. L. (in print as peer-reviewed proceedings by Springer). Conceptual geological models, its importance in interpreting vadose zone hydrology and the implications of being excluded. Proceedings IAEG X11 Congress – Engineering Geology for Society and Territory. Turin.
- Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, N. S. and Mulders, J. A. (2014a). Vadose Zone Hydrology: Concepts and Techniques. Water Research Commission report TT 584/13, project K5/2052. Pretoria.
- Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, N. S. and Mulders, J. A. (2014b). Part 3: Supporting Case Studies. In: Dippenaar, M. A., Van Rooy, J. L., Breedt, N., Huisamen, A., Muravha, S. E., Mahlangu, N. S. and Mulders, J. A. (2014). Vadose Zone Hydrology: Concepts and Techniques. Water Research Commission report TT 584/13, project K5/2052. Pretoria.

In response to the research rationale and objectives, it was envisaged to compile a manual on vadose zone hydrology to aid specialists working in the field and decision makers communicate better and improve the usability of the technical findings conducted by specialists. Certain niches have been identified, such as some high profile applications, the lack of a fixed set of minimum requirements for investigations, and the lack of cross-disciplinary understanding, that form some of the important outcomes of this work.

Basic concepts for a multi-disciplinary audience are addressed in Dippenaar (2014c). The relevance of vadose zone hydrology to specific applications is detailed in Dippenaar (2014d) at the hand of ephemeral inland wetlands (§8.1), cemeteries (§8.2), construction and engineering (§8.3), aquifer susceptibility (§8.4), ground-based sanitation (§8.5), riparian interaction and groundwater dependent ecosystems (§8.6), agriculture (§8.7) and urban hydrology (§8.8). This are furthermore motivated by three case studies pertaining to wetlands (vadose zone study area VZSA1), tailings (VZSA2) and cemeteries (VZSA3). The findings of these case studies are added as concluding remarks or provisional findings throughout the relevant subsections on the methods and guidelines and in Dippenaar (2014b) with data and interpretation documented in Dippenaar et al. (2014b).

Standard guidelines for investigation are also presently absent when the exact purpose of investigation and site conditions are not yet clear. Prior to land use change, for instance, it is not necessarily possible to identify whether a parcel of land will be used for waste disposal, high-density urban development, or no development at all. The possible presence of wetlands and seeps are yet unknown and their impacts on proposed land use change cannot be evaluated without knowledge of their existence. For this purpose, guidelines and minimum requirements are detailed for development-dependent investigations (where the purpose of investigation is clear; §9.1 in Dippenaar 2014d), as well as for generic tiers of investigation based on level of detail required (ibid. §9.2-§9.4). Competency and decision-making are finally addressed together with best practice guidelines and learned societies (ibid. §9.5-§9.6).

The final outcome was in the form of an urban hydrology workshop focussed around the water resources of the City of Tshwane and emphasising the importance of proper vadose zone hydrological understanding.

1.3.2. Congress and conference abstracts in proceedings

The following international conference presentations formed part of the research:

- Dippenaar, M. A. (2013). Cemeteries and the risks posed to water. Proceedings: Conference of the South African Cemeteries Association of the South African Local Government Authority (SACA of SALGA and eThekwini Local Municipality). Durban October 2013.
- Dippenaar, M. A. (2013). Conceptual geological models, its importance in interpreting vadose zone hydrology and the implications of being excluded. Proceedings: 40th Congress of the International Association of Hydrogeologists (IAH). Perth, Australia. September 2013.
- Dippenaar, M. A. and Breedt, N. (2013). Understanding subterranean hydrology in the delineation of wetlands – a phreatic hillslope wetland on Permian sandstone in South Africa. Proceedings: 24th Colloquium on African Geology (CAG). Addis Ababa, Ethiopia. January 2013.
- Dippenaar, M. A. and Breedt, N. (2011). Between surface water and groundwater – a look at the pathway in-between. Ground Water Division of the Geological Society of South Africa/ International Association of Hydrogeologists (Biennial GWD in association with IAH), Pretoria, South Africa. September 2011.

1.3.3. Short courses and workshops

Annual short course were presented in 2011 and 2013 through Continuing Education at University of Pretoria (CEatUP) entitled *Vadose Zone Hydrology for Geotechnical Engineers and Environmental Scientists*. The two-day course covered the multi-disciplinarity of vadose zone hydrology and was registered as a HQF-7 level and for two continuing professional development (CPD) points with the Engineering Council of South Africa (ECSA) through the South African Institution for Civil Engineers (SAICE).

A multi-disciplinary workshop aiming to improve dialogue related to urban hydrology in which the vadose zone is critical was presented on 23 and 24 January 2014. The conference included a talk by Matthys Dippenaar on Urban Hydrogeology focused around impacts of the vadose zone to urban development. Other related topics presented by the 22 local experts included wetlands, biodiversity, land use planning, water sensitive urban design, ecological infrastructure, hydrometeorological risk, water quality, and engineering risks exacerbated by improper understanding of subsurface moisture. This workshop entitled *Urban Hydrology Workshop – Water in the City of Tshwane* for the first time in South Africa managed to combine specialist engineers (hydraulic and geotechnical), geologists (engineering geologists and hydrogeologists), soil scientists and pedologists, ecologists, land use planners, architects and landscape architects, economists, social scientists, legal professionals and managers from academic institutions, private consultancies, the local municipality, Department of Water Affairs, CSIR, Council for Geoscience, SA National Biodiversity Institute and numerous other interested persons, institutions and societies.

1.4. Structure of this Thesis

This thesis presents findings as published in peer-reviewed literature with the aim of finding common ground between disciplines and of establishing standard minimum requirements rather than presenting case studies. Supporting information and data are available in the referenced literature.

Detailed information is supplied in the publications as cited throughout. Discussion in this section is intended solely to motivate for the use of given methods and selection of case studies, as well as to elaborate on critical contributions to the science of vadose zone hydrology applied to urban South African settings.

There is, therefore, no distinct section on Materials and Methods, given the publication of validated methodologies and case studies in peer-reviewed papers and research reports. The publications have been placed in sequence in this thesis, occasionally with minor edits from the pre-print format to avoid duplication and to promote readability.

1.4.1. Selection of case studies

Sensitive and high profile applications were selected to be incorporated in the work. Green lands, natural undisturbed areas and homogeneous low vulnerability terrains have been excluded under the premise that understanding of heterogeneous, high sensitivity and important (high profile) case studies will inevitably contribute to the understanding of lesser complex terrains. To accentuate the importance of the vadose zone in such instances where protection of the quality and quantity of all water resources are threatened and where development may be adversely affected, focus was on:

- Ephemeral temporary inland wetland systems located on hillslopes to exclude riparian and coastal systems and to place emphasis on periodical wetness
- Peri-urban cemetery sites and, to a significantly lesser extent, other localised point-sources of contamination such as on-site sanitation to address low-load contamination sources in densely developed areas where groundwater and surface water contribute to the water supply

- Urban hydrology in its entirety to emphasise the importance of all aspects of hydrology, viz. meteorology, surface hydrology, subsurface hydrology (phreatic and vadose), as well as engineered hydrology and the impacts on development.

1.4.2. Methodology

Given the vast range of disciplinarity involved in addressing the case studies noted, it became imperative to standardise concepts for use by scientists (soil scientists, pedologists, hydrologists, hydrogeologists and engineering geologists) and engineers (civil and geotechnical). Additional emphasis is needed on communicating technical concepts to non-technical or lesser-related audiences such as managers, environmental scientists and land use planners. This, therefore, resulted in a twofold approach:

1. Primarily, terminology, definitions and equations were standardised following discussion per discipline to ensure cross-disciplinary transfer of knowledge. Given the specialist's propensity to discipline-specific communication of science, it is hoped that the findings of this research will ensure knowledge transfer without loss of information and duplication.
2. Secondarily, basic concepts and findings were converted to boxed explanations and standard minimum requirements for expansion of vadose zone hydrological concepts to wide audiences. Better understanding of these concepts and methods will subsequently ensure inclusion of vadose zone hydrological investigations in relevant studies to minimise risk emanating from unforeseen circumstances.

Methods addressed aimed to cover the wide spectrum of available investigation techniques employed by individual disciplines. Methods were validated in the case studies in order to promote the use of data collected by seemingly unrelated investigations. Notable emphasis was placed on addressing accuracy of empirical, laboratory, field, modelling and other approaches to address issues of data accuracy and certainty. Minimum requirements once again contribute to methods as more advanced methods are linked to fixed tiers of investigation based on the data requirements and risks posed by the interaction of the hydrosphere and man.

Apart from those published in selected chapters as part of publications, methods as utilised in the study and as used by other specialists are detailed in §3. Existing methodologies and information requirements are detailed in §4 with final recommendations on a unified minimum requirements approach for vadose zone hydrology in general in §6.1.

2. INTRODUCTION TO VADOSE ZONE HYDROLOGY

2.1. The Vadose Zone and Vadose Zone Hydrology

2.1.1. Distribution of water in the crust

The vertical distribution of water in the Earth's crust is shown in Box 1. The ***vadose zone*** (also called the ***unsaturated zone*** or the ***zone of aeration***) stretches through the soil zone and intermediate zone and incorporates the complete ***capillary fringe*** where the medium is still below saturation, gradually becoming saturated towards the water table. This incorporation of the capillary fringe is occasionally questioned due to the saturated nature of the bottom part, but majority of sources agree that the vadose zone is primarily at pore pressures below atmospheric (therefore overlying the water table and including the capillary fringe where pore pressures are less than atmospheric) and only secondarily to be mainly unsaturated.

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

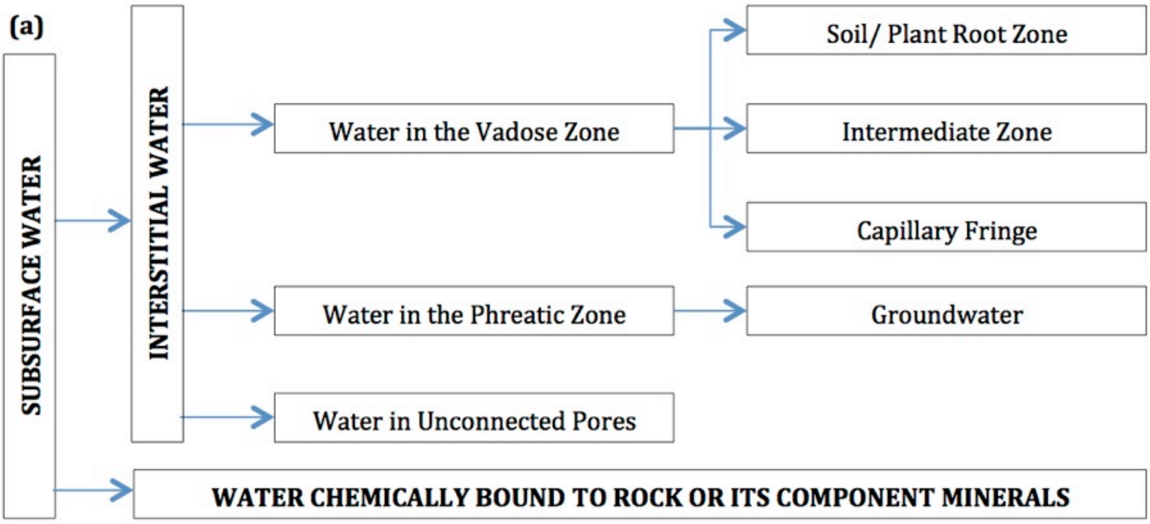
The ***water table*** (or ***phreatic surface***) represents the boundary between the phreatic and vadose zones as well as the surface where pressure equals atmospheric. The water table is represented by the ***water level*** in a well (indicated by an inverted triangle) to account for the deviation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

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

Box 1. Subsurface Water and its Distribution.

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

(a)

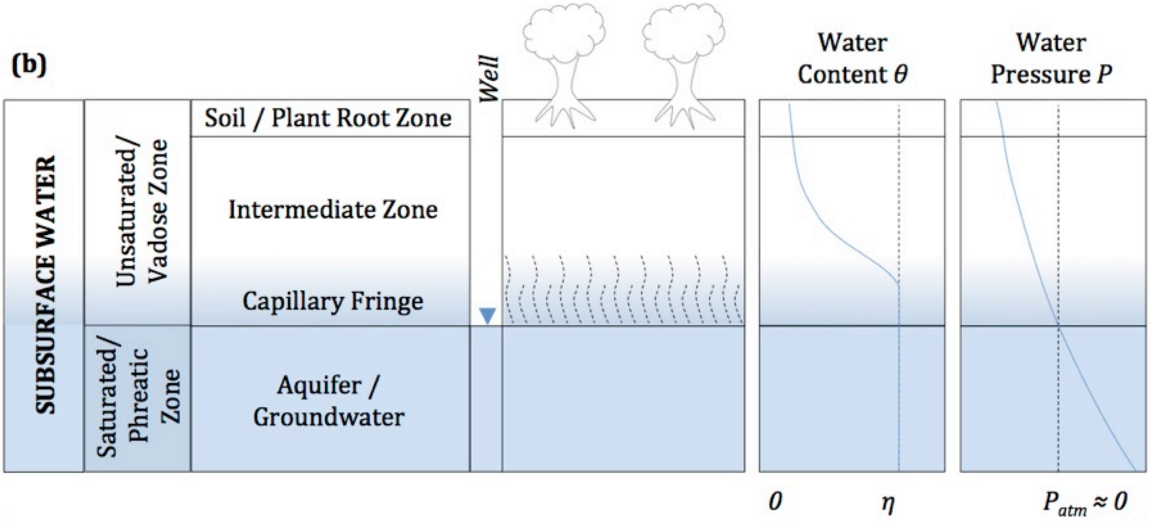


The ***vadose zone*** (also unsaturated zone or zone of aeration) stretches from the land surface through the soil zone and intermediate zone and incorporates the complete ***capillary fringe*** (where the medium may be saturated, but is always at negative pore water pressures).

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

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

(b)



READ MORE & CITED FROM:

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

2.1.2. The movement of water in the subsurface

The hydrological cycle (or water cycle) is an intricate interaction between water from the atmosphere, Earth surface and subsurface. The movement of water in the subsurface is shown in Box 2. Conventional hydrogeology is mainly interested in recharge which can be defined as water eventually reaching the saturated zone (Fitts 2002) or as that process whereby water infiltrates through the vadose zone, eventually reaching the groundwater surface and adding water to the aquifer, occurring as the net gain from precipitation or runoff (Jenn et al. 2007a; 2007b).

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

Before water can recharge the aquifer, it first needs to infiltrate from surface into the subsurface and then percolate through the vadose zone to the water table. Infiltration is often considered the most common process of groundwater contamination and refers to the downward migration of water (originating from precipitation) under the influence of gravity through the open pores within the soil matrix. During infiltration, materials such as ions and clays are being dissolved and/ or mobilised for possible precipitation or deposition further down in the profile. Infiltration continues sub-vertically under gravity until the groundwater level is reached, from which the infiltrating water (sic. 'percolating' based on the subsequent paragraph) will spread laterally in the direction of groundwater flow and vertically due to gravity (Boulding and Ginn 2004). Infiltration can also be defined as that process responsible for letting water on ground surface pass into the vadose zone, including the volume of the water, and is governed by gravity forces and capillary action. Allaby and Allaby (2003) define infiltration as the "downward entry of water into soil" which is confirmed by Keary (2001), stating that infiltration is the "entry of water into the soil, usually by downward flow through the surface". The American Geological Institute (1976) adds that this movement of water is through pores or small openings through the soil surface into the ground.

Once water has infiltrated into the subsurface, four processes can occur: adhesion to soil, interflow (lateral flow in the unsaturated zone), transpiration (or evaporation if shallow enough) or percolation (e.g. Fitts 2002; Shaw 1994). Interflow water can daylight on surface again or can start percolating further down-slope, adhesive water is trapped in the vadose zone and transpired water leaves the subsurface and returns to the atmosphere. Percolation refers to that vertical movement of water through the unsaturated zone to the water table (Shaw 1994) or to "pass through fine interstices; to filter, as water percolates through porous rock" (American Geological Institute 1976).

Box 2. The Water Cycle and Movement of Subsurface Water.

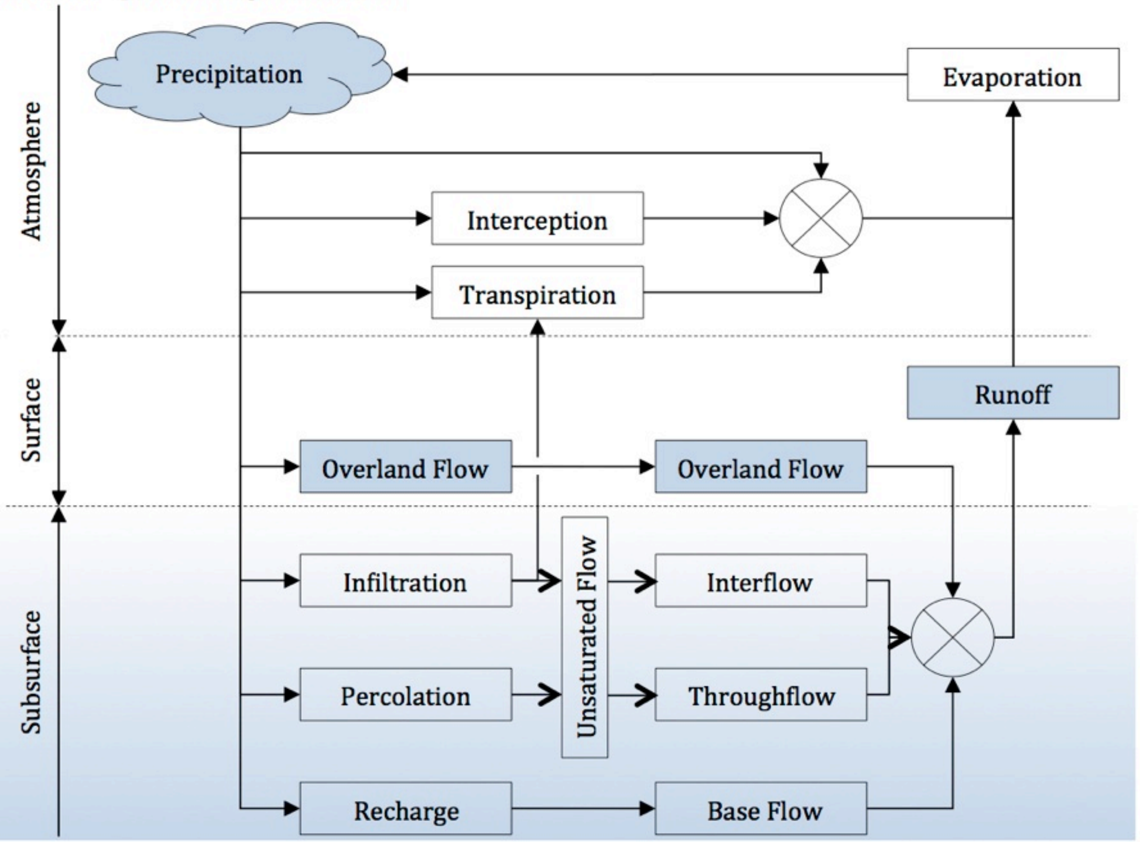
INFILTRATION refers to water entering the subsurface from the surface (due to the primary porosity or texture and secondary porosity or structure of the surficial soils which creates openings) and which is still affected by evapotranspiration; then moving sub-vertically downwards under the influences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

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

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

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

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



READ MORE & CITED FROM:

Dippenaar et al. 2010, Fetter 1994, Todd and Mays 2005, Younger 2007

In terms of pedology, percolation is considered that downward movement of water through soil material, notably in saturated or near-saturated conditions (Allaby and Allaby 2003). Rose (2006) replaces the term percolation with translocation, which is the subsequent movement of water down through the soil profile following infiltration into the soil surface. The term translocation is, however, elsewhere applied as the displacement of fines through moving water, and will henceforth be used in the latter context. Some sources consider percolation part of infiltration and do not distinguish between the two concepts, whereas others refer to (potential) recharge with reference to percolation, i.e. where infiltrating water exceeds the depth of influence of evapotranspiration.

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

2.1.3. Vadose zone hydrology per discipline

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

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

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

The study of subsurface hydrology generally falls within the earth scientific disciplines of soil science, geology and hydrology with notable input from other applied sciences such as botany, geography, meteorology and geomorphology. These latter disciplines involve the application of knowledge gained from earth science and water science to fields of importance such as plant water availability, biodiversity, water cycle interactions and geomorphological processes. The study of hydrogeology can be considered an intermediary between hydrology and geology as it represents some specialisation in both these fields.

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

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

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

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

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

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

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

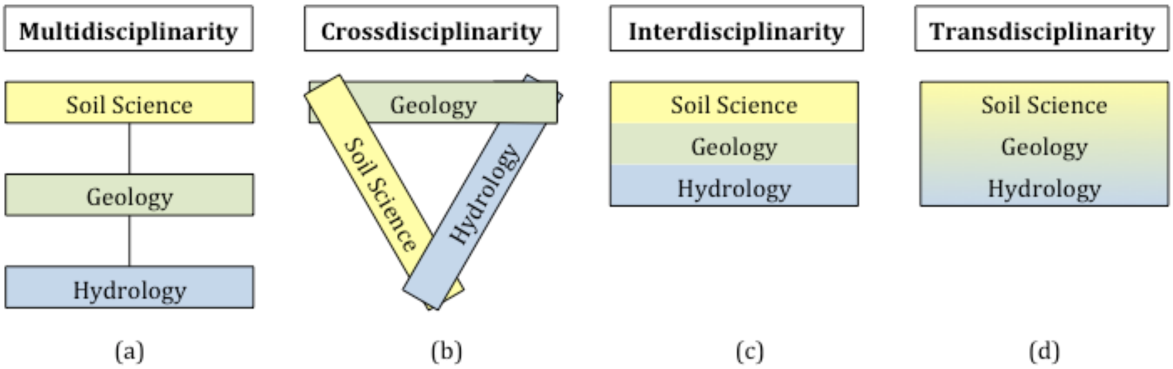


Figure 2-1. **Interaction between earth scientific disciplines.**

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

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

2.1.3.1. Environmental science and ecology

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

Wetlands, notably in arid countries such as South Africa, are critical in controlling the hydrological cycle and in ensuring biodiversity. Excluding the obvious wetlands in contact with surface water (fluvial, lacustrine, coastal), special types of ephemeral inland wetlands as addressed in §5.3 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) and SANBI (2009). 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, riparian interaction and habitat become dependent on the movement of water and nutrients through the vadose zone.

2.1.3.2. Hydrogeology and geohydrology

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

Aquifer vulnerability in general is addressed by Foster et al. (2002), 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).

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

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

2.1.3.3. Engineering geology and geotechnical engineering

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

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

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

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

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

2.1.3.4. Soil science, pedology and hydrology

For the soil scientist and pedologist, the vadose zone is important notably in the soil or plant root zone and involve application to plant water availability, irrigation efficiency, nutrients and more recently to the fields of contaminated land investigation from, for instance, tailings storage facilities and cemeteries. The development of the understanding of unsaturated flow and movement of solutes in the vadose zone is discussed by Fetter (1994, §4.1) and can primarily be attributed to the soil scientist with significant development in the field of contaminant transport through this zone.

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

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

2.1.4. Considerations in vadose zone hydrology

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

1. Surface
    1.1. Climate – precipitation, evaporation
    1.2. Plant water availability and transpiration
    1.3. Surface water – groundwater interaction
    1.4. Sensitive ecosystems
    1.5. Land use and land cover

2. Shallow subsurface
    2.1. Infiltration
    2.2. Perched water tables
    2.3. Interflow, throughflow
    2.4. Translocation and pedogenesis

3. Deep subsurface
    3.1. Percolation to eventual recharge
    3.2. Soil vadose zone
    3.3. Fractured rock vadose zone
    3.4. Variable saturation.

2.2. How we lose Ground when Earth Scientists become Territorial: defining "Soil"

We are a terrestrial species, and in the same manner we are territorial when it comes to our fields of expertise. In an ongoing study to link various disciplines interested in vadose (unsaturated) zone hydrology, it becomes evident that a serious communication gap exists due to the lack of interdisciplinary understanding, as well as the claim that your own discipline has the adequate answer.

This becomes increasingly important due to the fact that decision makers, environmental regulators and other involved parties very often rely on specialist reports without formal training in those relevant disciplines. Science is often the proof required in policy making, as discussed in interesting detail by Feller and Gamota (2007).

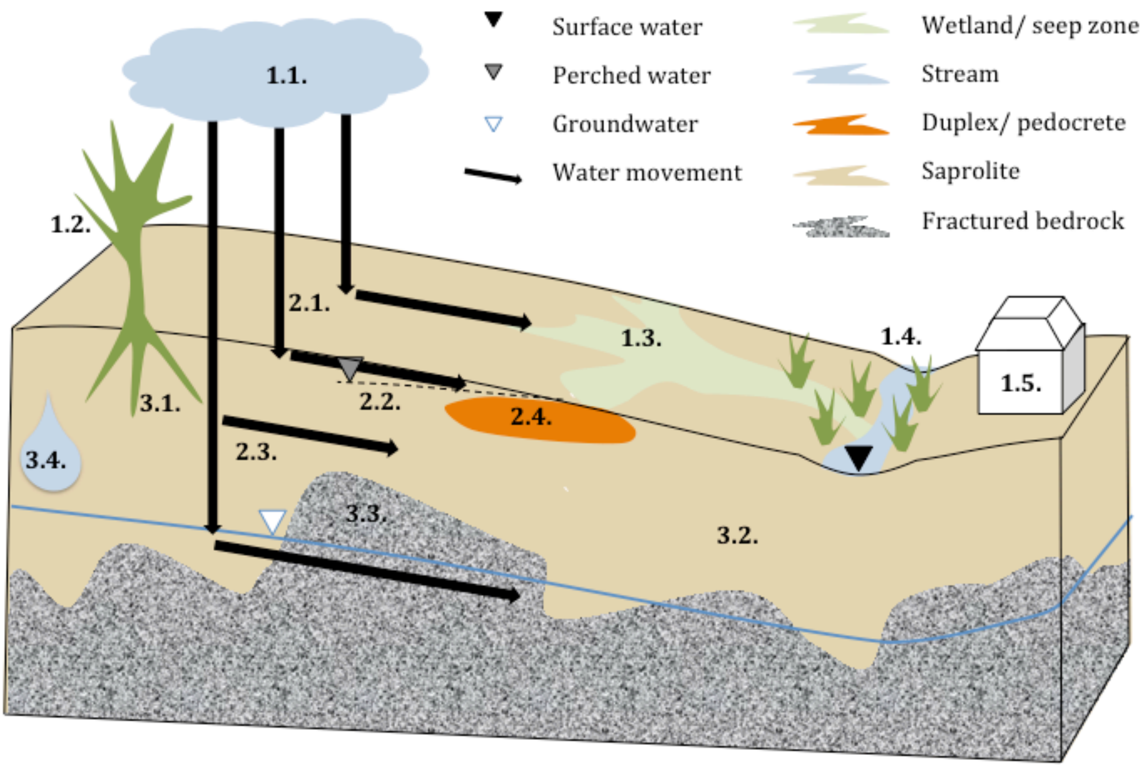


Figure 2-2. **Some considerations in vadose zone assessment.**

A World Bank publication (Foster et al. 2002) on groundwater quality protection also states this as part of the rationale, and then continues with the principles of aquifer vulnerability assessment which essentially entails qualification of the ability of the vadose zone to protect the phreatic zone from contamination. This can clearly not be possible without adequate understanding of all the variables and parameters.

Additional to this is the importance of grasping the full status quo of the science under investigation, thereby helping to avoid repetition of past mistakes, increasing the options of a way forwards, an promoting public understanding. These three are labelled efficiency, imagination and education by Maienschein (2000) and together with self-improvement and perspective are discussed as reasons for studying scientific history and, subsequently, different approaches and developments.

The purpose of this paper is not to find unanimity across all sciences. Each discipline has its own reasons for defining a certain term in a certain manner and this should not be replaced by broad, all-encompassing attempts consolidating a wide range of sub-disciplines into a single one. Rather, the aim is to clarify the importance of being aware of approaches and definitions pertaining to other related disciplines to ensuring better cross-disciplinary data sharing and the abiblity to extract valuable information from publications by parties with apparently dissimilar specialisation. Bouma (2006) elaborates on this in the context of the need of a proactive approach to hydrology and pedology and how each can add significant value to the other, provided that the necessary effort is made.

For the sake of this paper, the emphasis will be on two very broad aspects of importance to earth scientists, viz. the definition of soil and the classification of the vertical profile of the subsurface. Although numerous definitions and approaches exist, it is attempted to incorporate the most fundamental in this paper.

2.2.1. Earth science and approaches to the study of the Earth

Earth science refers to all Earth-related science and, although commonly used synonymously with geosciences or geology, includes any science studying any aspects of the Earth, including its age and structure (Lapidus 1990; CollinsLanguage.com 2011), and therefore incorporates, for instance, meteorology, oceanography, geography and geomorphology. Earth is capitalised here to distinguish it from the broader term "earth" which in itself is an argument in point; henceforth "Earth" will refer to the planet and "earth" to earth materials.

For the sake of this paper, the emphasis will be on five groupings of terrestrial Earth-related studies, viz. (1) geology, (2) engineering geology and geotechnical engineering, (3) soil science and pedology, (4) hydrology and hydrogeology, and (5) geography, geomorphology and environmental science. These disciplines consider the subsurface differently, mainly due to the various interests in the subsurface. Some approaches to weathering, for instance, were discussed by Ehlen (2005) and are available in the introductory sections of most topical references. Distinction with respect to the interest of a discipline to weathering (and subsequently soil formation) is made as follows:

1. Geology: Mineralogy and chemistry (especially clay chemistry); notably intact bedrock and not overburden; one-dimensional movement of elements
2. Engineering Geology/ Geotechnical Engineering: Physical environment; site characterisation; soil/ rock mechanics; one-dimensional rock material versus rock mass
3. Soil science/ pedology: Soil-forming processes; classification; shallow profiles from open pits; one-dimensional differentiation into (A, B and C) horizons
4. Hydrology/ Hydrogeology: Aquifer material; storage and transmissivity behaviour of materials and secondary structures; infiltration and flow
5. Geography/ Geomorphology/ Environmental Science: Weathering processes; spatial context; weathering versus landform evolution; weathering rates; dating of events

2.2.2. Clarifying basic concepts: what is soil?

Across these earth scientific fields of study, a wide range of different opinions and interpretations exist. One of the most basic, fundamental and yet inconsistent examples are the definition of soil and the vertical succession thereof.

In an attempt to define soil, FitzPatrick (1983) states that widely dissimilar views cannot be resolved and that one should maybe opt for a more concise description such as "soil is the space – time continuum forming the upper part of the Earth's crust". However, he continues to state that such a broad and short definition clearly excludes, for instance, the presence of plants and stable surfaces, and that one might just as well define soil as "anything so-called by a competent authority". Since then, the definitions have become significantly more formal and more discipline-specific. As an example of the complexity of inter-disciplinary understanding of basic concepts, some definitions of soil in various disciplines are discussed below.

Geology (when different from Soil Science):

- Dependent on origin, transport, subsequent stages of development and composition (Winegardner 1996)
- Finely divided rock material, weathered product of rocks and surface deposits containing varying amounts of organic material (Rahn 1986)

Engineering Geology/ Geotechnical Engineering:

- "Uncemented [sic.] or weakly cemented accumulation of mineral particles formed by the weathering of rocks" and the void spaces between these particles contain water and/ or air (Craig 1999)
- Finely divided rock material (White 1997)
- Material with physical and chemical properties which can be defined and manipulated or tolerated for construction (Winegardner 1996)
- Fragmented material finer than cobbles and excavatable without blasting and/or which disintegrates in water (Rahn 1986)

Soil Science/ Pedology:

- Unconsolidated mineral and organic material serving as growth medium, or that was subjected to and influenced by parent material, climate, macro- and microorganisms, topography and time (Schaetzl and Anderson 2005)
- Interface between Earth's surface and bedrock and subdivided into successive horizontal layers characterised by physical, chemical and biological properties (Council of Europe 1990 in Bridges and Van Baren 1997)
- Upper part of profile relevant to plant growth (Winegardner 1996)
- Material comprising soil horizon development and capable of supporting life (Rahn 1986)
- Natural body comprising animal, mineral and organic components with different horizons at depth and which differs from the material below in terms of morphology, physical composition and biological characteristics (Joffe 1948 in Bridges and Van Baren 1997)

Hydrology/ Hydrogeology:

- Uppermost unconsolidated Earth materials which can support plant life with the presence of sufficient moisture (Younger 2007)
- Storage reservoir influencing the catchment's water balance (White 1997)

Geography/ Geomorphology/ Environmental Science (when different from Soil Science):

- Mixture of eroded rock, mineral nutrients, decaying organic matter, water, air and living organisms (Miller 2000)

Following the broad definition of "soil", one is faced with the vertical variation thereof. Most disciplines have a means of "profiling" the vertical succession. This vertical distribution of earth materials is also commonly obscured by flexible definitions, for instance those conceptually indicated on Box 3 and comprising terms from a variety of disciplines. Although some of these horizons may be absent or amalgamated (e.g. the plant root zone will undoubtedly include the transported and/ or residual horizons and will also generally be the more organic horizon or topsoil), the general sequence remains fixed in undisturbed natural materials. Within this context, one can also add the pedological A, B and C horizons.

2.2.3. Soil in South Africa

Geologists and the wider engineering disciplines tend to describe the vertical variation in terms of transported (via erosion agents) materials overlying residual (derived from in-situ bedrock) material, eventually grading into fresh (intact) bedrock (e.g. Jennings et al. 1973). Weinert (1980) elaborates on these differences in a South African context, indicating that geologists consider soil to be the combined transported and residual material, which grades into completely weathered becoming fresh bedrock at depth. Residual soil – as opposed to completely weathered bedrock – loses the structure and mineralogy of the original rock type and subsequently is not classified as rock. Engineers, however, may consider this same profile and extend the soil well into the weathered bedrock, depending on its strength.

Engineering geology in South Africa defines soils for engineering purposes despite following geological investigative techniques. The reason for this is clearly the need for a non-geological audience to not only understand, but also apply results from scientific investigations to engineering applications. Brink and Bruin (2001) published guidelines on soil profiling for engineering geological purposes, clearly defining residual soil as material formed through in-situ weathering and with an unconfined compressive strength less than 1 MPa. More recent draft national standards lowered this strength distinguishing between rock and soil to 700 kPa (SANS 2009). Transported soil is defined as material transported by natural agents during relatively recent geological times respectively and not subjected to lithifaction or cementation (Brink and Bruin 2001).

The distinction in South Africa between transported and residual soil results from a long and complex geomorphological development (e.g. Partridge 1998) and this typical sequence is evident and very often divided by a pebble marker (stone line defining the contact between these two soil origins). The presence and easy identification of this pebble marker horizon therefore clarifies to the engineering geologist where one can expect residual material in the profile. Other stone lines do not characteristically indicate this separation and can be present within either of these two origins (e.g. Brink and Bruin 2001; Weinert 1980).

In a South African context, soil is defined as the unconsolidated mineral and organic material on the immediate surface serving as a natural growth medium for land plants, or alternatively as per Schaetzl and Anderson (2005), comprising the unconsolidated mineral matter on Earth's surface subjected to and influenced by parent material, climate, macro- and microorganisms and topography acting over a period of time (Van der Watt and Van Rooyen 1995). However, in a soil scientific context, classification is not based – as in Fig. 1 – in terms of origin. Soil scientists will rather opt for a profile based on vegetation-supporting properties into horizons based on the leaching and enrichment of colloids, soluble salts and organic material (Weinert 1980) and classify the vertical variation on, for instance, zones of eluviation and illuviation (e.g. Hillel 2003).

2.2.4. Interdisciplinary vadose zone research

Numerous interdisciplinary collaborations exist lately when considering vadose zone research. Examples are ample and include, for instance, the study of hydropedology (e.g. Bouma 2006), hydroecology , hydrogeoecology, groundwater ecology or studies for groundwater dependent ecosystems (e.g. Hymphreys 2009; Hancock et al. 2009) and biogeomorphology (e.g. Corenblit 2011). Such interactions are inevitably partially bridging the gap and hopefully encourage better knowledge of other sciences.

With the vast amount of subject-specific journals and books out there, and adding the research conducted by different parties from different disciplines, it becomes increasingly difficult to find similar work or data from publications due essentially to the confinement of results to a specific discipline. The results become, in effect, lost to the wider audience. A better understanding of the language (or jargon, if you will) of other sciences is needed to grasp the relevance of publications in a wider range of themes. A common example was illustrated briefly in terms of the definition of soil earlier in the paper, but applies to essentially every term. Engineers determine void ratios (volume voids / volume solids) where scientists prefer porosities (volume voids / total volume); some scientists refer to hydraulic pressures where others prefer the units of hydraulic head where 1 atm ≈ 10.33 m (e.g. Craig 1999; Koorevaar et al. 1999; Younger 2007).

From a hydrological (in its broadest sense) point-of-view, the problem becomes this: who stakes the claim on the unsaturated zone when most scientists are either interested in (a) infiltration, shallow interflow, and keeping water from recharge to ensure more plant water availability, or (b) groundwater flow where the complete vadose zone becomes a recharge estimate in groundwater characterisation. A definite interrelationship exists as we all know through the hydrological cycle, and yet most research focuses within convenient boundaries which essentially excludes very important influences. The problem, once again, is not necessarily ignorance or lack of awareness, but rather lack of appreciation of other approaches, methods and interpretations of existing knowledge.

Obviously, there is no solution to a lack of comprehension when reading academic literature not within one's own field of expertise. And, more importantly, there is no reason for a universal language, as this will inevitably be at a cost to the specialist sciences. Specialists are required, but not at the risk of not being understood. Rather than speaking one language, a need arises for more definitive text. Keywords and titles should reflect the primary intent of a paper, but should not exclude other sciences.

The only way that disciplinary interaction can be successful is with adequate understanding of the other disciplines – without this very small effort, no hydrogeologist can expect a soil scientist to appreciate his/ her results, and no soil scientist can add value to engineering. And this, for all practical purposes, slows down progress in science.

2.3. The Media

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

2.3.1. Basic phase relationships

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

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

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

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

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

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

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

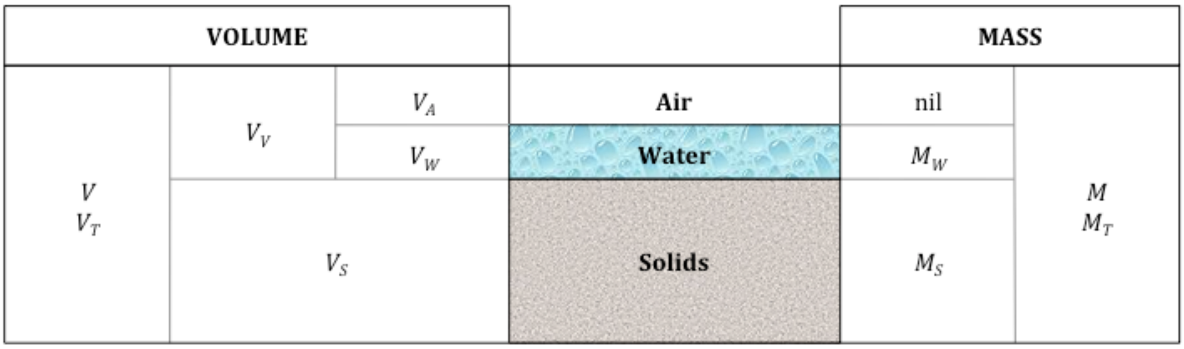


Figure 2-3. Phase relationships in unsaturated media.

Whereas porosity ratios pore volume to total volume, void ratio considers pore volume in relation to solid volume and, subsequently, only the numerator changes when void ratio changes, keeping the denominator constant and resulting in better application to scenarios of changing porosity (e.g. Hillel 2003).

2.3.2. Earth materials

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

- The medium itself changes over the range of organic, unconsolidated surface soils to hard, fresh, intact bedrock, which will indefinitely influence the effective porosity in the medium.
- The effective porosity can be governed by primary pore space or by secondary structures, or by a combination between these.
- The mineralogy will influence the leaching and deposition of clay minerals, as well as the mobilisation and precipitation of ions, both processes which will – over time – change the hydrology in certain horizons and will also affect capillary processes.

When distinguishing between rock and soil in terms of hydrology, the main importance is probably the significant differences between texture and structure that may influence the movement of fluids through the medium. Soil represents that interface between the atmosphere and lithosphere that interacts with the hydrosphere, sustains growth in the biosphere, can be distinguished from inert rock by the presence of organisms, is structurally organised due to pedogenic processes, and has a capacity to respond to changes in the environment (White 1997). However, soil can be defined in one discipline to include certain materials that in others are considered rock due to the application of the classification. Typical definitions for soil as well as the basic terminology pertaining to the vertical distribution of material in the Earth's crust are shown in Box 3, together with detailed combined definitions for soil and rock respectively.

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

Even though Box 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; similarly, the ecologist or agricultural soil scientist evaluates that portion of the material which is relevant to plant root penetration and water retention. For the geologist and geomorphologist, it becomes an indicator of the deeper and historical processes that shaped the landscape and formed the depositional environments. All definitions are in the end based on the need for defining soil and bedrock as separate entities.

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

Classification of soil also varies by discipline with the soil scientist being interested in the behaviour of the complete plant root zone, whereas the (engineering) geologist may be more interested in the relationship between the transported materials and the weathered bedrock. Classification in South Africa is briefly outlined in Box 4.

Foster (1984) and Foster (2012) present typical hydrogeological characteristics superimposed on a typified weathering profile for crystalline basement in south-eastern Africa. The same generic succession is followed by Koita et al. (2013) for granite in humid Ivory Coast. Although the climate inevitably results in more decomposition and deeper profiles, the proposed horizons provided are consistent with other terminologies with elaboration on the more specific terminology associated with the vertical succession of materials in Box 5.

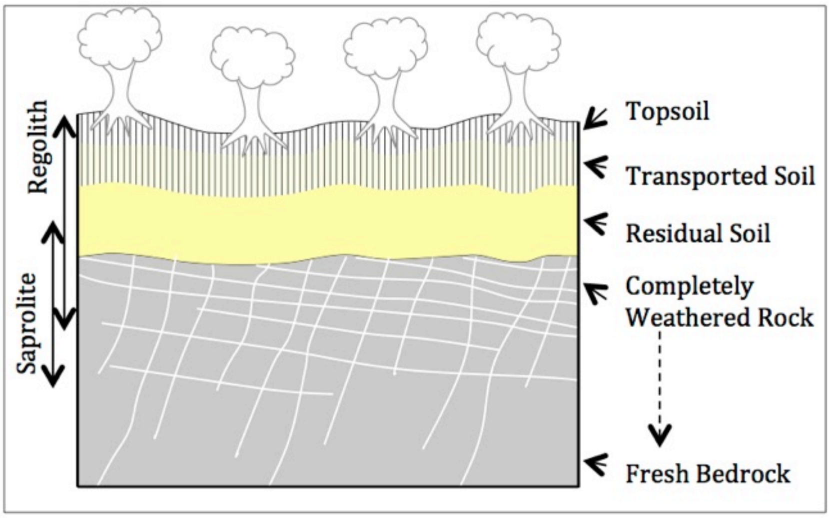
Rock and soil are both influenced hydrologically by the primary texture (or material) which forms during formation of the material, and the secondary structure (or mass) which is post-formational. For the sake of clarity, these aspects of ***material*** and ***mass*** will be addressed briefly for soil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

Box 3. Soil and the Vertical Succession of Earth Materials.

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

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

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



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

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

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

Box 4. Pedological vs. Geotechnical Soil Classification.

SOIL SCIENCE/ PEDOLOGY

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

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

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

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

ENGINEERING GEOLOGICAL/ GEOTECHNICAL ENGINEERING

Moisture:	Very dry, dry, slightly moist, moist, wet
Colour:	According to standard colour charts
Consistency:	Very soft, soft, firm, stiff, very stiff (cohesive soils; excess silt and clay) Very loose, loose, medium dense, very dense, hard (non-cohesive or granular soils) Very soft, soft, medium-hard, hard, very hard (rock)
Structure:	Intact (none), fractured, jointed, slickensided, shattered, laminated, pinholed, open
Soil Type:	Proportions gravel, sand, silt and clay (based on field estimation)
Origin:	E.g. colluvium, hillwash, alluvium, lacustrine, aeolian, anthropogenic (transported) E.g. iron-rich; ferruginized; powder, nodular, honeycomb, hardpan ferricrete E.g. residual, completely weathered to fresh bedrock

SOIL SCIENTIFIC/ PEDOLOGICAL

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

ENGINEERING GEOLOGICAL

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

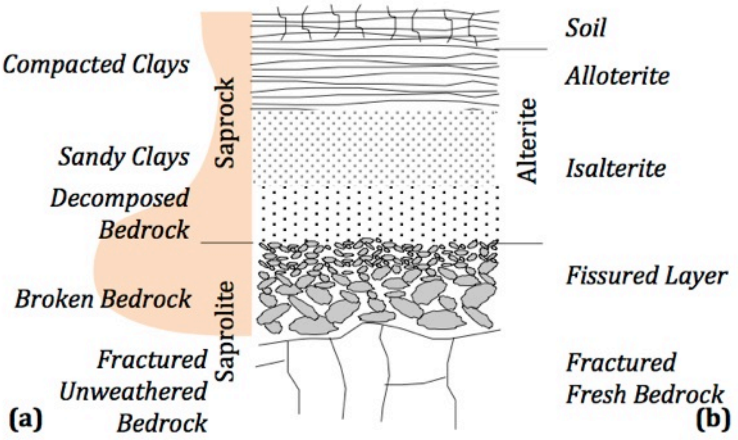
READ MORE & CITED FROM:

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

Box 5. Soil Profiles in Various Earth Sciences.

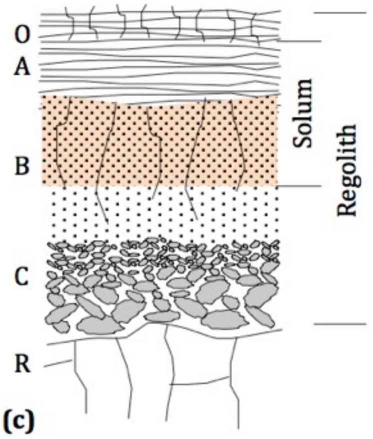
HYDROGEOLOGISTS

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

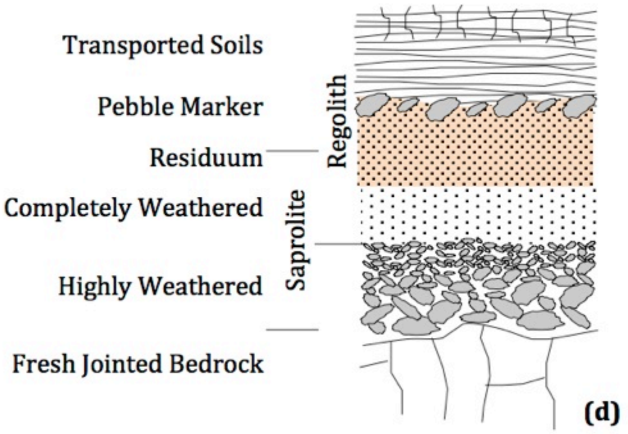


SOIL SCIENTISTS

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



ENGINEERING GEOLOGISTS



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

The shaded portions indicate the common position for pedogenetic enrichment.

READ MORE & CITED FROM:

Dippenaar and Van Rooy 2014; Foster 1984, 2012 (a); Hillel 2003 (c); Koita et al. 2013 (b)

2.3.2.1. Soil material, type or texture

Classification of soil texture is explained in Box 6. Particle size analyses refer to the percentage by mass of particles within different size ranges making up the bulk of a disturbed soil sample. For the coarse fraction, this is achieved by passing a soil sample through a series of test sieves, each with a very specific mesh size and subsequently able to allow only material finer than the mesh size to pass through. The mass of the retained soil is determined and a cumulative percentage is calculated for this fraction. The finer materials are determined through sedimentation techniques as a function of the velocity at which spherical particles settle from suspension according to Stoke's Law (Craig 1999).

The ***particle size distribution*** (or ***grading***) is usually presented on a semi-logarithmic plot with the cumulative percentage passing as the ordinate and the particle size as the abscissa as shown in Figure 2-4. A number of important parameters can be determined from the particle size analyses. Of these, the *d*-values refer to the particle size represented by a certain cumulative percentage passing. On Figure 2-4, the most important *d*-sizes are shown as follows:

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

Based on these *d*-values, certain coefficients can be defined, the most important at this stage being the coefficient of uniformity C_U as shown in Equation 7. The greater the value for C_U, the greater the range of particle sizes in the soil and the less uniformly graded the soil is.

$$C_U = \frac{d_{60}}{d_{10}}$$ **Equation 7**

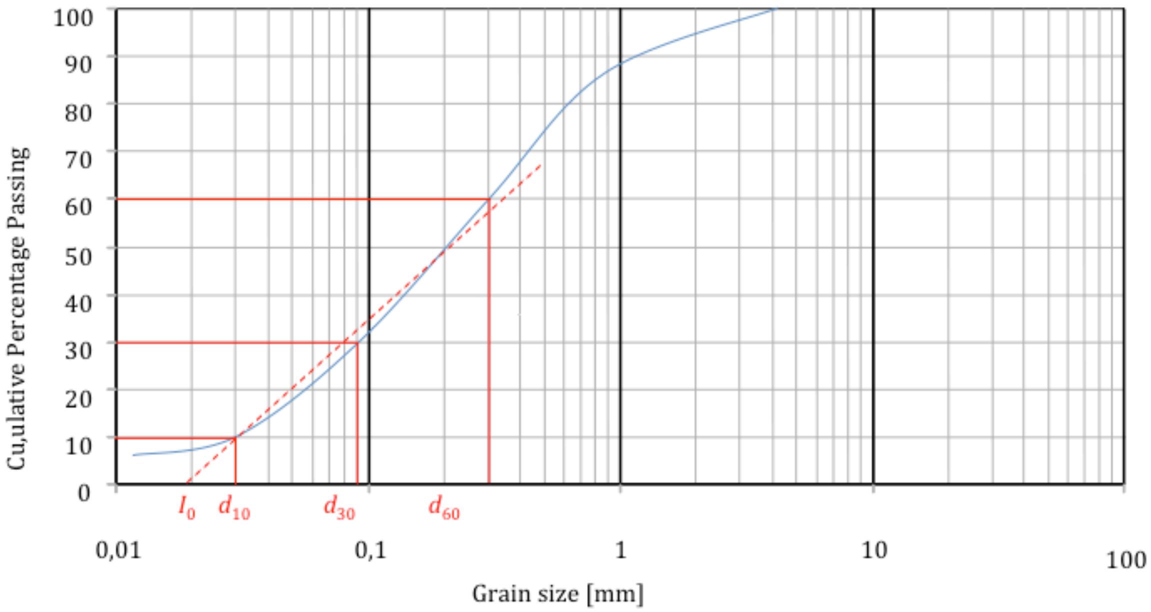
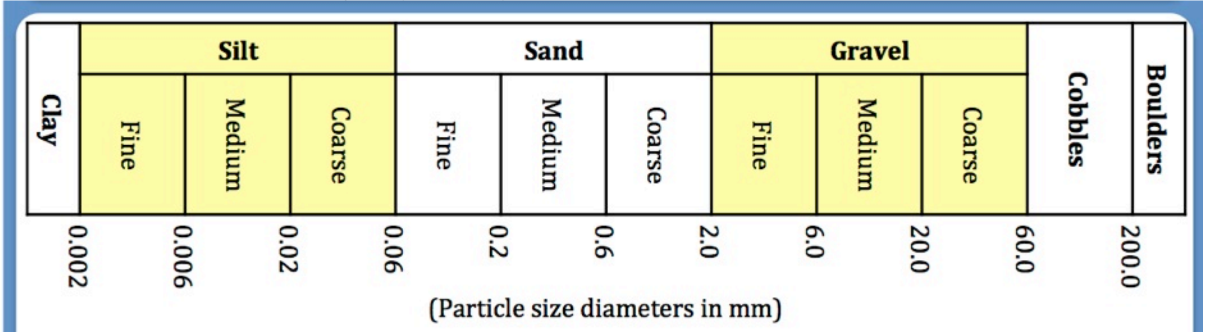
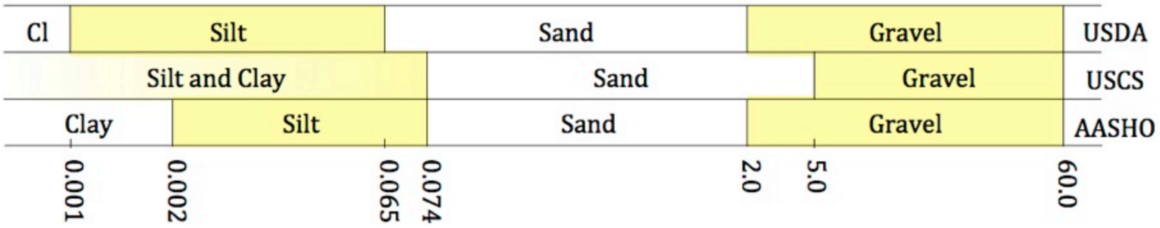


Figure 2-4. Determining the d-values from particle size distribution data.

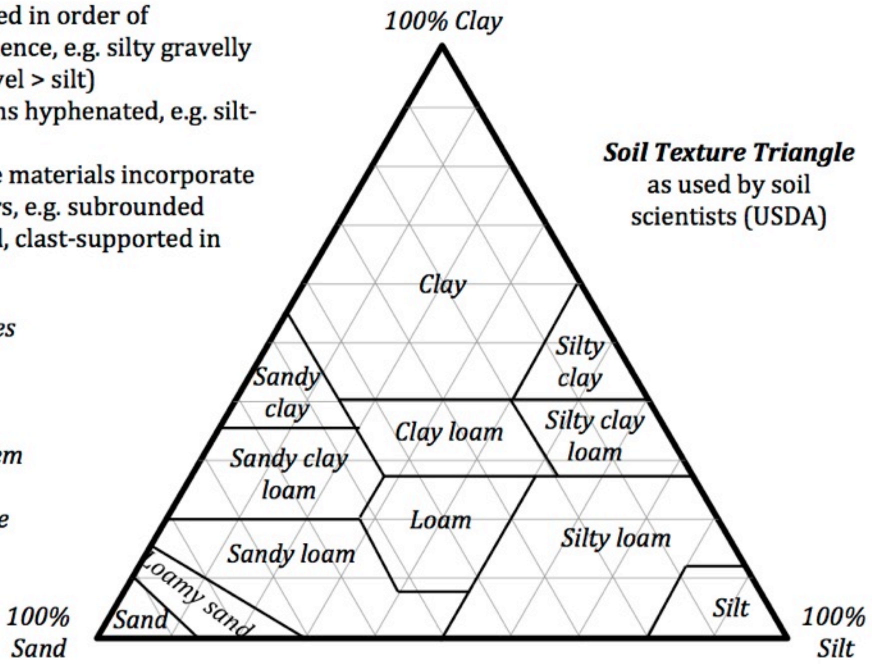
Box 6. Description of Soil Type (Texture).





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

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



Soil Texture Triangle
as used by soil scientists (USDA)

Descriptors for gravels, cobbles and boulders

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

READ MORE & CITED FROM:

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

For the example in Figure 2-4, C_U = (0.30 mm / 0.03 mm) = 10. Determination of the d_{10}-fraction is, however, not always possible as many grading analyses do not determine smaller diameters than 0.002 mm.

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 8 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 9 or Equation 10 can be used to determine that representative grain diameter d_i where f_i is the fraction of particles between the sieve sizes $d_{i(min)}$ and $d_{i(max)}$.

$$d_e = \frac{1}{\sum_{i=1}^{n}\left(\frac{f_i}{d_i}\right)} \quad or \quad \frac{1}{d_e} = \sum_{i=1}^{n}\frac{d_i}{f_i}$$ **Equation 8**

$$\frac{1}{d_e} = \sum_{i=1}^{n}\left(\frac{\sqrt{d_{i(max)} \cdot d_{i(min)}}}{f_i}\right)$$ **Equation 9**

$$\frac{1}{d_e} = \sum_{i=1}^{n}\left(\frac{d_{i(max)} + d_{i(min)}}{2f_i}\right)$$ **Equation 10**

2.3.2.2. Rock material

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

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

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

Mineralogy combined with origin also dictates the likelihood of water entering the rock and subjecting of these minerals to weathering.

2.3.3. Soil and rock mass (structure)

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

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

2.3.3.1. Soil mass or structure

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

- Structureless , i.e. not aggregated, and either single-grained (loose) or massice (hard mass when dray but without clear alignment)
- Blocky, i.e. roughly cubic aggregates, and either angular blocky or sub-angular blocky
- Prism-like, i.e. long vertical axes, and either prismatic or columnar
- Spheroidal, i.e. granular or porous crumb structures.

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

2.3.3.2. Rock mass or structure

Depending on the depth to ground water, bedrock can also form a major part of the vadose zone. The factors controlling flow through rock differ from those controlling flow through unconsolidated porous materials, notably due to the presence of a secondary porosity.

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

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

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

Some important considerations in the description of bedrock include:

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

2.3.4. Tertiary porosity

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

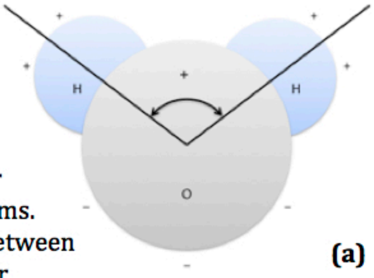
These weathering voids may, for instance, play significant roles in the vadose zone in karst areas where sinkholes and cave systems may serve as so-called swallow holes forming near-direct routes between the land surface and the groundwater table. In terms of soils, tertiary porosity may be linked to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

2.3.5. Fluid phase

Essentially two types of fluids can occupy the voids in a porous medium: liquids and gases. For the purposes of hydrogeology, these are almost always (with certain obvious exceptions) water and air. Water has a fundamental property whereby it is at its densest state as liquid and water is therefore practically incompressible. Some important properties of water are explained in Box 7.

Box 7. Properties of Water.

WATER, ITS PHASES AND PROPERTIES



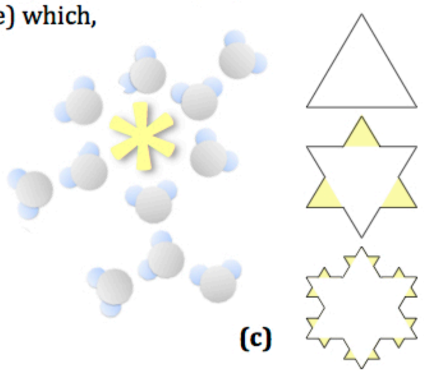
Water comprises of water molecules (H_2O) in the molecule dihydrogen monoxide and minor other trace ions and molecules. In its liquid state, water molecules are closely packed but constantly moving. Water molecules are polar with a more positive charge near the hydrogen atoms and a more negative charge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

Property	Symbol	Units	Value
Mass density	ρ_W	[M/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 x 10-10 m^2/N
Dynamic viscosity	μ	[FT/L^2]	1.4 x 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			

Above: some important properties of water.

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

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



FLUIDITY

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

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

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

READ MORE & CITED FROM:

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

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

Occasionally, fluids that are immiscible with water coexist in the void space. This in notably eminent in hydrocarbon contaminated sites where non-aqueous phase liquids (NAPLs) infiltrate into the subsurface. The concepts of wettability and capillarity become important here and will be discussed in detail in §2.5.2.1.

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

2.4. Porosity Reviewed: Quantitative Multi-disciplinary Understanding, Recent Advances and Applications in Vadose Zone Hydrology

Albeit a straightforward concept (how hard can determining the ratio of voids to solids possibly be?), quantification of porosity is often significantly simplified. The importance of porosity in hydrology as a primary input parameter in almost all subsequent calculations is overlooked and the parameter is estimated without any validation, resulting in significant unquantifiable errors in hydraulic parameters. However, the simple percentage value of porosity is only one such aspect. The importance of type, scale and connectivity of porosity is commonly understood, but rarely evaluated in significant detail.

A detailed discussion in Miller and Gray (2002) on the status of groundwater research accentuates a number of aspects requiring more research and where our understanding is often not sufficient. Reference is made particularly to preferential flow paths such as fractures and the resulting complicated accounting of interactions between these fractures and the flow through the primary pore space. They continue to elaborate on the difficulty of accounting for scale ranging from molecular to regional field problems. Fractured systems are singled out due to the difficulty in characterising and modelling fractures with available methods and because of their interaction with the porous matrix.

The importance of porosity spreads over a wide range of disciplines. For the hydrologist or hydrogeologist, the porosity determines the void space available for water storage, as well as the capillary rise and ability of the void space for fluid flow, which depend on the size and continuity of the pore spaces. For the engineers, geologists and soil scientists, additional emphasis is placed on consolidation, shrinkage and swelling behaviour, surface subsidence and variation in material properties due to leaching and precipitation processes. All of these are important, making it necessary to consider the widest possible definition of porous media; i.e. to include all types and scales of porosity, as well as all degrees of connectivity, as opposed to only connected matrix porosity.

2.4.1. Porosity explained

In any natural system, three inorganic phases can coexist as defined in §2.3.1. Numerous different symbols are used for porosity, including Greek eta (η as used henceforth), Latin n and Greek phi (Φ).

Unless undergoing volume change, the pore space or void space remains 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 storage and movement through porous media. It is, therefore, important to understand the void space geometry before considering the solids and fluids comprising the medium.

Classification of porosity can be based on a number of aspects. Essentially, three important aspects should be considered when addressing porosity:

- Type of porosity, i.e. primary (textural, soil material, matrix) porosity versus secondary (structural, soil mass, fracture) porosity to account for the differences in the nature of the void spaces and connectivity
- Scale of porosity, i.e. submicroscale, microscale, mesoscale and macroscale porosity to account for variations in porosity with varying scales of consideration (the Representative Elementary Volume concept as discussed later)
- Connectivity of porosity, i.e. whether it allows the transmission of water as opposed to porosity which cannot contribute to the flow of water (dead-end or non-connected pores).

Although these considerations are the personal view of the author, the inclusion of one or more of these considerations appear throughout academic research. Each of these will be addressed separately to clarify the context and to emphasise the importance of consideration of all three together.

2.4.1.1. Type of porosity

When distinguishing between rock and soil in terms of hydrology, the main importance is probably the significant differences between texture and structure that may influence the movement of fluids through the medium. Soil represents that interface between the atmosphere and lithosphere, interacts with the hydrosphere and sustains growth in the biosphere and can be distinguished from inert rock by the presence of organisms, a structural organisation due to pedogenic processes and a capacity to respond to changes in the environment (White 1997). However, soil can be defined in one discipline to include certain materials, which in others are considered rock due to the application of the classification (as evaluated in numerous cross-disciplinary papers and as summarised in for instance Dippenaar 2012). However, when considering the concept of porosity, which is clearly defined mathematically, nomenclature becomes irrelevant and the distinction between types of porosity is based on the morphology of the pore spaces resulting from the formation of said pore spaces.

This pore space geometry is subsequently subdivided into two (and occasionally three) distinct classes:

1. Primary porosity, also termed textural, matrix or interstitial porosity in science and porosity relating to soil or rock material in engineering, refer to the void space formed simultaneously with the formation of the soil or rock. This can, therefore, be viewed as the openings between distinct soil grains or minerals forming a rock.
2. Secondary porosity, also termed structural porosity in science and porosity relating to soil or rock mass in engineering, refer to the void space formed after formation of the soil or rock. This is more noteworthy in rock as fractures (resulting from, for instance, jointing and faulting) or metamorphic textures (such as gneissosity), and to a lesser extent in soils as preferential paths due to, for instance, plant roots, insect or worm burrows, prismatic jointing and dessication cracking.
3. Tertiary porosity is often considered together with secondary porosity and relate almost exclusively to soluble rock. In hydrogeology, karst is the prime example of this where primary and secondary porosity are altered by extensive chemical weathering processes such as dissolution to create large void space as is commonly represented by dolomite cavities.

Primary porosity is the easiest to quantify as fairly homogeneous soils in a naturally consolidated packing will result in porosity being a function of the effective grain size (d_e) and the packing of the uniform spherical grains of diameter d_e. With increasing textural variability, the empirical estimation of primary porosity becomes increasingly inaccurate. Applying the effective grain size diameter to tetrahedral and cubic packings, standard pore relationships and porosities exist as shown in Figure 2-5.

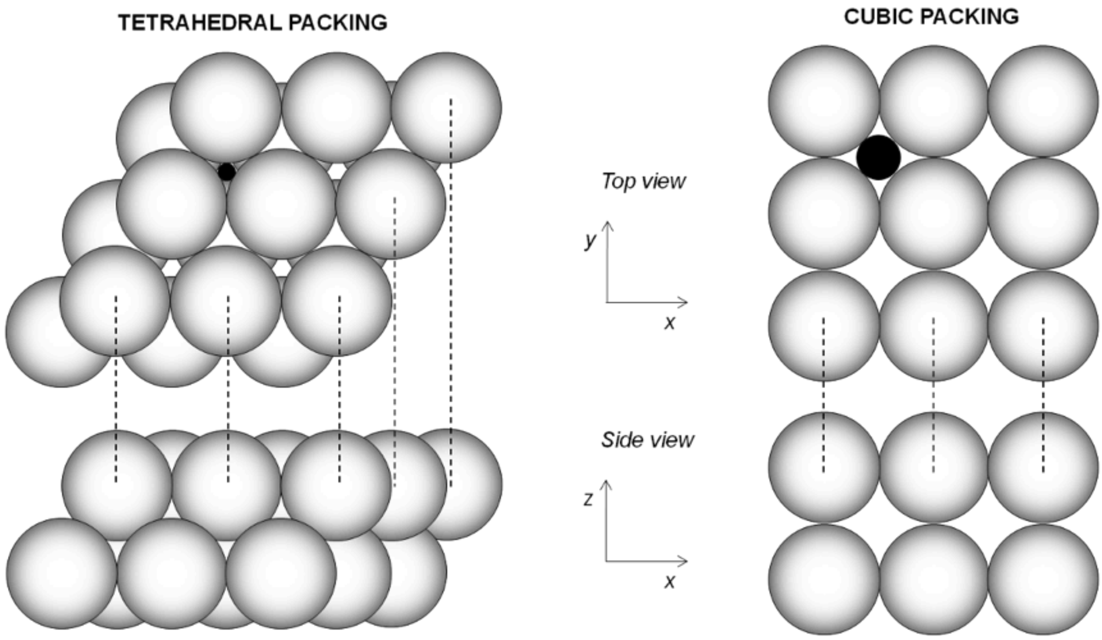


Figure 2-5. **Typical packing of naturally consolidated uniform spherical grains of similar diameter; black grains indicate probable clogging of void spaces by smaller diameter particles which result in lower porosity.**

Given this scenario, the porosity results in 0.260 (26.0%) for tetrahedral packing and 0.476 (47.6%) for cubic packing. Important to note is that the porosity is for materials composed of uniform sized spherical particles is not dependent on the effective grain size diameter, but solely on the packing of the grains. However, in non-uniform materials, finer grains are able to clog the void spaces formed and the porosity will be lowered substantially. This concept has been discussed in a vast amount of topical groundwater-related textbooks (e.g. Bear 2007; Fetter 1994; Todd and Mays 2005; Younger 2007).

Primary porosity is common in most unconsolidated sediments and unmetamorphosed sedimentary rocks such as sandstone. An example of Karoo Supergroup sandstone from the Kruger National Park (South Africa) is shown in thin section microscopy in Figure 2-6, clearly showing the quartz grains and the open voids.

Secondary porosity is more difficult to quantify, especially as a separate porosity has to be determined for primary porosity as well, and because each structure can have it's own properties. Zoomed in to a wide-open structure (the REV concept as will be discussed later), the structure may have a porosity of unity as it comprises only void space. In this instance, characterisation of other aspects become increasingly important, notably the continuity of the structure, its aperture and clogging or coating of the planes by for instance clay minerals and precipitates. An example of secondary porosity is shown in Figure 2-7 in outcropping fractured Lanseria gneiss from Midrand to the north of Johannesburg (South Africa).

Regarding 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 United States of America, to replace fracture. According to the American Geological Institute (1976) a fissure is "… an extensive crack, break or fracture in the rocks" and usually excludes mere joints or cracks that persist only for short distances. As opposed to fractured or fissured rock, intact refers to unweathered and unfractured state and therefore the absence of secondary porosity.

Fractures include faults and joints and the further distinction between fractured rocks and fractured porous rocks become important. Fractured rocks relate to the fractures themselves, whereas fracture porous rocks include the contribution of the porous host rock. This distinction results in different porosity and permeability values and is characterised based on single fracture models or fracture networks (Berkowitz 2002). Potential problems with fracture models and, notably, the cubic law is discussed in great detail by Witherspoon et al. (1980) and include the difficulty of measuring exact facture aperture, the roughness of the fracture surfaces, the closing of portions of the fractures under stress and the influence of weathering

Pore radii and its influences on capillarity are a function of pore geometry. Three idealised geometries (cylinder, parallel plates and sphere) are shown in Figure 2-8 together with the calculation of pore volume, surface area, and volume to surface ratio.

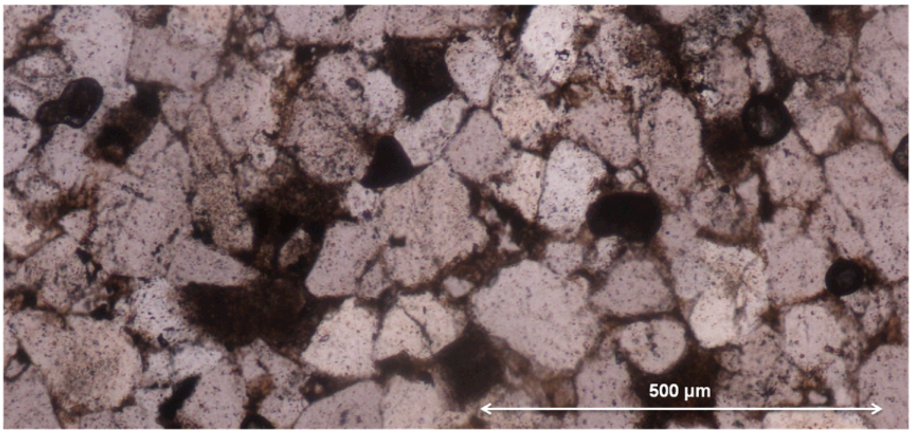


Figure 2-6. Primary porosity (dark patches) in Karoo Supergroup sandstone from the Lower Sabie region (Kruger National Park, South Africa); note the lack of connectivity between some of the void spaces.

Figure 2-7. Secondary porosity in the form of parallel joints in fractured Lanseria Gneiss (Johannesburg Dome Granite) from Midrand (Gauteng Province, South Africa); note the varying apertures.

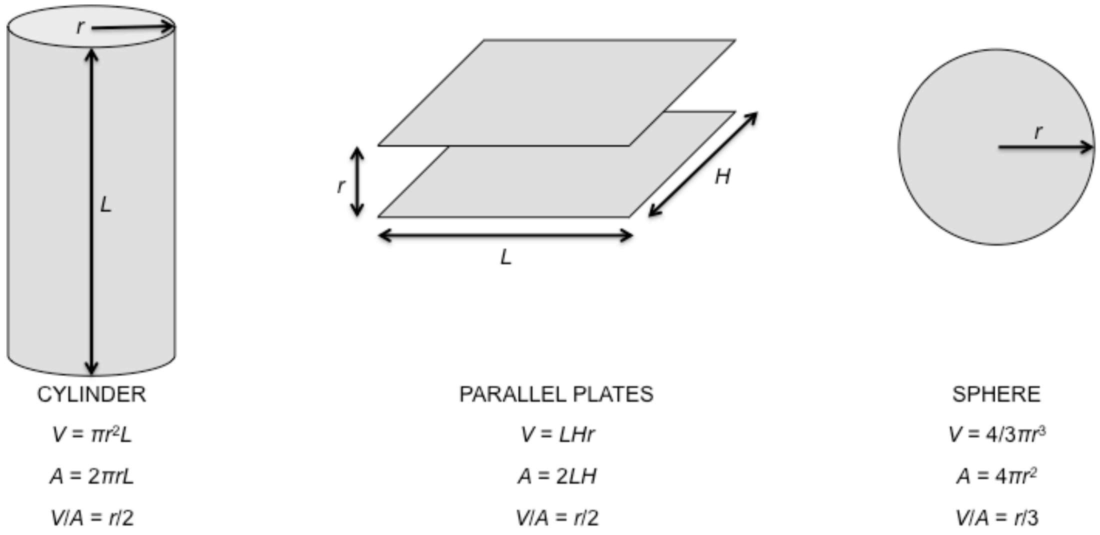


Figure 2-8. Idealised soil pore geometries (after Lu and Likos 2004).

2.4.1.2. Scale of porosity

The scale of porosity can best be visualised by the representative elementary volume (REV) concept described in detail by numerous authors (most notably in Bear 2007; Bear 1988). These so-called domains of microscopic and macroscopic heterogeneity refer to the different scales of porosity detected at varying scales of investigation with the domain of macroscopic heterogeneity possibly referring to, for instance, major structural features such as faults and shear zones (Figure 2-9).

Another means of simplifying the concept is to visualise a fixed unit volume with fixed porosity with uniform distribution of the porosity. Figure 2-10 shows a possible three-joint fractured system (two vertical, one horizontal) resulting a rock blocks of different size and voids with different apertures. Although the porosities of all three these systems may be similar, the noteworthy distinction is in the scales resulting in different pore sizes. From a purely sedimentological point-of-view this may not be extremely important, but the competing adhesive-cohesive forces will vary significantly in these systems, resulting in the retention of certain moisture contents in the smaller pore spaces while resulting in gravitational flow in the larger ones. Additionally, the radius of the pore space is inversely proportional to the height of capillary rise.

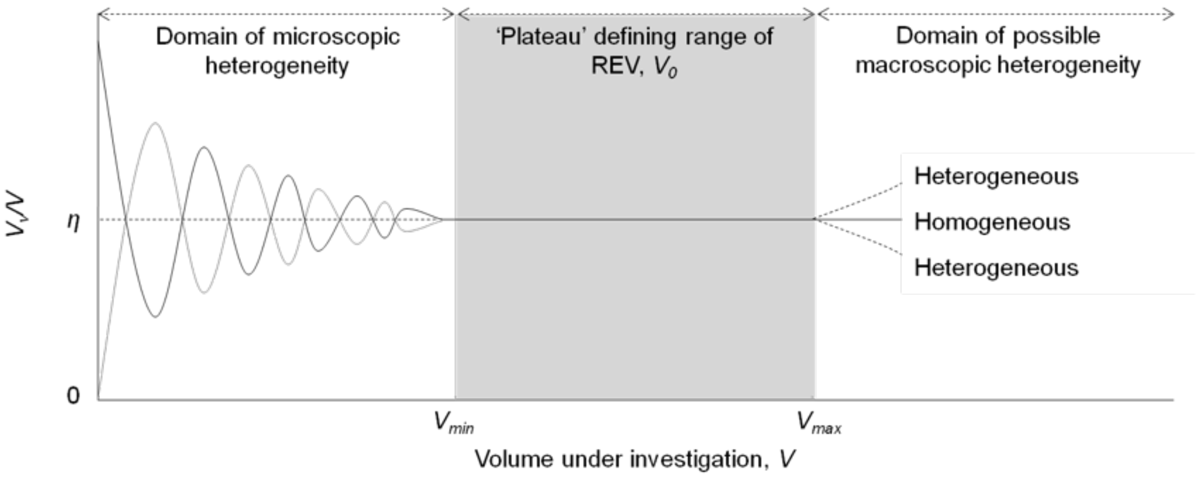


Figure 2-9. The representative elementary volume depicting zones of microscopic and macroscopic heterogeneity (after Bear 2007).

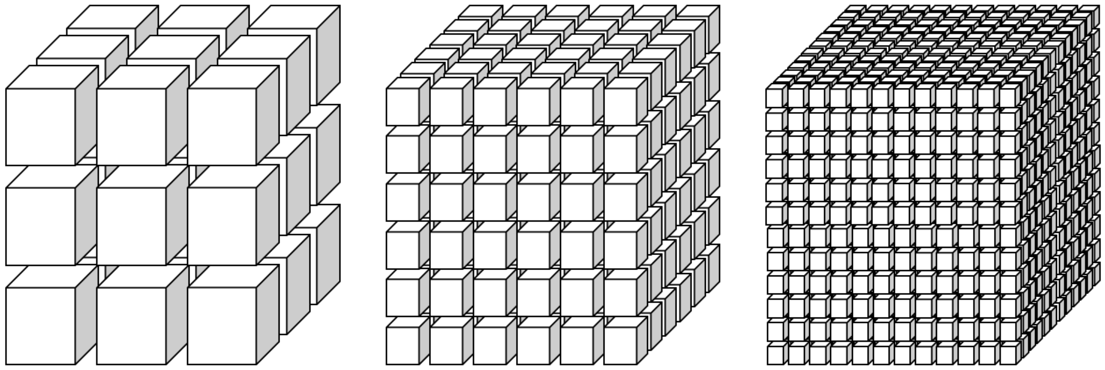


Figure 2-10. Similar porosity schematically depicted at varying scale in a fixed unit volume.

Multiple REVs can exist depending on the scale of investigation. It is, for instance, possible that a sample of 1 cm^3 can have a fixed 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 overriding the hydraulic properties of the smaller scales. Numerous authors (e.g. Dexter and Richard 2009; Dudoignon et al. 2007; Kutílek 2004) evaluated the various scales of porosity. In summary, for soils, macropores typically relate to vertical prism joints or any other pores which are non-capillary; mesopores are typically due to shrinkage cracking and 100 – 2 000 μm; micropores are due to the clay-matrix and particle arrangement and are capillary pores; and submicropores relate to water molecules and flow path inhibiting sized capillary openings. The pore sizes according to these texts roughly correlate as follows: macropores typically relate to coarser than gravel, mesopores fall within the sand and silt range, micropores are typically related to the clay fraction, and submicropores go into the water molecular size range.

Figure 2-11 summarises typical influences of soil and rock texture and structure 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.

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

Figure 2-11. Summary of typical (although not as clearly definable) scales of porosity at the hand of relevant examples (adapted from Dippenaar et al. 2010).

Additional to the scale of porosity is the homogeneity and isotropy and the natural system. With vertical and spatial variation in earth materials (texture, consolidation, structural influences, pedogenetic processes, eluviation and illuviation, etc.) porosity will also change. Cognisance of this is required when addressing hydrology, as different porosities will indefinitely influence the hydrological behaviour of earth materials.

2.4.1.3. Connectivity of porosity

When considering porosity in hydrology, it can be subdivided into essentially two components, namely effective (drainable or interconnected) porosity and non-effective (non-drainable, disconnected or dead-end) porosity. The sum of these two are referred to as the volumetric porosity as determined in Equation 5 and the non-drainable porosity should theoretically be excluded from hydrological assessments as it cannot contribute to the movement of water, although it is an important parameter in engineering, notably when quantifying consolidation. Effective porosity is sometimes estimated based on the specific yield, S_Y, referring to that "volume of water that will drain by gravity per unit drop in the water table per unit volume of aquifer" or the drainable porosity. The remaining water attached to the solid surfaces in the voids is referred to as the specific retention, S_R (Weight 2008) as shown in Equation 11.

$$\eta_T = S_Y + S_R$$ **Equation 11**

Various terminologies exist when relating porosity respectively contributing to and not contributing to flow. The terms effective porosity (η_E as the dominant mode of fluid transport through flow), diffusion porosity (η_D as the dominant mode of aqueous diffusion) and residual porosity (η_R where not flow takes place due to lack of inter-pore connection) are described by Norton and Knapp (1977), whereas Tullborg and Larson (2006) employ connected porosity (η_C which are pores available for water saturation) and unconnected porosity (η_N = total porosity minus connected porosity). These parameters are placed in context in Equation 12 (symbols and subscripts have been standardised from original texts).

$$\eta_T = \eta_E + \eta_D + \eta_R = \eta_C + \eta_N$$ **Equation 12**

Effective porosity is governed by the interconnectivity of voids, which result essentially from the pore space geometry due to the packing of the solid phase of the material. At the most basic level, this entails cubic versus tetrahedral packing as shown in Figure 2-5. 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 in soils
- Effects of cementation and lithification in sedimentary rocks, crystallisation in igneous rocks and subsequent metamorphism.

Based on this heterogeneity and anisotropy, void spaces cannot merely be measured and assumed for the bulk of the sample and two additional 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 ellipse with an area equal to that of the cross-section of the pore. To help with the calculation of this pore space geometry, the feret concept can be used where a feret represents the spacing between two parallel tangents to a void feature in a given direction. The maximum feret refers to the maximum possible distance between two such lines and the minimum feret to the minimum distance or to that distance perpendicular to the maximum feret (Mathews et al. 1997). Entrance of water into the pore therefore depends on the size of the pore throat and the storage of water on the size of the pore itself – an important aspect, which also governs the processes of drainage and imbibition. Figure 2-12 illustrates pores and throats, the ferret concept and the presence of unconnected pores.

The connectivity of pore spaces also governs the movement of ions and fines (clay minerals) with moving water. These ions can mobilise and precipitate and the clay minerals can clog the soil skeleton depending on the ability of water to move through the material. The result of these processes is very distinct vertical and spatial variation in soil hydraulic properties, as certain portions of the profile will become more porous whereas a subsequent horizon may become clogged. Figure 2-13 shows typical clay-related clogging microstructures in context of the vertical distribution of water in the crust.

The vertical leaching of clay minerals – notably kaolinite in coarse-grained soils – typically result in a kaolinite-rich horizon overlain by a leached collapsible horizon, both with distinctly varying porosity. Aggregate formation results in increased strength and changes in soil structure, which – as a direct function of porosity – will inevitably influence hydraulic behaviour (e.g. Horn et al. 1994; Skolasinska 2006).

Changes in hydrological behaviour can also result in perched or fluctuating water levels, which in turn may result in the development of pedogenic soil horizons. 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. Based on the climatic conditions and the available ions mobilised, these pedocretes include, for instance, ferricrete (Fe-enriched), laterite (generally aluminous) and calcrete (Ca-enriched). Of importance here is that the pedocrete is formed from either gravitational or rising water and therefore alters the porosity vertically downwards or upwards as pedogenetic or groundwater pedocretes respectively and the direction of formation is evident by increasing mottling (§2.7.1; McFarlane 1976). The resulting pedocrete can then range from highly porous to very low porosity depending on the stage of formation. Alternative terminologies and theories on the development of these cemented soils (e.g. duripans, duricrusts, plinthites) are discussed in numerous topical references (e.g. Blatt and Tracy 1997; Brady and Weil 1999), but pedocretes almost always refer to cemented materials, whereas the pans in soil sciences often involve compacted materials which do not necessarily exhibit any cementation, or alternatively entail cementation by means of clay minerals.

2.4.1.4. Type, scale and connectivity combined

Each in its own capacity appears easily identifiable, notably form visual observation of specimens at different scales. Nonetheless, the quantification of each in order to accurately determine hydraulic conductivity, for instance, is required for proper hydrological understanding. Porosity in hydrology and, more specifically, vadose zone hydrology and hydrogeology, is not merely a volume relationship. The type, scale and connectivity need to be addressed quantitively in detail.

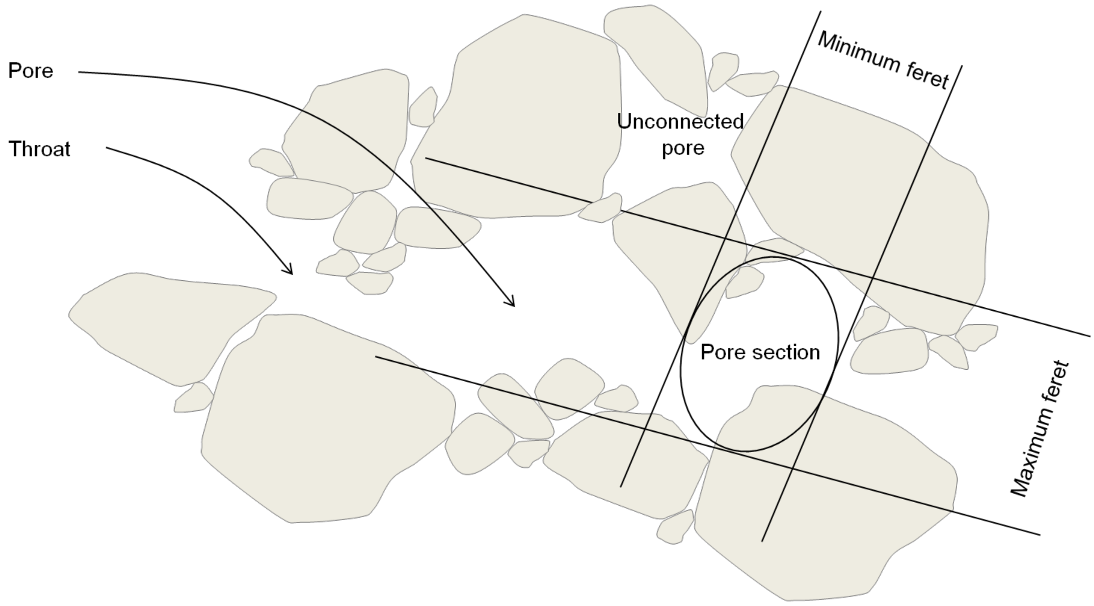


Figure 2-12. Pores, throats, ferrets and unconnected pores (adapted from Mathews et al. 2007).

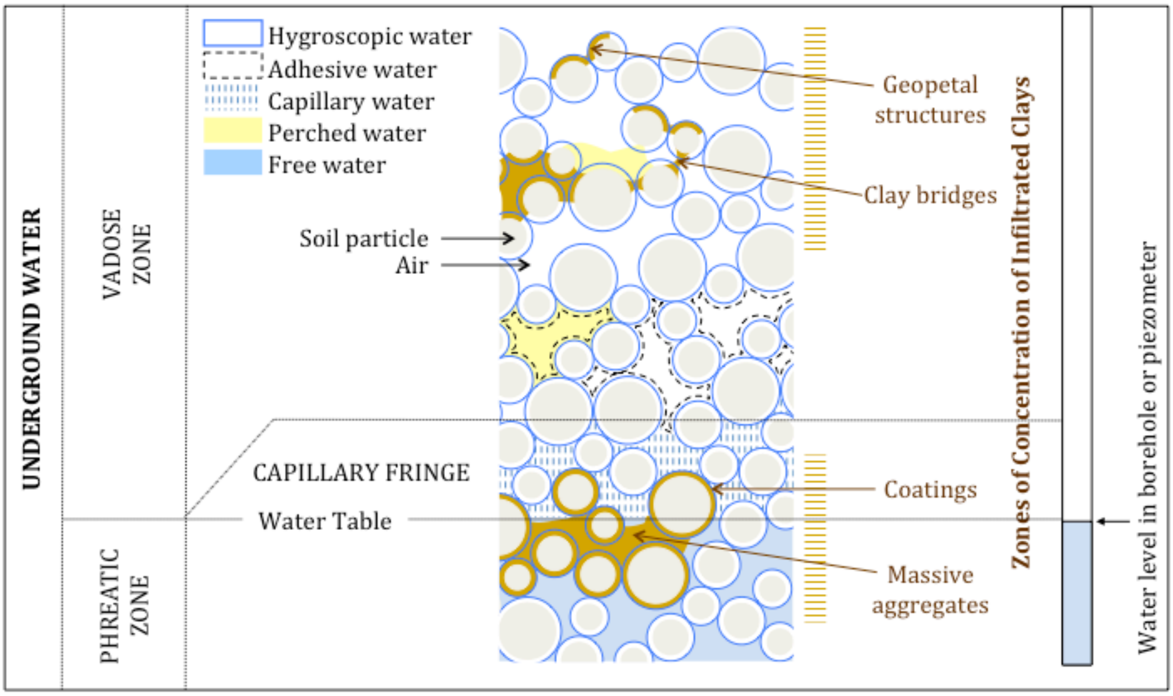


Figure 2-13. Vertical distribution of water in the crust and the concomitant clogging structures (adapted from Moraes and de Ros 1990, Shaw 1994, Skolasinska 2006).

2.4.2. Porosity in hydrology

Although significant overlap exists in the consideration of type, scale and connectivity of porosity in hydrological terms, the inclusion of specific attributes to the three considerations are based on the influences of the attribute to the hydrological behaviour of the material. In more practical terms, type of porosity relates to what needs to be investigated (texture or structure) and to how a hydrogeologist would classify it was it an aquifer. Similarly, scale of porosity addresses adhesion and cohesion and subsequently influences important concepts such as soil suction, capillarity and field capacity. The connectivity is determined directly from the type and scale of porosity, but pertains exclusively to the ability of the medium to allow water entry to a pore, to store the water in said pore and to transmit water between pores.

Movement of water is governed by a number of forces, notably gravity for acceleration (also influenced to a lesser degree by overburden pressures and degassing) and adhesion, turbulence and friction for retardation (Kovács 1981). The presence of connected pores will undoubtedly act to promote the movement of water, provided that the pore spaces are vacant for the entry of water and that the porosity does not significantly decrease in the direction of flow. However, the counteracting forces are all also directly dependent on the porosity. Whether adhesion will retain water to the mineral surfaces or whether cohesion will result in pore water available for drainage is a relationship between the surface area of the pore and the available water in the pore space. As the moisture content increases, more of the pore space becomes occupied with water, resulting in increased unsaturated hydraulic conductivity until a theoretical maximum saturated hydraulic conductivity is encountered at saturation (e.g. Fitts 2002). This basic yet fundamental relationship is shown in Equation 13 where the volumetric moisture content θ is the volume water divided by the total volume, Equation 14 where the water saturation S_W is volume water over volume voids, and Equation 15 where, at saturation, $S_W = 1$ resulting in $\theta = \eta$ and the hydraulic conductivity K equal to the theoretical maximum saturated value K_{sat}.

$$\theta = \frac{V_W}{V_T}$$ **Equation 13**

$$S_W = \frac{V_W}{V_V}$$ **Equation 14**

$$S_W = 1$$
$$\Rightarrow \theta = \eta \; and \; K = K_{sat}$$ **Equation 15**

In hydrology, this therefore adds a fourth consideration to the concept of porosity, viz. water saturation of the pore space, as changes in the moisture content or the degree of saturation will result in different hydrological behaviour of the same porous material. The evaluation of the three porosity considerations and the fourth consideration relating to water saturation of the pores combined will increase confidence in vadose zone hydrological assessments (Figure 2-14).

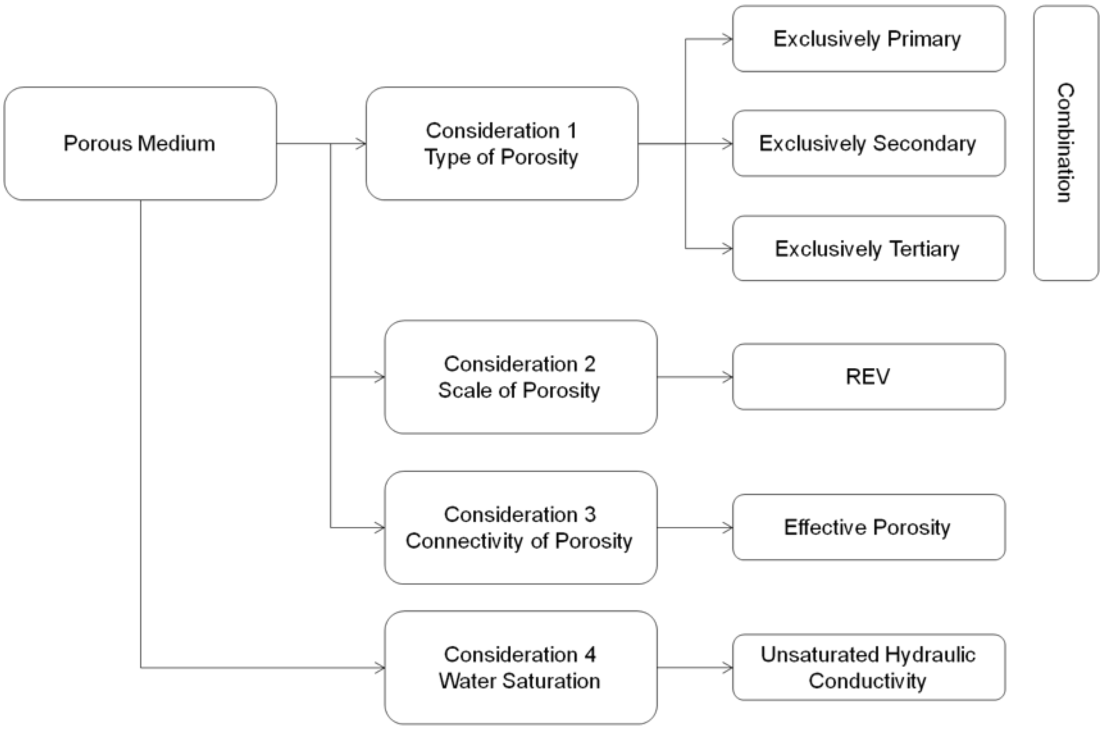


Figure 2-14. **Evaluation of porosity in a porous medium for application in vadose zone hydrological studies.**

2.4.3. Quantification of porosity

2.4.3.1. Basic relationships to quantify porosity

Porosity is often estimated based on the uniformity coefficient according to Istomina (1957), as discussed in Van Schalkwyk and Vermaak 2000). The uniformity coefficient C_U relates the particle size diameter that 60% of the material is finer than, to that diameter where 10% of material is finer (Equation 16). This is, however, only applicable to soils with fairly uniform fractions and cannot be applied when clay is present in the soil.

$$\eta = 0.255(1 + 0.83^{C_U});\ C_U = \frac{d_{60}}{d_{10}}$$ **Equation 16**

A more common laboratory method relates the saturated density ($V_V = V_W$) to the oven-dried density ($V_V = V_A$) as shown in Equation 17. The saturated density ρ_{sat} minus the dry density ρ_D can be converted to the moisture content, which equals the available porosity at saturation.

$$\rho_{sat} = \frac{M_S + M_W}{V_T}$$

$$\rho_D = \frac{M_S}{V_T}$$ **Equation 17**

$$\frac{\rho_{sat} - \rho_D}{\rho_W} = \frac{V_W}{V_T} = \theta_{sat} = \eta$$

Another effective method of determining porosity is through quantitative mineralogical composition as supplied through X-Ray Diffraction (XRD) and X-Ray Fluorescence Spectroscopy (XRF). 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. 1996). These results can be used to determine an average solid phase density (ρ_S) that relates to the bulk dry density of the sample (ρ_D) as shown in Equation 18. 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.

$$\eta = 1 - \frac{\rho_D}{\rho_S} = 1 - \frac{\rho_D}{\sum f_M \cdot \rho_M}$$ **Equation 18**

2.4.3.2. Advances in quantification of porosity

A number of authors has considered alternative means or have reviewed existing approaches to the accurate quantification of porosity during the last two decades. Too numerous to supply in this paper, selected approaches to the conceptual understanding of porosity quantification are briefly detailed below.

Density relationships

A study evaluated the porosity of drill core by comparing bulk dry and grain densities. Two of the key findings were that connected porosity are aligned parallel to foliation and that laboratory porosities are generally higher than in situ because of factors such as stress release during sampling (Tullborg and Larson 2006).

Empirical relationships

Effective porosity is roughly equal to the total porosity minus the volumetric water content at field capacity, or alternatively at –33 kPa of suction to – 66 kPa of suction for very clayey soils. This was evaluated for paddy soils and used to estimate saturated hydraulic conductivity according to the Kozeny-Carman equation (e.g. Aimrun et al. 2004). Flint and Selker (2003) considered the porosity function applied in numerous empirical hydraulic conductivity estimates in Nevada, concluding that *K* ranges over two to four orders of magnitude when using these empirical relationships.

Visual, remotely sensed and porosimetry methods

The historical developments in soil micromorphological imaging are discussed in detail by Mermut (2009), noting a number of problems, including the need to evaluate shape, size, distribution and nature of soil particles and pores.

Pore geometry and porosity were investigated through thin section analyses to evaluate the influences thereof on initial water saturation, finding that an increase in smaller pores result in higher initial water saturations (Coskun and Wardlaw 1995). Virgin et al. (1996) considered the relationship between two-dimensional and three-dimensional porosities to address the randomness of microstructure in order to address macroscopic physical properties. Applications pertaining to geographic information systems (GIS) have also been used to compile schematic maps of soil pore spaces with the benefits of seeing distinct grains, distinguishing sizes and shapes of pore spaces, pedofeatures and plant residues (Skvortsova et al. 2006).

A fuzzy random model of soil pore structure was evaluated through converting the medium to a set of pixels with a value of zero for solids and unity for pore spaces. Pixel swapping was employed to generate structures and further work towards a three-dimensional approach has been stated as on going (Moran and McBratney 1997).

Microstructure techniques and their importance in unsaturated investigations relating to engineering are discussed in a review by Romero and Simms (2008). They specifically evaluate mercury intrusion porosimetry (MIP) and environmental scanning electron microscopy (ESEM). Similar porosimetry techniques are also discussed by, for instance, Miguel and Bonder (2012). The parameters relating to porosity evaluated via these methods include dominant pore sizes, pore size distribution (PSD), soil microstructure and predictions if volume changes. This review also supplies an summary of microstructural methods and the physical properties at microstructural scale as well as the macroscopic behaviour.

Geostatistical analyses of borehole image data and the use of borehole resistivity imagery have been used with success to visualise porosity in heterogeneous borehole core (Tilke et al. 2006), finding that other standard logging methods might smooth out heterogeneity.

Shougrakpan et al. (2010) evaluated soil macroporosity in different land uses and covers in NE India based on dye patterns analyse, concluding that such analyses can be beneficial in groundwater contamination assessments due to preferential leaching and infiltration.

Random and densest packing simulations

True porosity is defined as the porosity of randomly packed material in a container without influence by the container's walls and is related to density and is inversely proportional to the representative size of the container into which particles are deposited. A simulation of random packing of equal spheres in a finite cubic box followed by simulations adjusting the floor of the box resulted in good findings with an assessment of the influence of the walls and floor on the estimates (Furukawa et al. 2000).

Straughan (2010) considered the dependence of the Darcy and Forschheimer coefficients on porosity in a porous material comprised of spherical beads. These are both, however, based on disturbed materials composed of uniform spherical grains and, therefore, not applicable to undisturbed materials of varying texture and with possible structural influences.

Geometrical models

Hilfer (2002) evaluated the scale-dependent characterisation of the microstructure in porous or heterogeneous media to predict transport parameters. The author summarises – at the hand of reference to numerous authors involved in such modelling exercises – capillary tube and slit models, grain models, network models, percolation models, fractal models, stochastic reconstruction models and diagenetic models.

Pore network analyses were conducted by Tsakiroglou and Fleury (1999) and included microscopic parameters such as pore geometry, pore-size distribution, pore space topology and fractal roughness. The authors supply a detailed review of the resistivity index, as well as the development of percolation theory applied to transport in disordered media. A dynamic pore-scale network model was also reviewed and applied by Hassanizadeh et al. (2002). Earlier work by Giménez et al. (1997) reviewed the most important fractal models for predicting soil hydraulic properties, including the Cantor bar, Kock curve, Sierpiński carpet and Menger sponge. Vita et al. (2011) evaluated specifically the Menger's Sponge model of porosity (essentially a three-dimensional depiction of Sierpiński carpet scheme) with the aim of improving accuracy by modelling towards infinitesimal pores. Although not the detail covered in this paper, the two-dimensional Sierpiński carpet scheme showing the principle of moving towards the infinitesimal is shown in Figure 2-15.

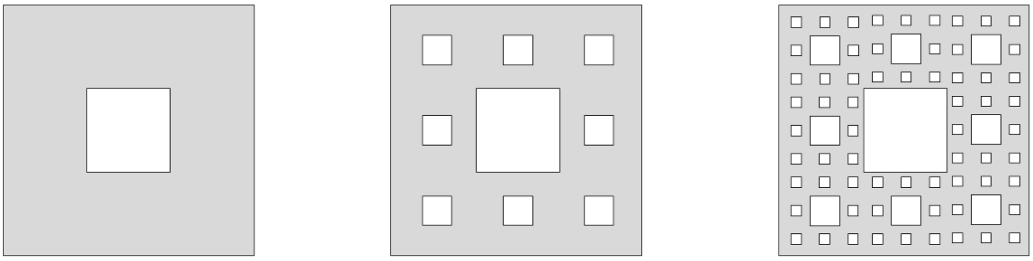


Figure 2-15. The Sierpiński carpet scheme to illustrate the principle of infinitesimal pores (adapted from Vita 2011 et al.).

A numerical comparison between the equivalent continuum (EC), non-homogeneous or discreet fracture (NH) and dual porosity (DP) models for flow through fractured porous media is discussed by Samardzioska and Popov (2005). Although not quantifying porosity per se, the paper evaluated the simplifications of natural porous systems to conceptual systems, which represent the natural system most accurately. This conceptualisation is shown in Figure 2-16.

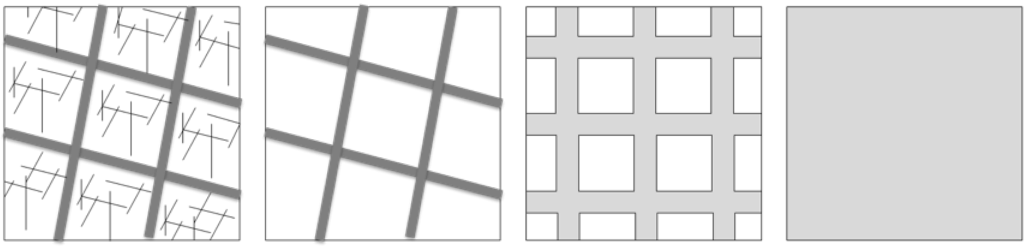


Figure 2-16. Grey denoting pore space and white matrix blocks for, from left to right, the natural fractured porous medium, followed by the non-homogeneous, dual porosity and equivalent continuum representations (adapted from Samardzioska and Popov 2005).

Upscaling of porous media (what the statistical distribution of a set of properties at a small scale says about the statistics of the same property at a larger scale) has been addressed to various levels of detail by a number of authors, of which the mathematical derivations are detailed in the respective studies (e.g. Hunt 1998; Guéguen et al. 2006; Hunt 2004; Hunt and Gee 2002; Pickup et al. 2005; Pickup and Hern 2002; Taggart 2002). Fractal analyses were also considered by many of these authors, assuming proportionality between pore radii and particle radii to generate water-retention curves, and also because of the lack of assumption of statistical homogeneity.

A three-dimensional geometrical-topological system of intersecting ellipsoids was generated from three-dimensional information of pore space by Yanuka et al. (1985). Neck (throat) radii were calculated from overlapping ellipsoids for simple cubic, orthorhombic and rhombohedral packing, as well as for glass beads and sandstone. More recently, Youngs (2008) considered steady water flow, also through cubic and tetrahedral (rhombohedral) packing, via modelling soil aggregates as uniform spheres.

Local porosity distributions and percolation probabilities were applied to yield a scale dependent characterisation of the microstructure in porous media with the aim of quantifying transport. A detailed review on characterisation of geometric observables and application to microstructure specifically are detailed by Hilfer (2002).

Changing porosity (consolidation and swell)

A number of authors have recently considered the movement of moisture through cracked clays. Murad and Cushman (1997) and Murad and Moyne (2008) consider expansive clays as a dual-porosity system whereby the swelling medium is considered on three scales, viz. nano- (clay polarity, or submicro- as per previous literature), micro- (clay clusters) and macro-scale (dual-porosity system), resulting in multiscale electro-chemo-mechanical modelling of expansive soils (Figure 2-17 and elaboration in §4.3). Fredlund et al. (2010) elaborate on the commencement of cracking in clayey soils from ground surface with increasing matric suction. They evaluate the soil-moisture characteristic curves for intact clay, cracked soil mass and finally the cracked portion alone. This accentuates the importance of considering changing porosity in natural materials with changing moisture content.

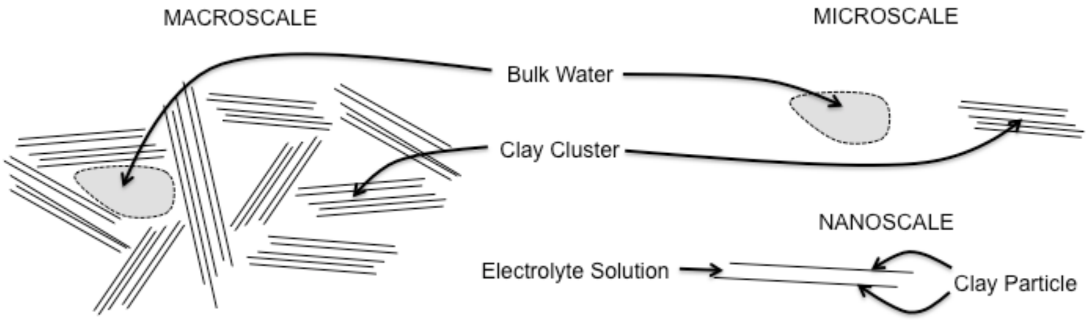


Figure 2-17. Three-scale clay model (adapted from Murad and Cushman 1997; Murad and Moyne 2008).

Another study considered the changes in suction with associated shrinkage of swelling clays in terms of constant porosity approaches (although not theoretically viable as porosity should change with shrinkage) and geometrical similar shrinkage approaches (Gregory et al. 2010).

Swelling and shrinkage occur depending on moisture content. Consolidation, however, is a function of applied load and may result in a more permanent change in porosity. The quantification thereof is discussed in detail by Bear and Cheng (2010) who consider it important as deformation affects the water storage and may result in surface subsidence. This was further evaluated by, for instance, Moosavi et al. (2012), who considered the change in porosity due to pore volume compression.

2.4.4. Relating porosity to hydraulic parameters

Numerous empirical methods exist to correlate porosity to hydraulic conductivity. Selected recent applications and developments include (in alphabetical order):

- Aimrun et al. (2004) evaluated saturated hydraulic conductivity in paddy soils applying Kozeny's equation.
- Dexter (2004) used the slope of the soil water retention curve at its inflection point.
- Dexter and Richard (2009) applied a multi-exponential water retention function and Marshall's capillary tube approach to freshly tilled soils.
- Flint and Selker (2003) evaluated hydraulic conductivity of volcanic tuffs from the Yucca Mountain using the Kozeny-Carman equation.
- Jarvis et al. (2002) considered available soil information (including effective porosity and grading curves) to quantify hydraulic conductivity, concluding that a major issue remaining is variations in pore structures and that direct methods may still be more reliable.
- Kutílek (2004) considered soils with bimodal pore distribution (matrix and structural pores) and related these soil structural properties to soil hydraulic properties.
- Lipiec et al. (2006) evaluated soil porosity and water infiltration influenced by tillage methods.
- Neuman (2005) reviewed and evaluated the directional dependence of advective porosity (effective porosity to flow) specifically applied to tracers.
- Podgorney and Fairley (2008) investigated episodic flow from unsaturated porous media into a single vertical macropore of known dimensions, noting that consideration of possible permeable pore walls, hysteresis in the pore due to varying diameter and film flow is required.
- Vervoort and Cattle (2003) determined saturated hydraulic conductivity from the model based on lognormal pore size distribution by Kosugi. They focussed specifically on incorporating tortuosity (crookedness of flow path) and lack of connectivity.

2.4.5. Case studies

2.4.5.1. Materials and methods

Extensive excavation has commenced at VZSA1 followed by the identification of a temporary hillslope wetland. Although the wetland has been destroyed in the process, a 200 m long downslope view to depths ranging between 2 m and 8 m make the study of these systems possible.

Methods employed include the collation of historical data (comprising 23 test pit descriptions prior to construction for the initial geotechnical studies of the site and the site upslope on the hill crest, as well as all associated sample results of soil grading, hydrometer and Atterberg limits), logging of 16 additional profiles through the exposed section and sampling of each different horizon. Soil profiles were recorded according to the draft SANS 633 (2009). Laboratory analyses included – for each horizon at distinct points down the slope – soil grading, hydrometer, Atterberg limits, X-Ray Fluorescence Spectroscopy (XRF) and X-Ray Diffraction (XRD).

2.4.5.2. Results

A vast amount of data has been generated during the course of the study). The scope of the inclusion in this section is to emphasise the proper understanding of porosity as a fundamental parameter in understanding special flow systems.

The typical soil succession for four positions along the slope (hillcrest, upper slope, midslope and lower slope) have been simplified to emphasise important aspects and are as follows:

- Colluvium at surface, typically well leached and predominantly sandy in texture; often pinholed or voided
- Ferricrete (nodular to hardpan) in the pebble marker horizon or the residual granite; notably absent on the hillcrest and midslope)
- Residual granite, distinctly mottled in a silty gravelly sandy soil
- Completely weathered granite, occasionally mottled in a sandy gravelly soil exhibiting original rock joints
- Weathered and fractured granite bedrock with distinct Fe-precipitation evident on joint planes.

Porosities were calculated based on density relationships and according to the empirical approach of Istomina (1957) as shown comparatively in Figure 2-18. Mineral densities were taken as per Table 2-2.

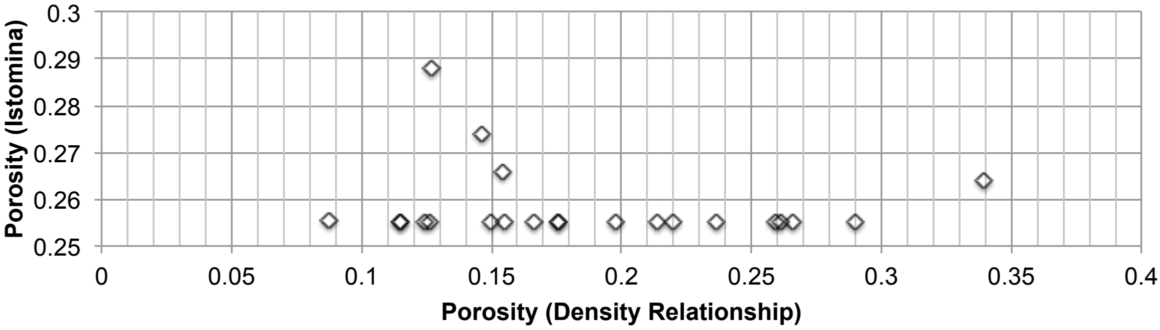


Figure 2-18. Porosity calculated through density relationships compared to those calculated according to Istomina for a temporary hillslope wetland underlain by granite.

Table 2-2. Mineral densities used in the calculation of porosity (specific gravity ranges after Deer et al. 1996).

Mineral	Specific Gravity Range	Assumed Mineral Density (kg/m^3)
Alkali Feldspar (K → Na)	2.55 - 2.63	2 560
Plagioclase (Na)	2.62	2 620
Plagioclase (Ca)	2.76	2 760
Quartz	2.65	2 650
Goethite	~ 4.3	4 300
Kaolinite	2.61 - 2.68	2 640

Much more pronounced variation in porosity according to density relationships are evident with the more porous soil horizons being the ferricrete and residual granite. Calculated values of porosity range between 0.15 and 0.23 for transported soils, 0.26 and 0.31 for ferricrete and residuum, and 0.11 and 0.14 for weathered granite. The results are validated by visual seepage from the ferricrete horizon where porosity is not only high, but pore spaces are generally large to allow free drainage (Figure 2-19).

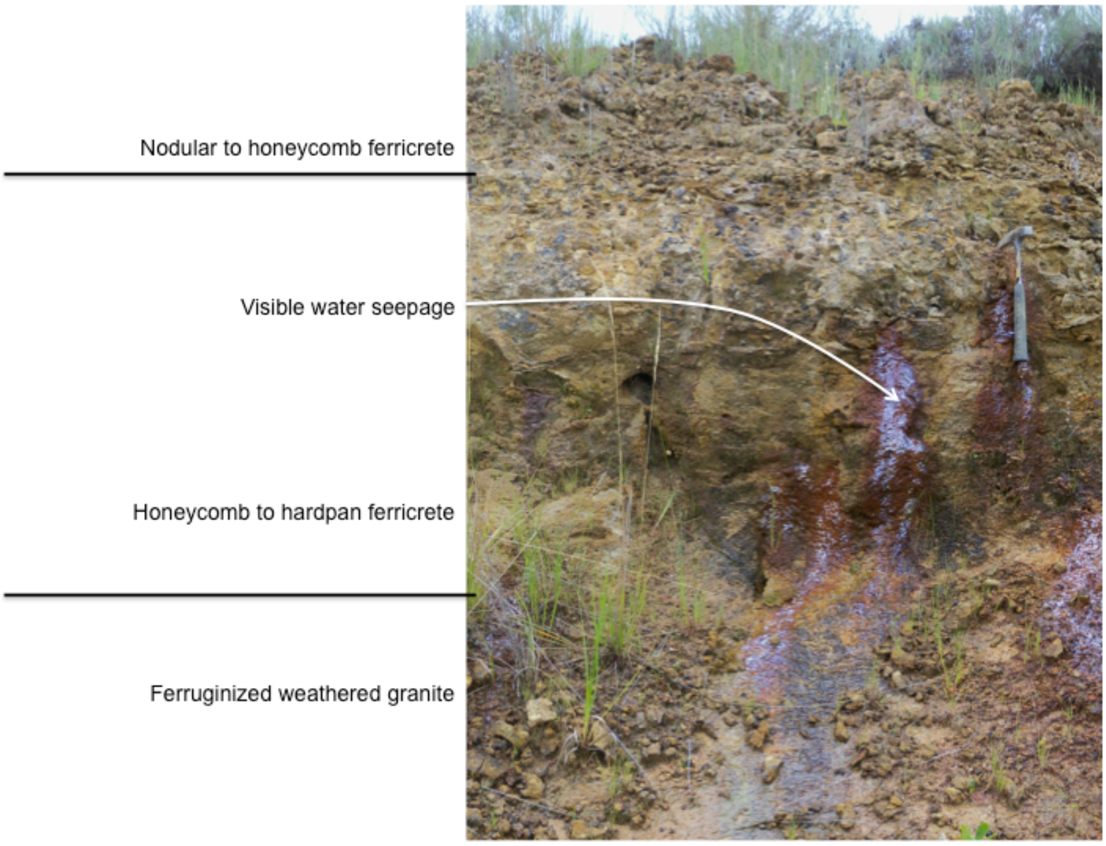


Figure 2-19. Seepage from ferricrete in a temporary hillslope wetland underlain by granite.

The system can be classified vertically as follows:

- Surface (transported) materials, zone of infiltration and leaching
- Ferricrete, high porosity and zone of interflow with elevated anticipated hydraulic conductivity

- Bedrock, low porosity resulting in low storage with limited vertical flow through open fractures, if present, and distinct precipitation of Fe-minerals on joint planes, indicating the periodical presence of water.

2.4.6. Conclusions

Porosity applied to vadose zone hydrological investigations should include

- Specification of the type of porosity and the medium, namely primary, secondary or tertiary, and whether in soil or rock
- Evaluation of the different scales of porosity, including submicro, micro, meso and macro, and accounting for multi-scale systems and including all heterogeneity and anisotropy
- Understanding of the effective porosity as well as the non-effective porosity which may still influence consolidation, cracking and subsidence
- Water saturation to address the ability of the void space to store and transmit water, as well as to understand the different hydraulic conductivities at different moisture contents.

An exposed temporary hillslope wetland on Archaean gneiss was used to illustrate the importance of understanding basic concepts of porosity. It is hoped that this paper will result in a more universal language and understanding of the concept for application in hydrology, hydrogeology, engineering, soil science and related disciplines.

2.4.7. The Way Forward

Several specific issues have been identified as problematic when determining porosity. These are noted below and are presently being investigated further.

Consolidation results in a permanent change in porosity. However, seasonal wetting and drying of expansive clays result in cycles of swelling (decrease in porosity) and shrinkage (leading to cracking and subsequently increase in porosity). Some definable moisture content should govern this process and, if quantifiable, will aid in the understanding of when clays are porous and when clays serve as low permeability barriers. Large cracks are generally non-capillary and induce flow, whereas expanded or consolidated clays are highly capillary despite the potential of being highly porous as well.

Fractures are variable in terms of (a) spacing and directions of different joint sets, (b) apertures and (c) the influence of weathering and precipitation on the continuity thereof. Straightforward fracture porosity is therefore not straightforward to estimate and the notable difficulty arises when considering fractured vadose zone.

Leaching processes may result in, for instance, collapsible soil fabric where the material is at a density well below that of densest packing with large non-capillary pore spaces highly prone to rapid consolidation (collapse). With the clay leaching from these horizons, the horizon below such a horizon is often enriched in clay (notably kaolinite) which may result in perching of water, further exacerbating the influence of moisture on the soil, notably as a triggering mechanism of collapse under load.

Although numerous advances on the quantification of porosity are evident in recent literature, special emphasis is required for selected case studies such as the above.

2.5. Partial and Variable Saturation

2.5.1. Moisture below Saturation

Terminology related to moisture contents below saturation and/ or water occurring in the vadose zone are summarised in Box 8 and Box 9.

Moisture contents are usually denoted as a fraction or percentage of the void spaces occupied with water, or alternatively in units of per mille (mm/m or ‰). Three main forces affect the energy level of soil water, namely:

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

These three forces define the difference in energy level of water between sites or conditions that can be defined as the ***soil water potential***. Water always moves from a point with high potential to a point with lower potential and the ***total soil water potential*** Ψ_T can be defined as the sum of the ***gravitational potential*** Ψ_g, ***matric potential*** Ψ_m, ***osmotic potential*** Ψ_o and any other possible contributions of additional potentials (Equation 19). A collective term, ***pressure potential***, is often used for the matric potential combined with the submergence potential Ψ_s due to hydrostatic pressures of overlying water in the saturated zone (Brady and Weil 1999).

$$\Psi_T = \Psi_g + \Psi_m + \Psi_o + \cdots \qquad \textbf{Equation 19}$$

Gravitational potential is the product of the height of the water column above a reference elevation h and gravitational acceleration g as shown in Equation 20. The reference point is usually in the soil profile at depth to ensure that gravitational potential of the soil water will be a positive value.

$$\Psi_g = gh \qquad \textbf{Equation 20}$$

Whether actual ***field capacity*** as per Box 8 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).

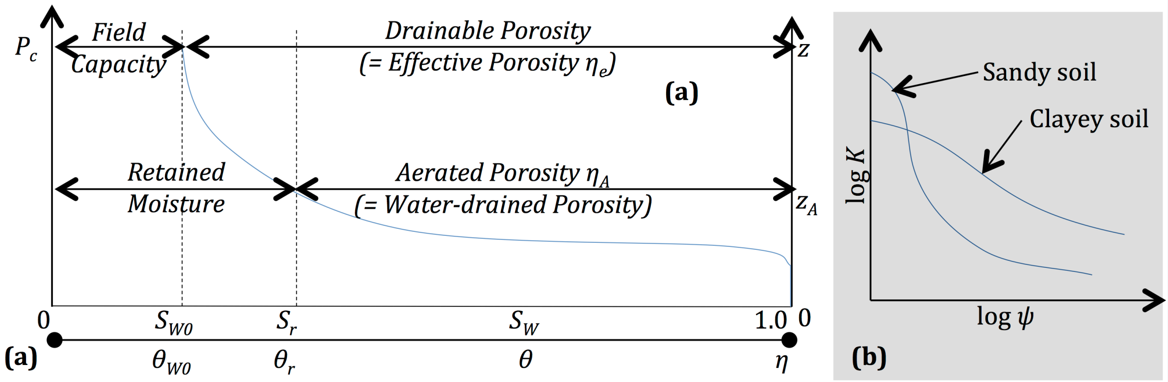
Box 8. Terminology related to Soils below Saturation (Part 1).

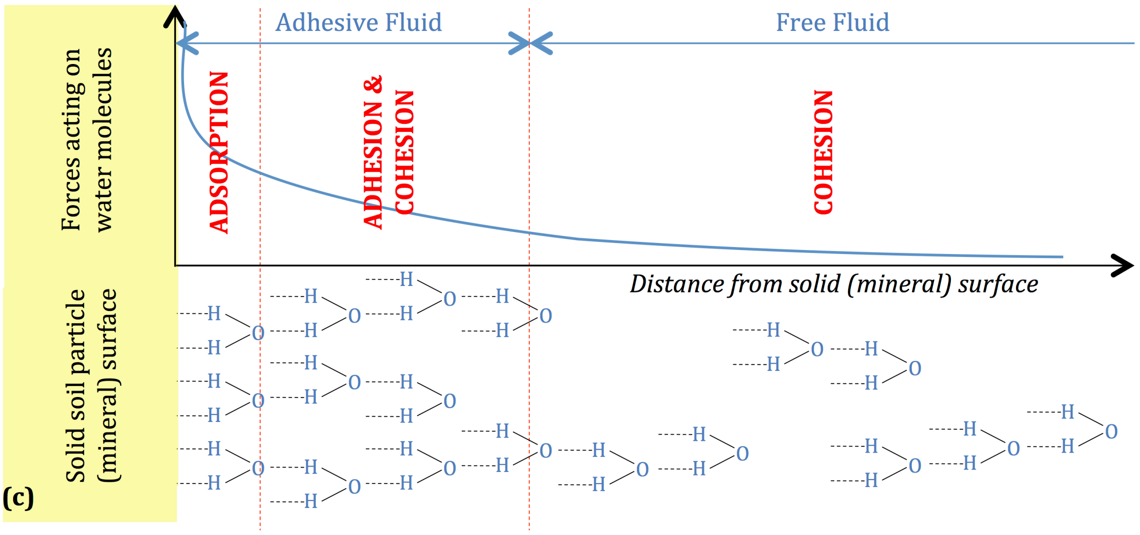
FIELD CAPACITY (FC) refers to that moisture content θ the soil can retain after excess water has seeped away under gravity; therefore the volume of water introduced to the subsurface but not available for percolation. At this moisture content, the complete ***effective porosity*** – which is that portion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

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

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

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

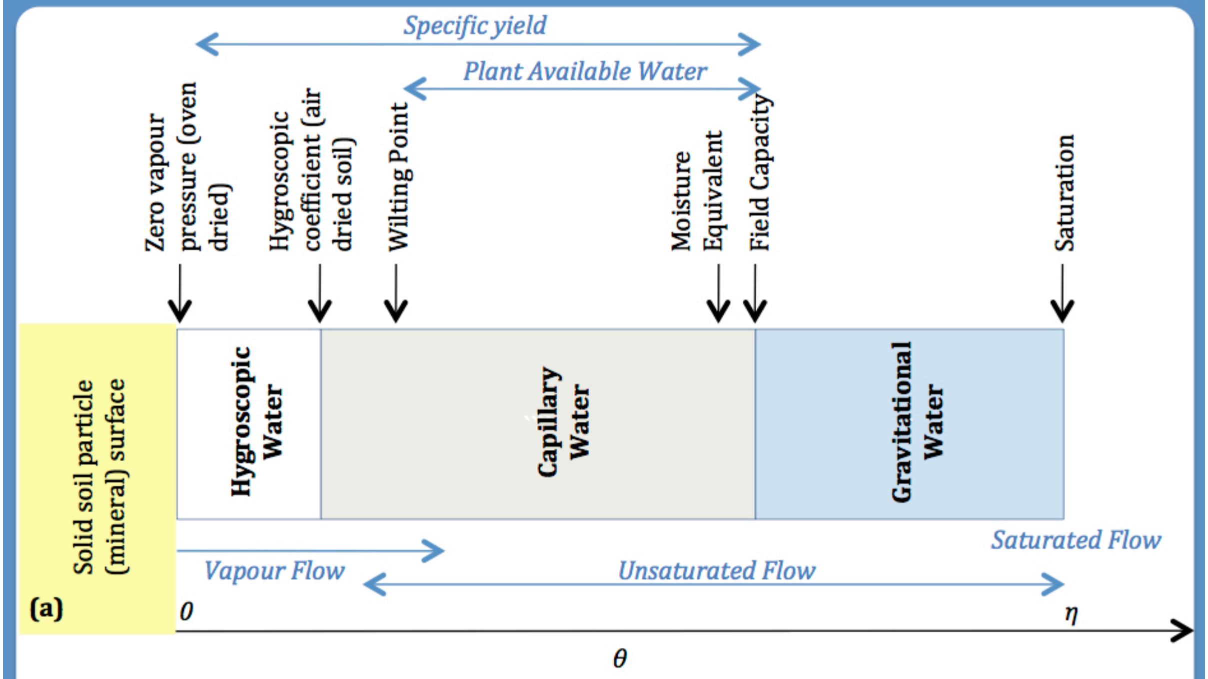


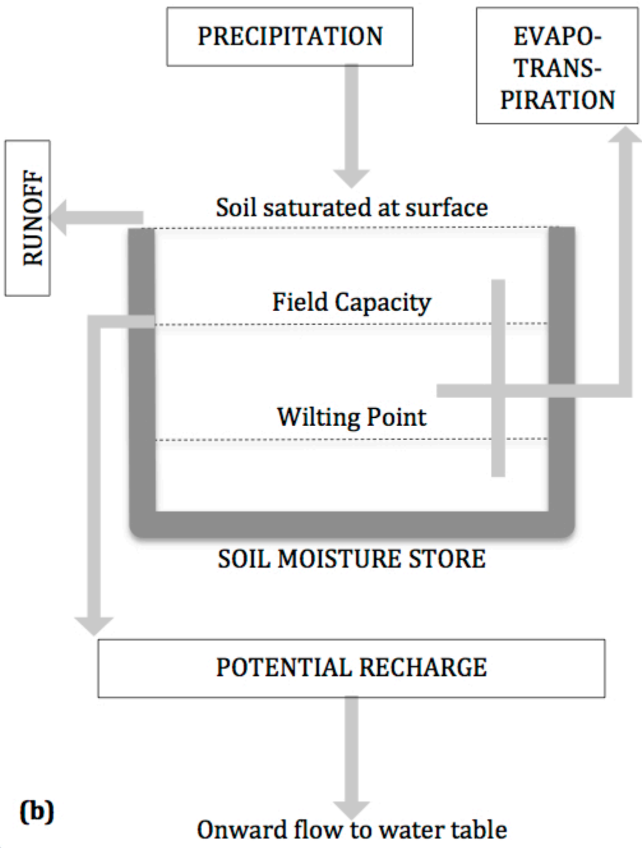


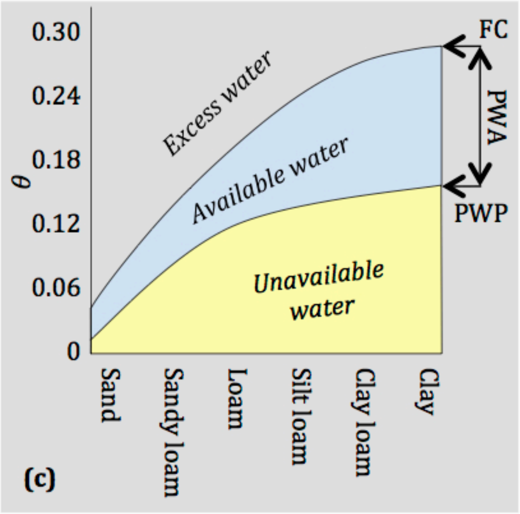
READ MORE & CITED FROM:

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

Box 9. Terminology related to Soils below Saturation (Part 2).







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

READ MORE & CITED FROM:

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

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 21 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 22 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 21**

$$S_e = \frac{S - S_r}{S_{sat} - Sr}$$ **Equation 22**

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).

2.5.2. Interaction between solid and fluid phases

2.5.2.1. Surface tension and wettability

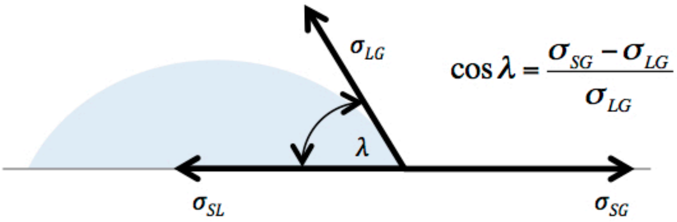
A liquid in contact with a solid surface can, according to Berg (1993 in Doe 2001):

- Spread spontaneously and form a film 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 (attraction of water molecules to solid surfaces) and cohesion (attraction of water molecules to each other; Brady and Weil 1999).

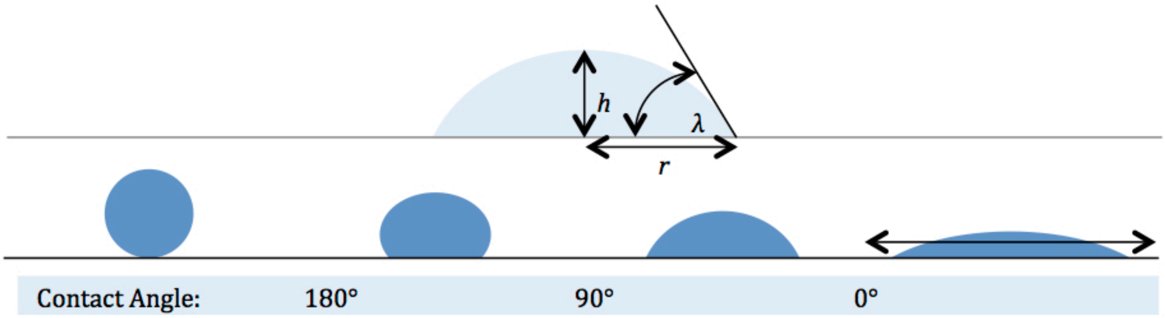
The processes of cohesion and adhesion require work and relate to specific critical angles as shown in Box 10. Equation 23 shows the calculation of the work of cohesion as a function of the surface tension of the liquid. ***Cohesion*** relates to the water's attraction to itself, and W_C is the work 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 (Doe 2001).

Box 10. Surface Tension, Wettability, Adhesion and Cohesion.



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

<table>
<tr><th>NON-ADHESION</th><th colspan="2">ADHESION</th><th>SPREADING</th></tr>
<tr><td colspan="3">Drops and Rivulets</td><td>Films</td></tr>
<tr><td>Cohesion; no Adhesion</td><td colspan="2">Cohesion > Adhesion</td><td>Adhesion > Cohesion</td></tr>
<tr><td colspan="2">Non-wetting and Hydrophobic</td><td colspan="2">Wetting and Hydrophilic</td></tr>
</table>



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

READ MORE & CITED FROM:

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

$$W_C = 2\sigma_L \qquad \textbf{Equation 23}$$

Adhesion, on the other hand, relates the interface between different materials, e.g. water and a solid. W_A here refers to the work required to de-wet or disjoin a unit area of solid-liquid interface, thereby creating two new surfaces with the respective solid and liquid energies and removing the solid-liquid interface (Equation 24). ***Wetting*** W_W refers to the work to de-wet a unit area of solid surface, thus creating a solid-gas interface from the initial solid-liquid interface (Equation 25). The work of ***spreading***, finally, refers to the work required to create a unit area of solid-gas interface while removing the initial liquid-gas and solid-liquid interfaces, or through differencing the work of cohesion and the work of adhesion (Equation 26) (Doe 2001).

$$W_A = \sigma_S + \sigma_L - \sigma_{SL} \qquad \textbf{Equation 24}$$

$$W_W = \sigma_{SG} - \sigma_{SL} \qquad \textbf{Equation 25}$$

$$W_S = W_C - W_A = (2\sigma_L) - (\sigma_S + \sigma_L - \sigma_{SL}) = \sigma_S - \sigma_L - \sigma_{SL} \qquad \textbf{Equation 26}$$

For a threefold phase comprising solid, liquid and gas, the contact angle, λ, of the junction can be related to the surface tensions, σ, according to Young's Law as shown in Equation 27. Subscripts denote the interphases between solid (S), liquid (L) and gas (G) phases (Doe 2001).

$$cos\lambda = \frac{\sigma_{SG} - \sigma_{SL}}{\sigma_{LG}} \qquad \textbf{Equation 27}$$

Incorporating wetting relationships into Young's Law allows Equation 28 to Equation 30 to hold (Doe 2001).

$$W_A = \sigma_{LG} \cdot (1 + cos\lambda) \qquad \textbf{Equation 28}$$

$$W_W = \sigma_{LG} \cdot (cos\lambda) \qquad \textbf{Equation 29}$$

$$W_S = \sigma_{LG} \cdot (cos\lambda - 1) \qquad \textbf{Equation 30}$$

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

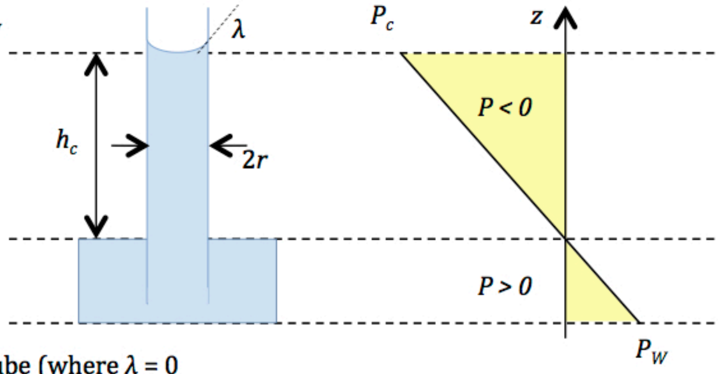
2.5.2.2. Capillarity

Water can occur in soils as gravitational, capillary or hygroscopic water. ***Gravitational*** water is free flowing and moves vertically downwards under the influence of gravity at a tension of less than 0.1 bar. ***Capillary water*** is held on the soil particles and in the pores at 0.1-31 bar and moves in the direction as determined by the prevailing moisture gradient (Box 11). ***Hygroscopic water*** moves essentially in the vapour phase and is attracted to the soil surfaces at suctions exceeding 31 bar (FitzPatrick 1983).

Box 11. Capillarity.

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

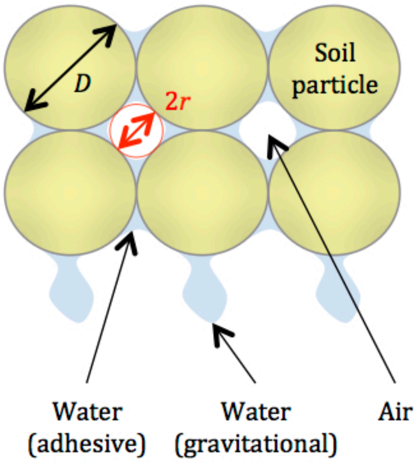
$$h_c = \frac{2\sigma_W}{r \cdot \gamma_W}\cos\lambda = \frac{2\sigma_W}{r \cdot \rho_W \cdot g}\cos\lambda$$

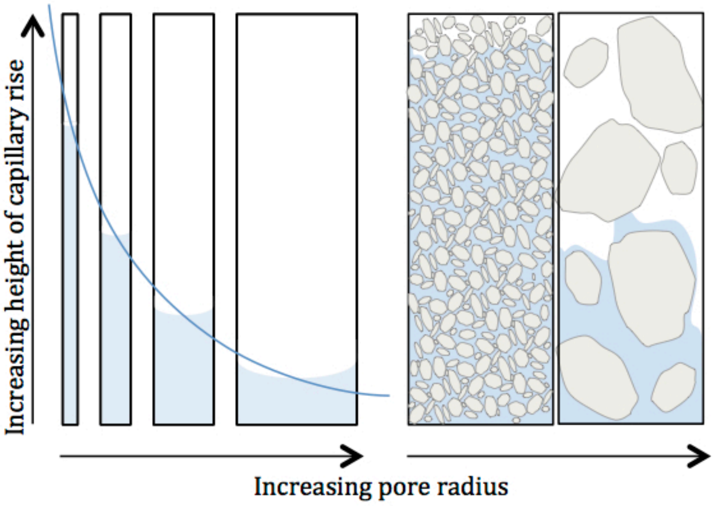


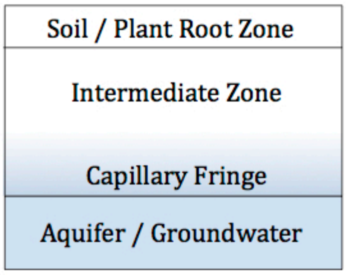
Assuming pure water in a clean glass tube (where $\lambda = 0$ and at 20°C, $\sigma = 0.074$ g.cm^{-1} and $\gamma = 1$ g.cm^3), the height of capillary rise can be estimated as follows:

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

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







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

READ MORE & CITED FROM:

Bear 2007; Deming 2002; Doe 2011; Fetter 1994; Todd and Mays 2005

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

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

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

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

Hagen-Poiseuille's law states the flow through a single vertical pore as a function of the effective pore diameter and includes the dynamic viscosity of water μ_W and the microscopic hydraulic gradient S (Equation 31) (e.g. Das 2008) or as the cross-sectional area $a = \pi r^2$ (Equation 32).

$$Q(r) = \frac{\gamma_W S}{8\mu_W} r^2 a$$ **Equation 31**

$$Q(r) = \frac{\pi \rho_W g}{8\mu_W} r^4$$ **Equation 32**

2.6. Movement of Water in the Subsurface

2.6.1. *Mechanisms of fluid flow*

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

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

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

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

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

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

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

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

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

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

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

Finally, unsaturated flow can be (Kovács 1981):

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

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

2.6.2. Bernoulli's Law and Hydraulic Head

Box 12 describes Bernoulli's Law and the concept of hydraulic head. The first component relates to the kinetic energy due to the motion of moving water, the second to potential energy due to gravity, and the third potential energy due to the fluid pressure.

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 33. 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 34.

$$h = h_p + z = \psi + z$$ **Equation 33**

$$(-\psi) = z =-(\psi)$$ **Equation 34**

2.6.3. Darcy's Law and Associated Parameters

The term seepage applies to moisture moving through a porous material. Engineers and geologists tend to interchange the symbols used, with engineers often utilising k for hydraulic conductivity (or coefficient of permeability) and K for (intrinsic) permeability. Similarly, Q and q as discussed hereafter are also often interchanged. For the sake of consistency, the hydrogeologically notations will be used where K represents hydraulic conductivity and k the intrinsic permeability. The concepts pertaining to Darcy's Law and the important parameter, hydraulic conductivity, are discussed in Box 13. For unsaturated conditions, K_{unsat} is determined through so-called characteristic curves of moisture content and pore water pressure.

Darcy's law applies under small enough groundwater velocities to ensure laminar flow. This is characterised by high viscous forces, small velocities and momentum, and the absence of swirls or eddies. Turbulent flow, on the other hand, is characterised by eddies. Distinction between these two parameters can be based on the so-called ***Reynolds number*** R_e as a function of the fluid density ρ, flow velocity v, mean pore or grain size d and dynamic viscosity μ (Equation 35 and Figure 2-20). Where R_e is less than some unspecified value between one and 10, flow in granular media can be considered laminar and Darcy's law applies (Fitts 2002).

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

Equation 35

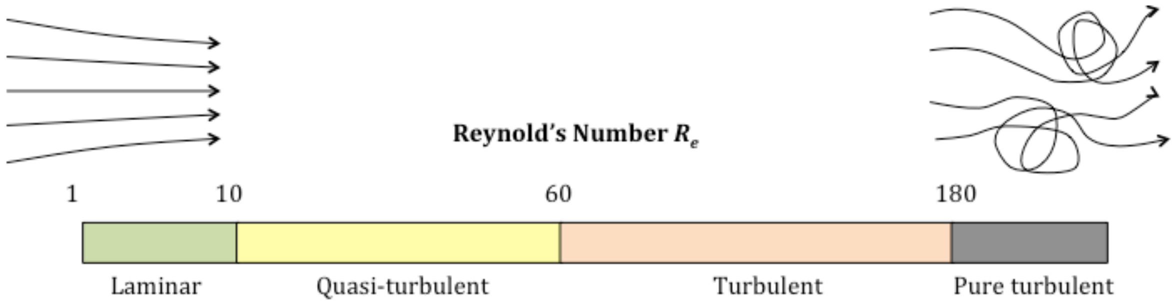


Figure 2-20. The Reynolds number showing the occurrence of laminar and turbulent flow (e.g. Bear 2007; Fitts 2002; González de Vallejo and Ferrer 2011).

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

Box 12. Bernoulli's Law and Hydraulic Head.

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

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

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

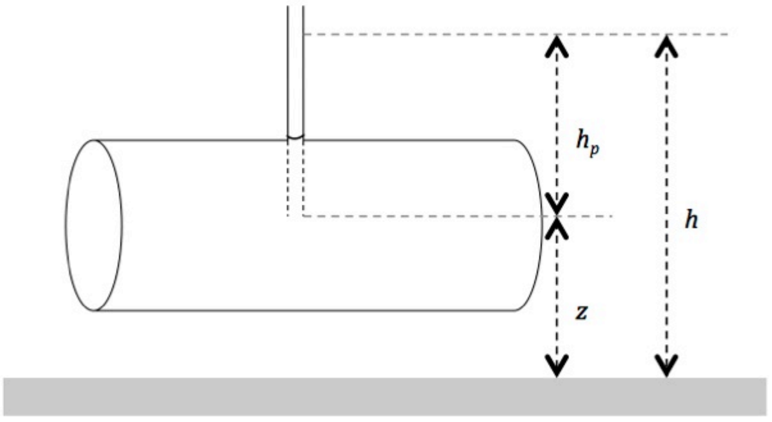
$$\text{Unit volume: } V = 1 \text{ and } \frac{m}{V} = \rho$$

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

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

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

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



Hydraulic Head:

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

$$h_v + z + h_p = h$$

Hydrostatic Conditions:

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

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

READ MORE & CITED FROM:

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

Box 13. Darcy’s Law and Associated Parameters.

The **(HYDRAULIC) CONDUCTIVITY**, coefficient of permeability or constant of proportionality, *K*, is a measure of the resistance of the soil to the flow of water and has the units of velocity [L/T]. Hydraulic conductivity is applied when the fluid is known to be water and therefore represents a property of the medium and the ease with which the medium can transmit water.

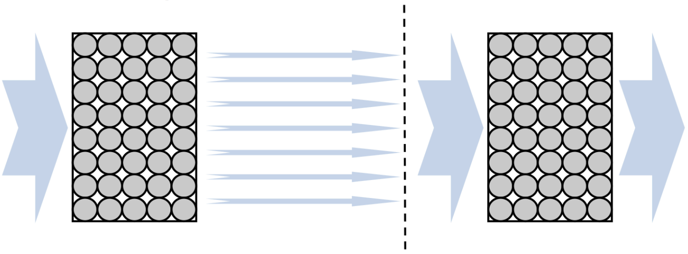
The **(INTRINSIC OR ABSOLUTE) PERMEABILITY**, *k*, on the other hand, is defined as the soil property allowing seepage of fluids through interconnected void spaces and has the units of area [L^2]. Permeability applies to any fluid and not necessarily water and is a function of *K*, the fluid density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

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

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

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

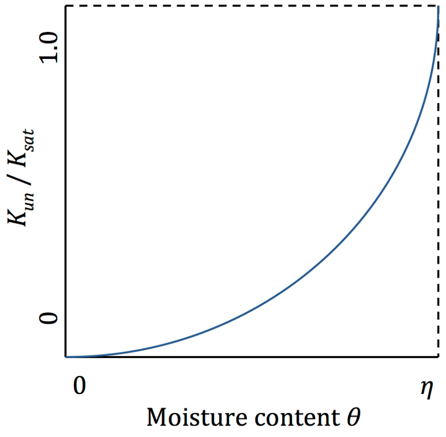
$$v = \frac{q}{\eta_e} = \frac{q}{A \cdot \eta_e}$$



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

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

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



READ MORE & CITED FROM:

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

In certain scenarios, differing K-values will exist for the x, y and z-directions. In such a situation, q can be determined for each direction separately and based on a distinct corresponding K-value as shown in Equation 36 and Equation 37.

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

Equation 36

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

Equation 37

Unsaturated flow is typically estimated by means of Darcy's Law applied to unsaturated conditions where hydraulic conductivity becomes a function of water content or saturation (Equation 38) or the Richards's equation where suction and gravity require incorporation (Equation 39), or rewritten in vertical, one-dimensional coordinates (Equation 40; Karamouz et al. 2011; Ruan and Illangasekare 1999).

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

Equation 38

$$q_v = -K(\psi)\nabla h$$

Equation 39

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

Equation 40

2.6.4. Unsaturated flow

When considering the hydrological cycle, precipitation events supply water to the land surface from where three natural processes can continue: infiltration, overland flow or evaporation. Infiltration is increased by porous and permeable materials and is more pronounced during the first moments of a large precipitation event when the material is still fairly unsaturated (Fitts 2002). This is explained in Box 14 where the wetting front of this infiltrating water is characterised by a fingering effect rather than a discrete line of wetting. This was experimentally measured in one-minute intervals and also shows how – during the vertical migration of these "fingers" – lateral dispersion takes place to create a less saturated "fringe" between these saturated fingers. This fingering effect is ascribed to two processes, *viz.* (a) the textural change within the soil matrix and (b) the presence of macropores in the topsoil, which concentrates the flow of water non-uniformly in the subsurface layers (Glass et al. 1988).

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

Flow (***seepage***), wetting (***imbibition***) and drying (***drainage***) in unsaturated media become increasingly complex as explained in Box 15 and Box 16.

Box 14. Mechanisms of Water Movement in the Vadose Zone.

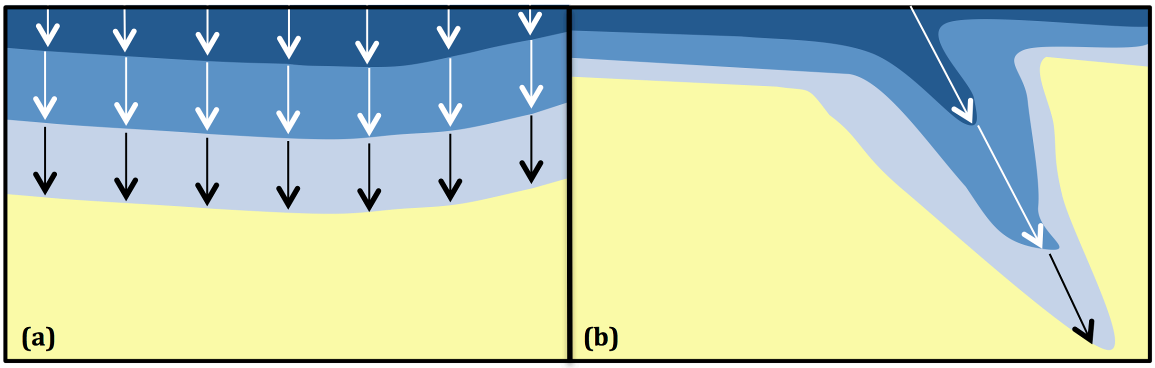
Water movement in the vadose zone is influenced by wetting front instability, fluid retention and release due to capillary and gravity actions competing, and small changes in boundary conditions such as temperature and pressure. This leads to so-called episodic, intermittent, pulsating or threshold-like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

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

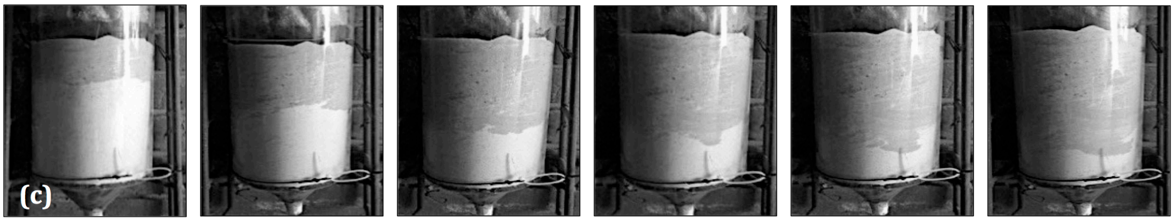
PREFERENTIAL FLOW resulting in **FINGERING** or **UNSTABLE FLOW** concentrates flow through macropores, preferred pathways or due to changing soil texture rather than wetting the complete medium.

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

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



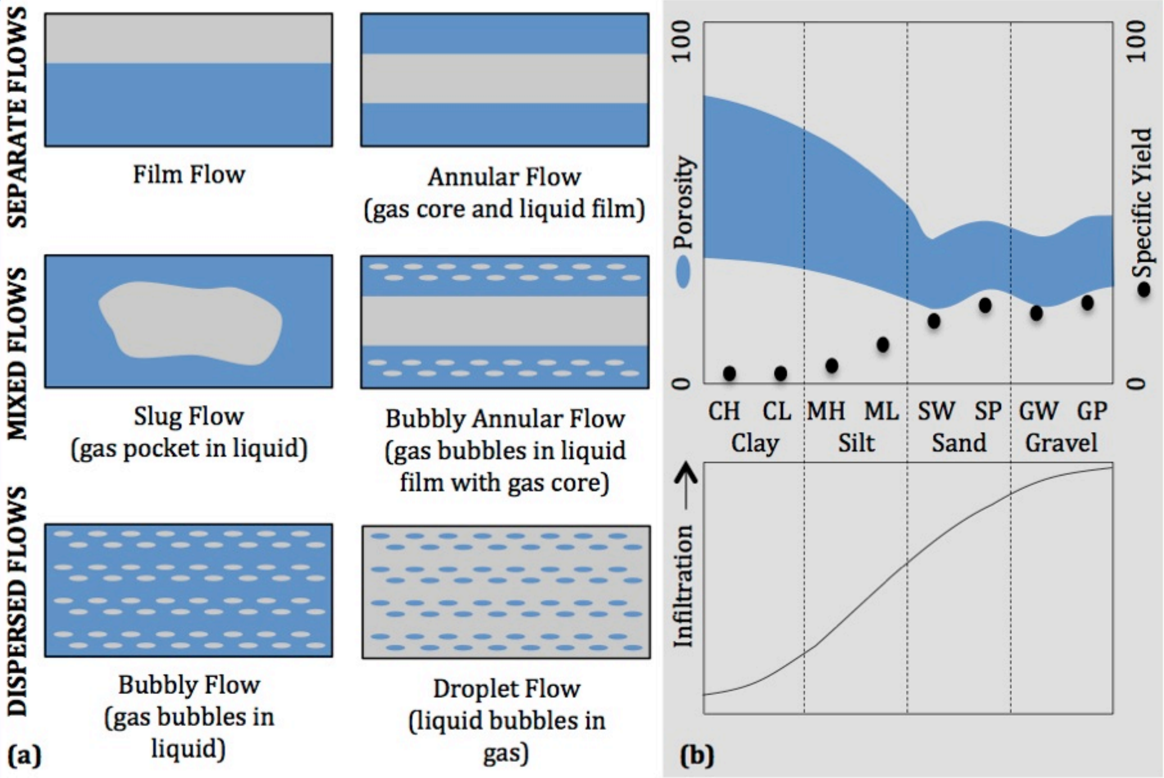
(c) Movement of a wetting front in medium-grained sand at ten-second intervals. Note how the shape of the wetting front remains fairly constant.



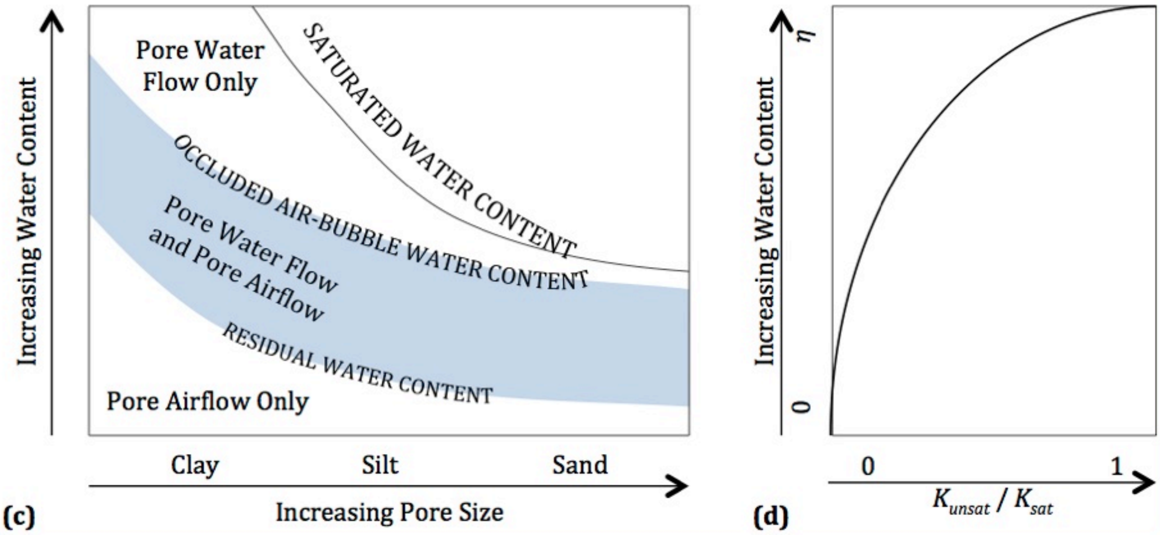
READ MORE & CITED FROM:

Beekman & Xu 2003, Glass et al. 1988, Podgorney & Fairly 2008

Box 15. Unsaturated Flow.



(a) Flow mechanisms of water–air systems through fractures or macropores.
(b) Influence of soil texture on porosity, specific yield and infiltration rate.
(c) Influence of water content and soil texture (pore size) on water flow and airflow
(d) Influence of water content on the relative hydraulic conductivity K_{unsat} / K_{sat}.



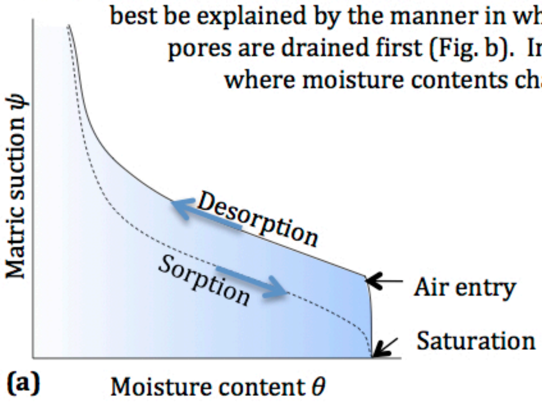
READ MORE & CITED FROM:

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

Box 16. Characteristic Curves and the Hysteresis Effect.

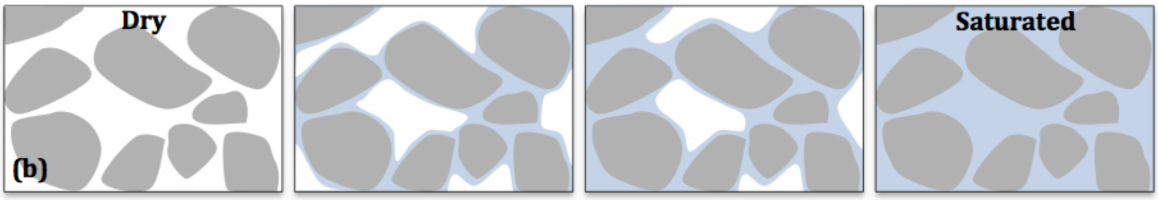
Characteristic curves comprise the ***main branches*** (Fig. a), including the extremes of (i) saturation of a dry soil (sorption) and (ii) drying of a saturated soil (desorption; soil-moisture release). This can best be explained by the manner in which smaller pores are wetted first and larger pores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

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

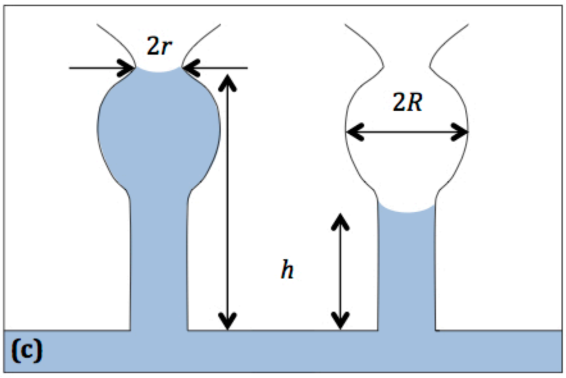


Equilibrium at a certain suction may be obtained with different values of saturation, and, for a given capillary pressure, a higher saturation is obtained when a sample is being drained than during imbibition.

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



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



Hysteresis can be ascribed to:

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

READ MORE & CITED FROM:

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

Retention curves or ***characteristic curves*** relate water saturation to capillary pressure and are a function of soil texture and structure. Initially saturated soils will drain to a moisture distribution based on its retention curve and can be approximated by means of the specific yield. More development in soil-moisture characteristic curves is well documented and includes, for instance, Das et al. (2005), Dexter (2004), Van Genuchten (1980). Berkowitz (2002) accentuates the issues of partially saturated flow through fractured systems, noting that uncertainty is high and that open questions to be addressed include:

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

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

2.7. Subsurface Translocation Processes

2.7.1. Water and pedogenesis

Perched water tables or fluctuating ground water levels can lead to the development of pedogenic soil horizons that lowers the permeability and the subsequent vertical percolation. The process of pedogenesis is influenced by the subsurface, down-slope drainage of water until a point on the slope is reached where precipitation of transported ions commences. This is then referred to as the zone of pedogenesis and includes ***pedocretes*** such as laterite, ferricrete, calcrete, silcrete or other pedogenic materials based on the available ions and the climatic conditions (Box 17).

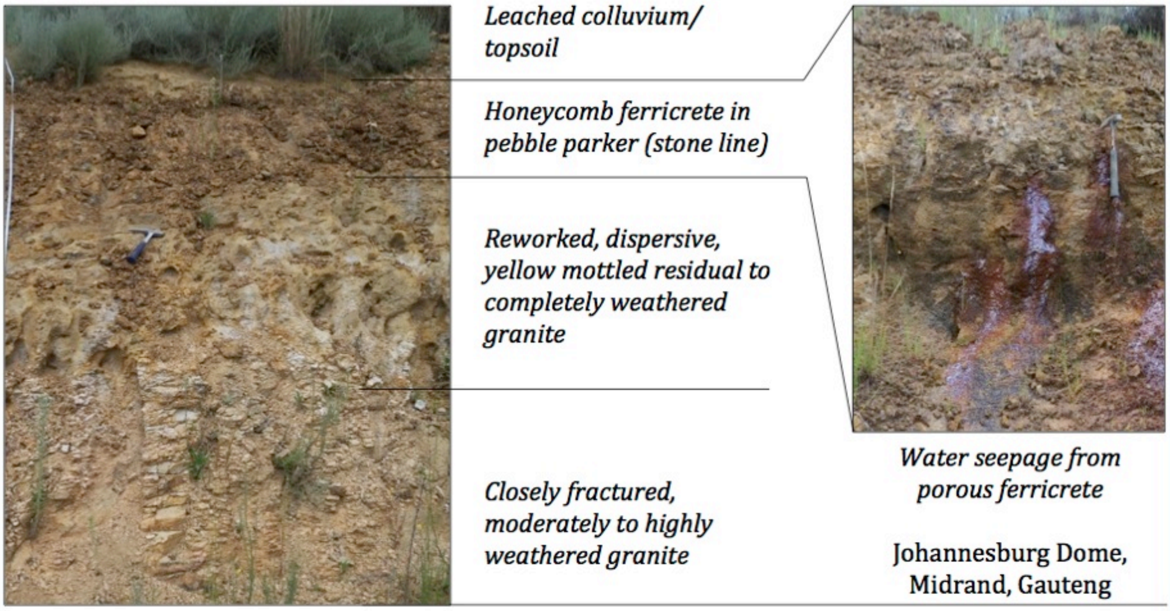
This soil horizon can be either a ***pedogenetic pedocrete*** (due to percolating water from surface and the precipitation of mobilised elements above a less permeable horizon) or a ***groundwater pedocrete*** (due to seasonal fluctuations in ground water level or ground water perching and the concomitant precipitation of elements dissolved in ground water) as shown in Box 17 (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).

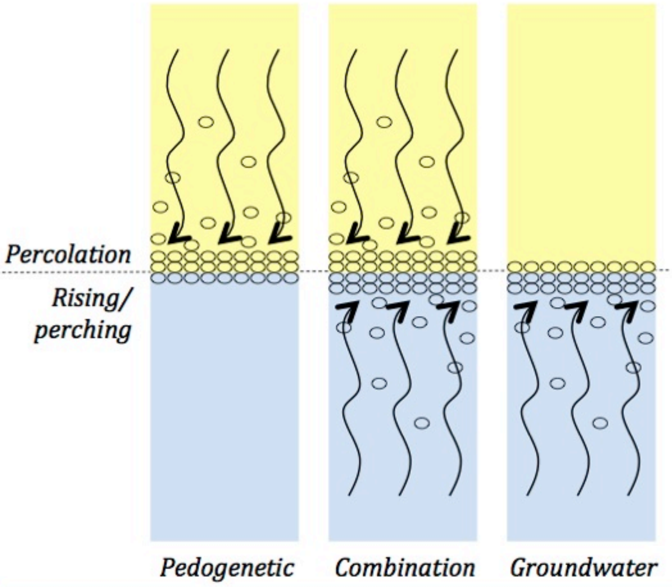
Box 17. Pedogenesis: Formation and Classification.

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

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



Johannesburg Dome, Midrand, Gauteng



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

Right: ferruginization in Karoo Supergroup sandstone in Ermelo, Mpumalanga

READ MORE & CITED FROM:

McFarlane 1976

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.

2.7.2. Water and clay minerals

Clay concentrates essentially in the vadose zone, over the water table and above impermeable barriers, mainly in the form of geopetal structures, meniscus-shape bridges, coatings (cutans), loose aggregates and massive aggregates. These so-called clogging microstructures alter the soil material and soil mass as well as the seepage behaviour (Figure 2-13). Leaching of clay minerals from a generally coarse-grained soil with percolating water can furthermore lead to a change in soil structure to a so-called collapsible fabric. 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.

3. VADOSE ZONE HYDROLOGY – METHODS

3.1. Profile Description

3.1.1. Soil profile description

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

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

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

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

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

Elaboration on the MCCSSO system for engineering geological soil classification in shown in Box 18 with additional elaboration on different soil texture classification systems in Box 6.

Box 18. MCCSSO: Moisture, Colour, Consistency and Structure.

1. MOISTURE

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

3. CONSISTENCY: NON-COHESIVE SOILS

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

3. CONSISTENCY: COHESIVE SOILS

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

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

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

3.1.2. Rock description

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

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

Details regarding the importance of discontinuity surveys and important considerations in describing rock mass are available in Box 19 (e.g. Anon. 1977). Additional input from the classical approaches to discontinuity surveys are added for weathered rock to incorporate relic structures and those related to soils in the classification.

3.1.3. Improved earth scientific profile description

In order to maximise the information obtained from description of material successions, a multi-disciplinary approach is beneficial. Inclusions of principles from both soil science and geology will significantly improve the profile log and will aid in better application of the information. The paradigm shifts in profiling detailed below are recommended for improved information from soil profile descriptions. These "paradigm shifts" are summarised in Figure 3-1 and discussed below. Credit should be given to each individual specialist field for their contributions to material descriptions. However, given the huge disciplinary overlap in the field of vadose zone hydrology, it becomes imperative that the specialist is also able to deduce information from other specialists' data.

Box 19. Rock Mass Description and Discontinuity Survey.

1. TYPE OF STRUCTURE

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

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

2. APERTURE (mm)

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

- Address the consistency in the aperture.

3. INFILLING - NATURE

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

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

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

5. ROUGHNESS

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

6. WAVINESS

1	Wavelength (m)
2	Amplitude (m)

7. WATER

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

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

ADDITIONAL CONTRIBUTIONS:

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

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

READ MORE & CITED FROM:

Anon. 1977

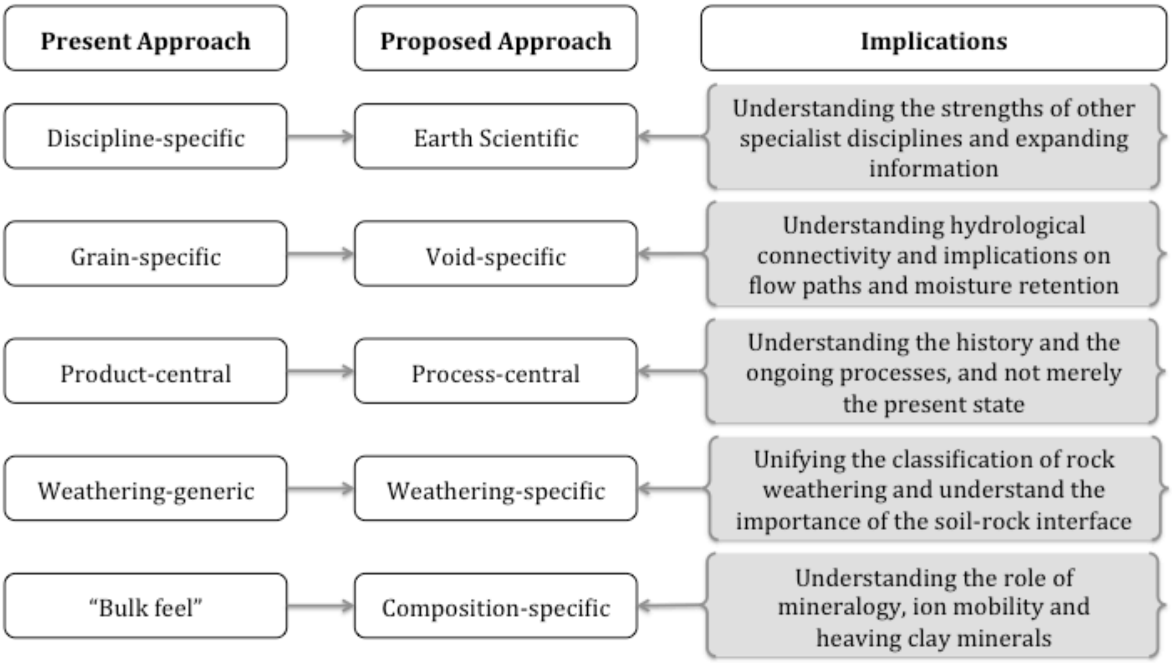


Figure 3-1. Proposed paradigm shifts for an improved earth scientific profiling methodology for applications in vadose zone hydrological studies.

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

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

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

Profiling should be ***weathering-specific*** and not weathering-generic. Hydrogeologists notably classify weathered rock as that rock at depth where a zone of more transmissive material is present for the transmission of water. However, rock weathering descriptors are standardised as per §3.1.2 and weathered zones at depth should not be described in a manner contradicting generic geological classifications. Proper understanding of the origin of soils will distinguish between transported soil, residual soil and weathered bedrock. It is imperative that the earth scientist logging the material properly understands the difference between these three origins and can clearly identify saprolite and regolith in a soil profile. As a rule of thumb, South African soils typically have a characteristic pebble marker indicating the boundary between transported and residual soils.

Profiling should be ***composition-central*** and not "bulk feel"-central. Minerals and crystals should be noted as the prior determines the nutrients and weathering products, and the latter the shapes of the grains. Processes are governed by the availability of ions and the ease of preferential weathering. Potentially expansive and inert clay minerals should be noted specifically and secondary minerals should be included in both the soil and rock horizons to address weathering and translocation of fines in the profile. Pedogenetic horizons should be addressed in the dual manner (discussed in §2.7.1) 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.

3.2. Porosity

Porosity is addressed extensively in §2.4. Additional contributions are added in this section.

3.2.1. Changing porosity of problem and pedogenic soils

Porosity is not always constant and may change over time, either permanently or temporarily, and either gradually or suddenly. 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. These are soils prone to (1) swelling/ shrinking, (2) settlement or (3) differential movements associated with these, and are discussed in Box 20 and Box 21.

Box 20. Problem Soils.

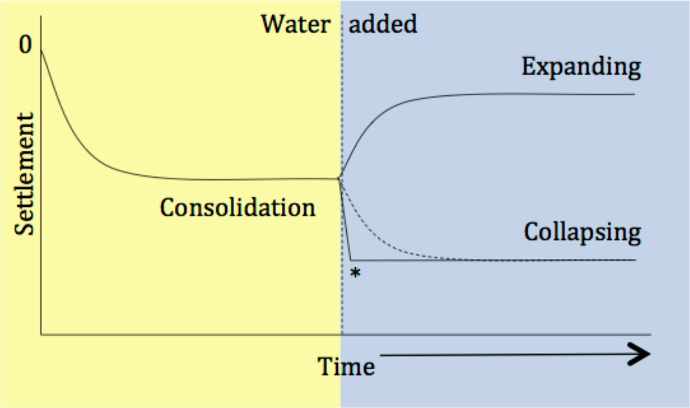
Changing moisture conditions, together with changes in applied load at surface, may induce surface movement. This affects infrastructure, resulting in, for instance, subsidence of structures, cracking of foundations and structures and water entering excavations and foundations. Typical problem soil behaviour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

EXPANSIVE SOILS:

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

SETTLEMENT AND VOLUME DECREASE:

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



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

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

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

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

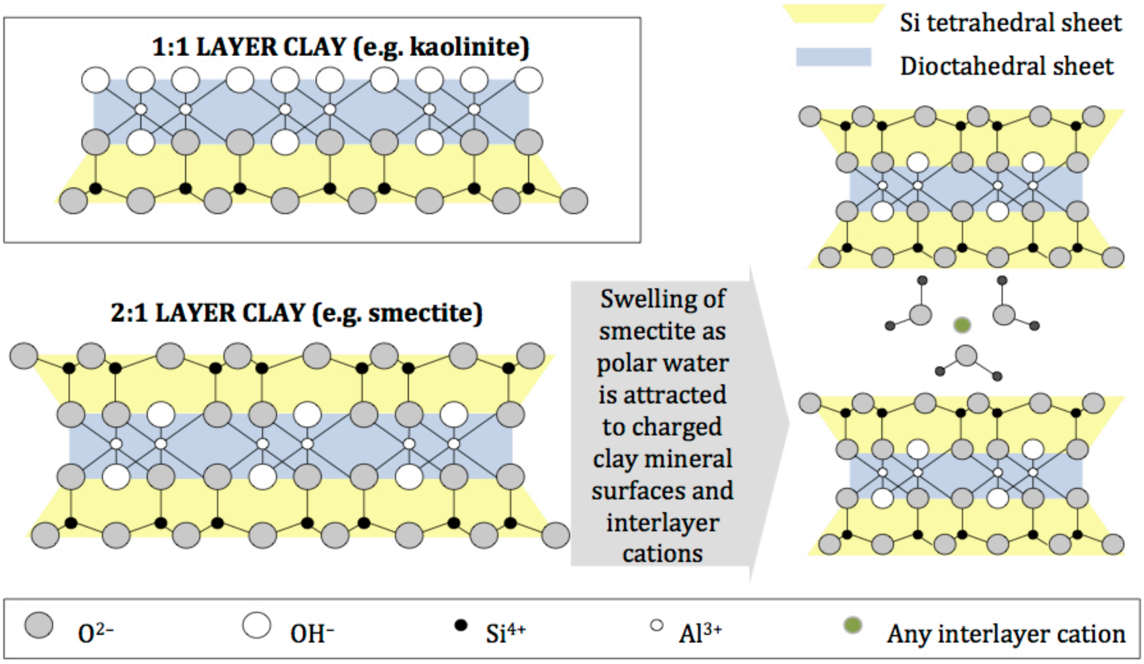
READ MORE & CITED FROM:

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

Box 21. Mechanisms of Heave, Consolidation and Collapse.

CLAY MINERALOGY AND HEAVING

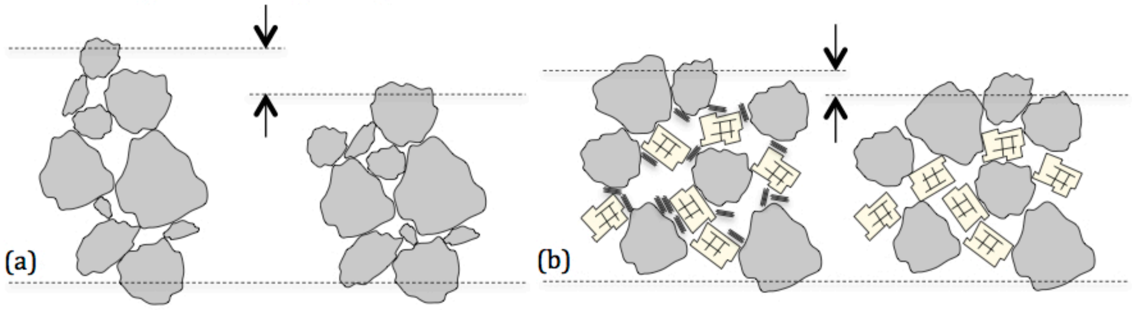
2:1 layer clays are prone to expansion on wetting and shrinkage on drying. This results in lower porosity as volume increases, or increased porosity, likely as dessication cracking, on drying.



SETTLEMENT OF NON-EXPANSIVE SOILS

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

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



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

READ MORE & CITED FROM:

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

The influence of ferricrete (ferrous pedocrete) as identified at VZSA1 is shown in Figure 3-2. Cementation may – at different stages of pedocrete behaviour – result in either more or lesser porous horizons.

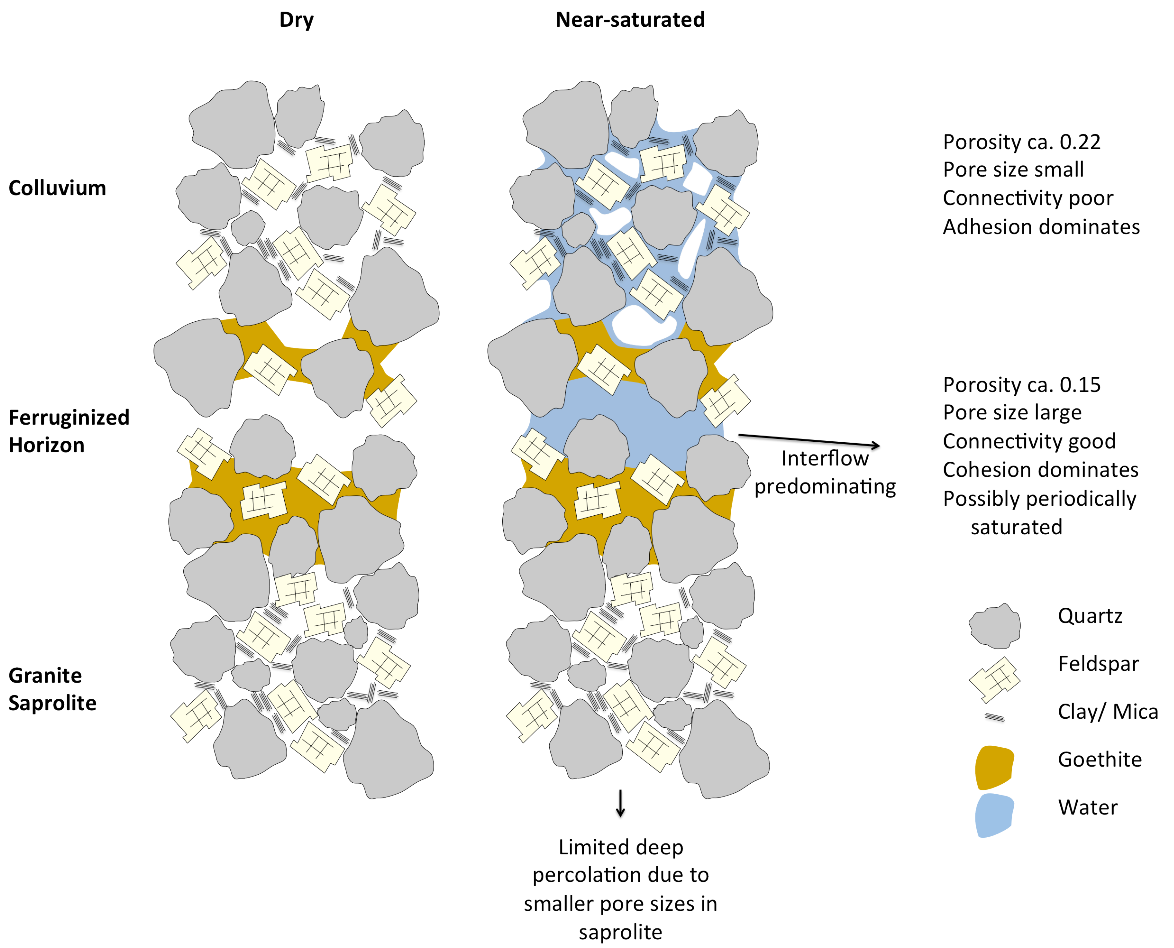


Figure 3-2. Inferred dry and near-saturated conditions for the typical ferruginized granitic soil profile at VZSA1.

3.2.2. Considerations with respect to porosity

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

a) Cubic packing of fairly uniform near-spherical grains
b) Tetrahedral or rhombohedral packing of fairly uniform near-spherical grains
c) Random packing of fairly uniform grains of variable shape
d) Cubic packing of fairly uniform near-spherical grains of finer texture
e) Elongated grains
f) Elongated clay platelets or micas

g) Coarse quartz and finer feldspar in a randomly packed mixed texture material
h) Varying grain size, grain shape and random densest packing
i) Clogging of pores by precipitates or fines
j) Open collapsible structure due to leaching of fines
k) Open structure due to animal burrows or plant roots.

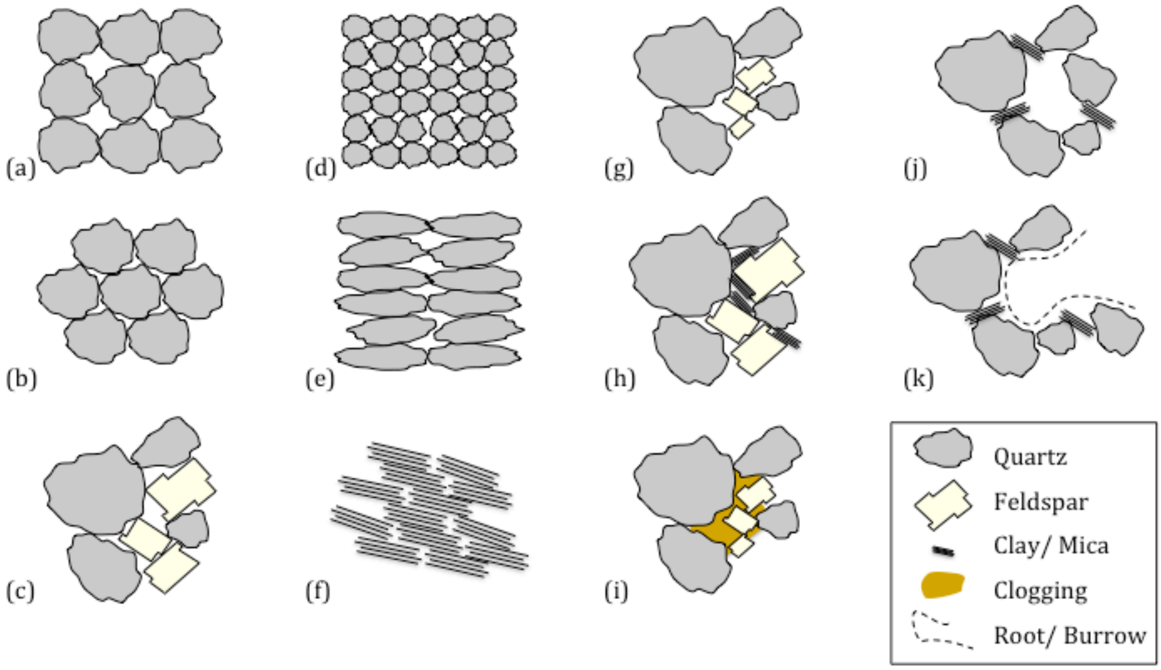


Figure 3-3. **Porosity influenced by (a) cubic, (b) rhombohedral/ tetrahedral and (c) random packing; influence of grain shape ((d)-(f)), variable grain size ((g)-(h)), clogging structures (i) and large open voids due to (j) leaching or (k) plant roots or animal burrows.**

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

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

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

3.2.3. *Bias in the quantification of porosity*

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

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

3.2.4. *Advances in the quantification of porosity*

Proper quantification and understanding of porosity with respect to the vadose zone require specific considerations as shown in Figure 2-14. Although a significant oversimplification of the complexity of porosity, incorporation of all these aspects will improve hydrological interpretation.

Specific issues pertaining to the quantification of porosity have been identified and include:

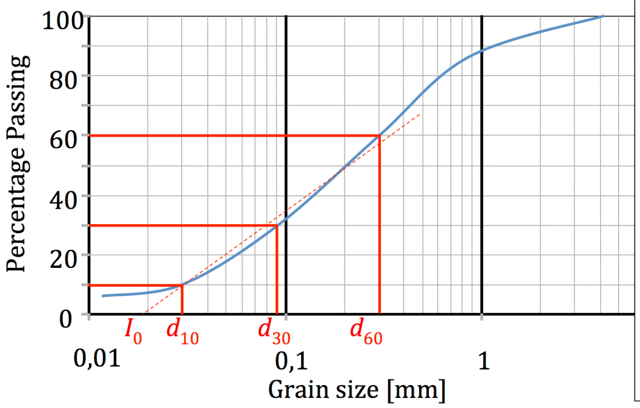
- Changing porosity from consolidation (permanent) and shrinkage-heave (temporally variable)
- Fracture porosity and the influence of spacing, directions, apertures, weathering, precipitation and continuity
- Leaching processes changing porosity over time.

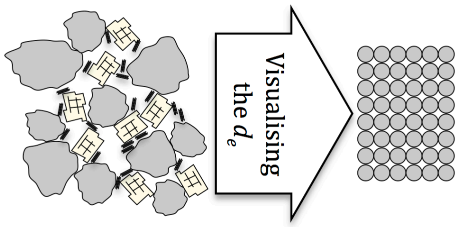
3.3. Grading-based Empirical Hydraulic Conductivity Estimation

The basic principles of the empirical grading-based hydraulic conductivity estimates, a comparison of the parameters for some of the methods, and their ranges of application are supplied in Box 22. The hydraulic conductivity is estimated by multiplying the constant relationship with the porosity function and the effective grain size function, and the units are in accordance with the input parameters. Evaluation of such methods is well published in, for instance, Cheong et al. (2008) and Odong (2007).

Box 22. Empirical Hydraulic Conductivity Estimation.

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





The dimensionally homogeneous form comprises:

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

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

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

READ MORE & CITED FROM:

Amer and Awad 1974; Carrier 2003; Das 2008; Fitts 2002; Hazen 1911;Kenney et al. 1984; Odong 2007; Shababi et al. 1984; Van Schalkwyk and Vermaak 2000; Vukovic and Soro 1992

3.3.1. Development of empirical approaches

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

$$K\left(\frac{cm}{s}\right) = c \cdot d_{10}(\mathrm{mm})$$

Equation 41

$$K = \left(4.6\times10^{-3} + 4.6\times10^{-2}(\eta - 1)\right)(0.70 + 0.03 \cdot T)d_{10}^2$$

Equation 42

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

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

Equation 43

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

Equation 44

Through simplifying above equations for the shape factor C_S ($\approx$ 2.5 for granular soils), tortuosity factor T ($\approx 2^{0.5}$) and microscopic hydraulic gradients S, the Kozeny-Carman function as applicable to coarse-grained soils is a function of the void ratio or porosity as per Equation 45 (Das 2008). An alternative derivation as a function of a shape factor and the effective grain size as determined as the fraction fi between sieve sizes $d_{i(min)}$ and $d_{i(max)}$ (Equation 46) (Carrier 2003).

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

Equation 45

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

Equation 46

3.3.2. Standardisation to dimensionally homogenous form

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

- g / ν = gravitational acceleration / kinematic viscosity; $\nu = \mu / \rho$ (dynamic viscosity / density)

- C = sorting coefficient
- $f(\eta)$ = porosity function
- d_e = effective grain diameter.

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

Equation 47

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

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

Equation 48

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

$$K = \frac{g}{\nu} \cdot (8.3\times10^{-3}) \cdot \left[\frac{\eta^3}{(1-\eta)^2}\right] \cdot d_{10}^2$$

Equation 49

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

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

Equation 50

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

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

Equation 51

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

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

Equation 52

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

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

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

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

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

$$K = \frac{g}{\nu}(0.05) \cdot d_5^2$$ **Equation 54**

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

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

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

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

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

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

3.3.3. *Efficacy of Empirical Porosity and Hydraulic Conductivity Estimates*

Data from VZSA 1 (ephemeral hillslope wetland on Lanseria Gneiss) are shown in Figure 3-4, superimposed on the ranges of applicability of the respective empirical methods for hydraulic conductivity estimation (as discussedin in §3.3.2). As most methods require fairly uniform materials predominantly of sand fraction, bulk of the methods is not applicable to the materials analysed. The resulting hydraulic conductivities are, therefore, also not considered representative and empirical methods fail when applied to non-uniform materials of varying grain sizes.

The same data, for five empirical approaches and field percolation tests, are shown in Table 3-1 and Figure 3-5. Note the range of values per method over orders of magnitude, in comparison to field percolation tests showing little variation. This can be ascribed to the reliability of the empirical approaches on a single grain size diameter (d_{10}) and uniform materials, whereas field methods include for site conditions.

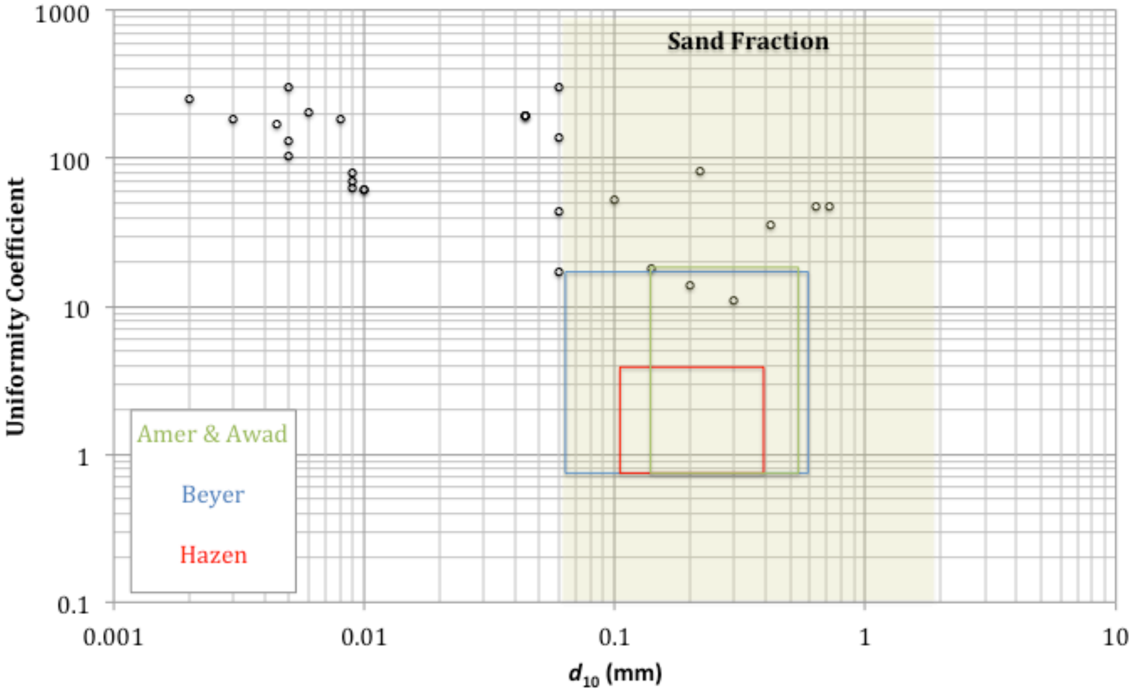


Figure 3-4. Ranges of applicability of empirical methods and data (VZSA1).

Table 3-1. Correlation between empirical K-values and field percolation tests (m/s) (VZSA1).

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

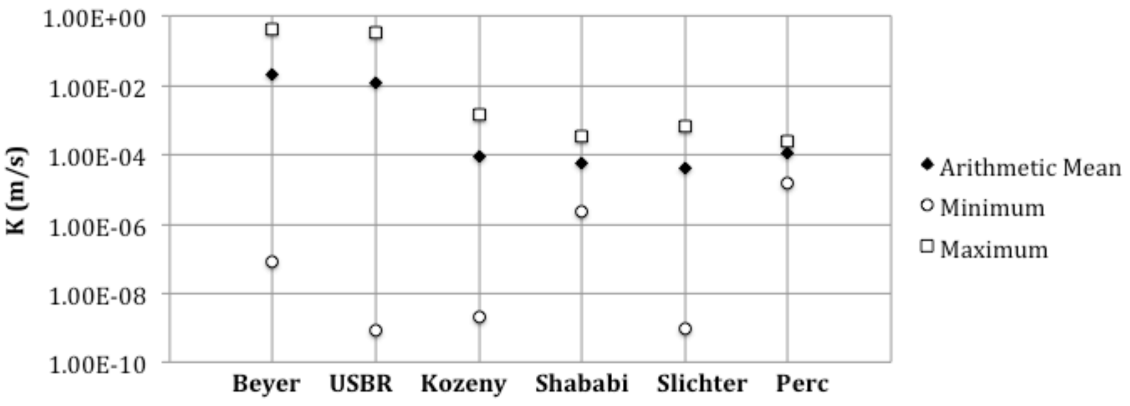


Figure 3-5. Correlation between results of empirical estimates (Beyer, USBR, Kozeny-Carman, Shababi et al. and Slichter using density-relation porosity) and field percolation testing (Perc) to estimate hydraulic conductivity (VZSA1).

Table 3-2 shows the porosities by soil horizon as calculated using Istomina's approach and density relationships (using published mineral densities from Deer et al. 1996) for VP01-VP07.

Seven empirical methods are also indicated, comparing the calculated hydraulic conductivities for all materials using the two different porosity calculations.

Table 3-2. Calculated porosities and K-values summarized based on porosity function (VZSA1).

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

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

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

Hydraulic conductivities estimated based on empirical approaches are shown in Figure 3-6 and are based on the data summarised in Table 3-2. Of the numerous methods employed, only the depicted eight supplied results falling within the reasonable scale. Excluded methods yielded zero values, negative values or Excel™ errors due to, for instance, zero-value denominators. The Amer & Awad approach were also excluded as it supplied estimates in the 10^{-12} m/s range which fall completely outside of the reasonable average values as depicted for the remaining seven methods. Little variation exists in hydraulic conductivities calculated using these empirical approaches when varying only the two porosity functions. Density relationships generally showed marginally lower K-values, although always still well within the same order of magnitude.

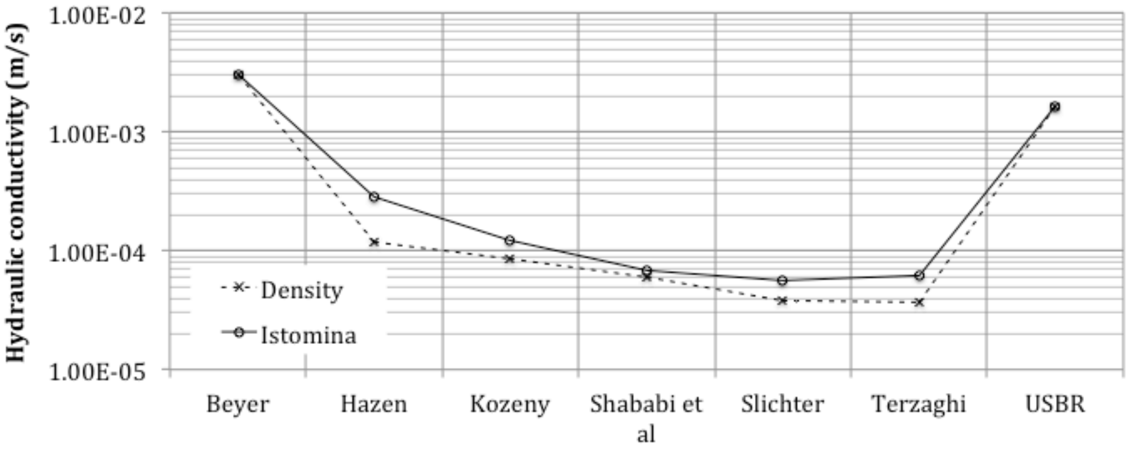


Figure 3-6. **Correlation between empirical hydraulic conductivity estimates calculated by means of density-relation and Istomina porosities (VZSA1).**

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

For uniform material, such as the crushed tailings from VZSA2 (Dippenaar et al. 2014d), empirical approaches are more applicable given the fairly uniform grain size of the tailings material. Laboratory permeability testing yielded an average hydraulic conductivity of 4.0 x 10^{-9} m/s. Tailings material was consolidated under hydrodynamic compaction and is assumed to mimic natural conditions. The porosity was assumed to be 0.22 and the material was initially assumed homogeneous (C_U = 1) as the tailings are crushed to 86 μm. This, however, made estimation of the d_e-values difficult, seeing that only the mean grain size (d_{50}) is available, and as different methods employ the d_5, d_{10} or d_{20} grain sizes. For comparative purposes, hydraulic conductivities were calculated using the mean grain size as equal to the d_e as this will be the case in completely uniform materials. To incorporate for possible deviations in grading, a second calculation assumed d_e = 10% d_{50}, regardless of whether the 5%, 10% or 20% cumulative grain size was used. This latter approach resulted in K-values approximately two orders of magnitude smaller and closer to the laboratory value of 4 x 10^{-9} m/s (Table 3-3).

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

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

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

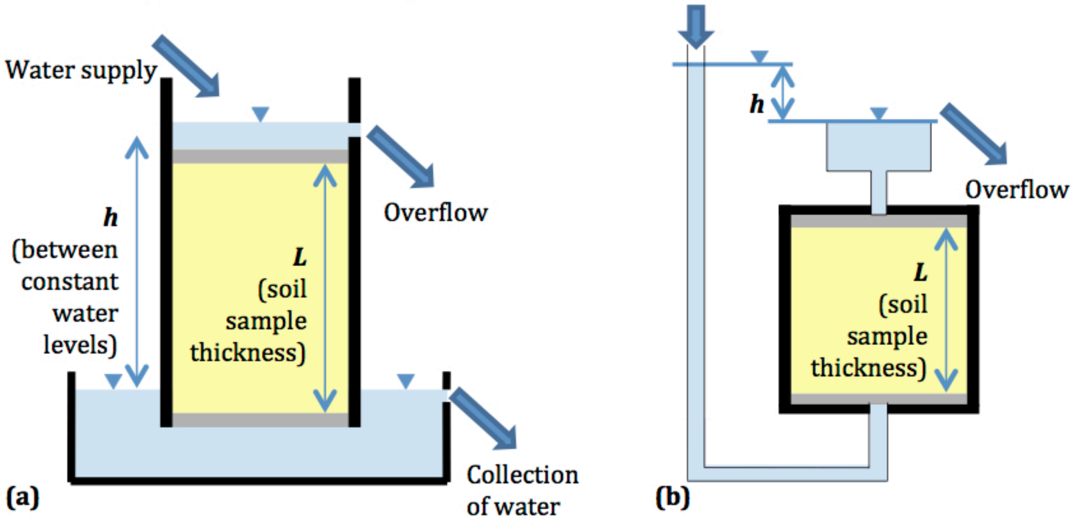
- Material should comply with the recommended ranges of applicability as defined by the respective methods (Box 22).
- Empirical estimates are almost always higher than laboratory or field values. Depending on the efficacy of the relevant method, the estimated value may be orders of magnitude higher 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.

3.4. Laboratory Permeability Methods

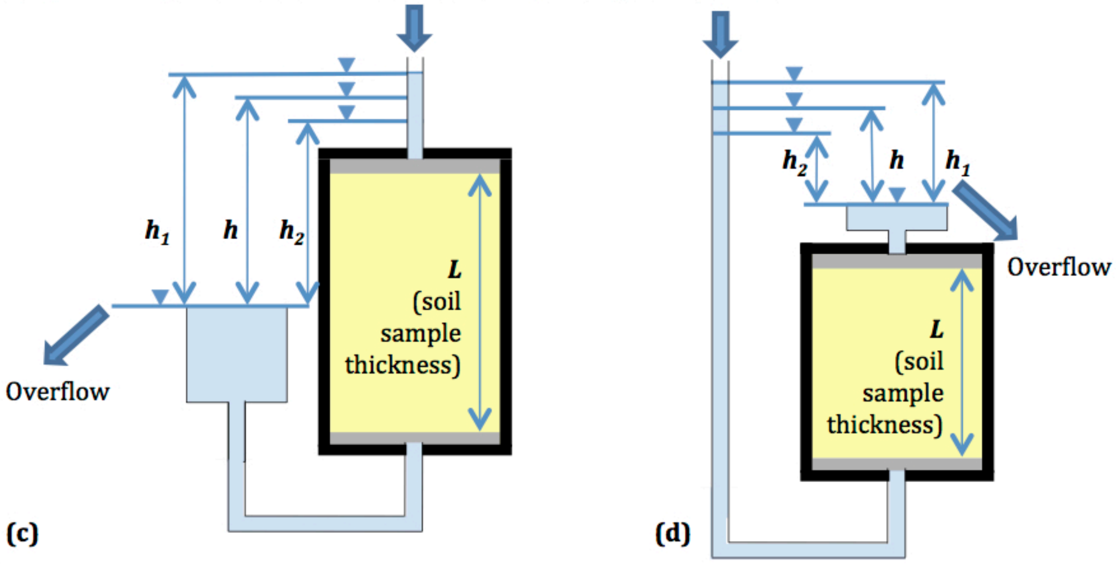
Hydraulic conductivity can be determined in the laboratory by means of constant-head tests, falling-head tests and indirectly from consolidation tests. The determined K represents the hydraulic conductivity parallel to the sample axis as calculated by inducing flow through a saturated sample and solving for K according to Darcy's Law. In all instances, the soil specimen is confined between two porous plates, essentially to maintain the structure and compaction in the column (Box 23).

Box 23. Constant-head and Falling-head Permeability Tests.

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



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



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

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

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

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

Equation 58

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

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

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

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

Equation 59

3.5. Geotechnical/ Civil Engineering Centrifuge Modelling

A centrifuge (Figure 3-7) 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 hm equal to that in the prototype according to hp = Nhm. 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).

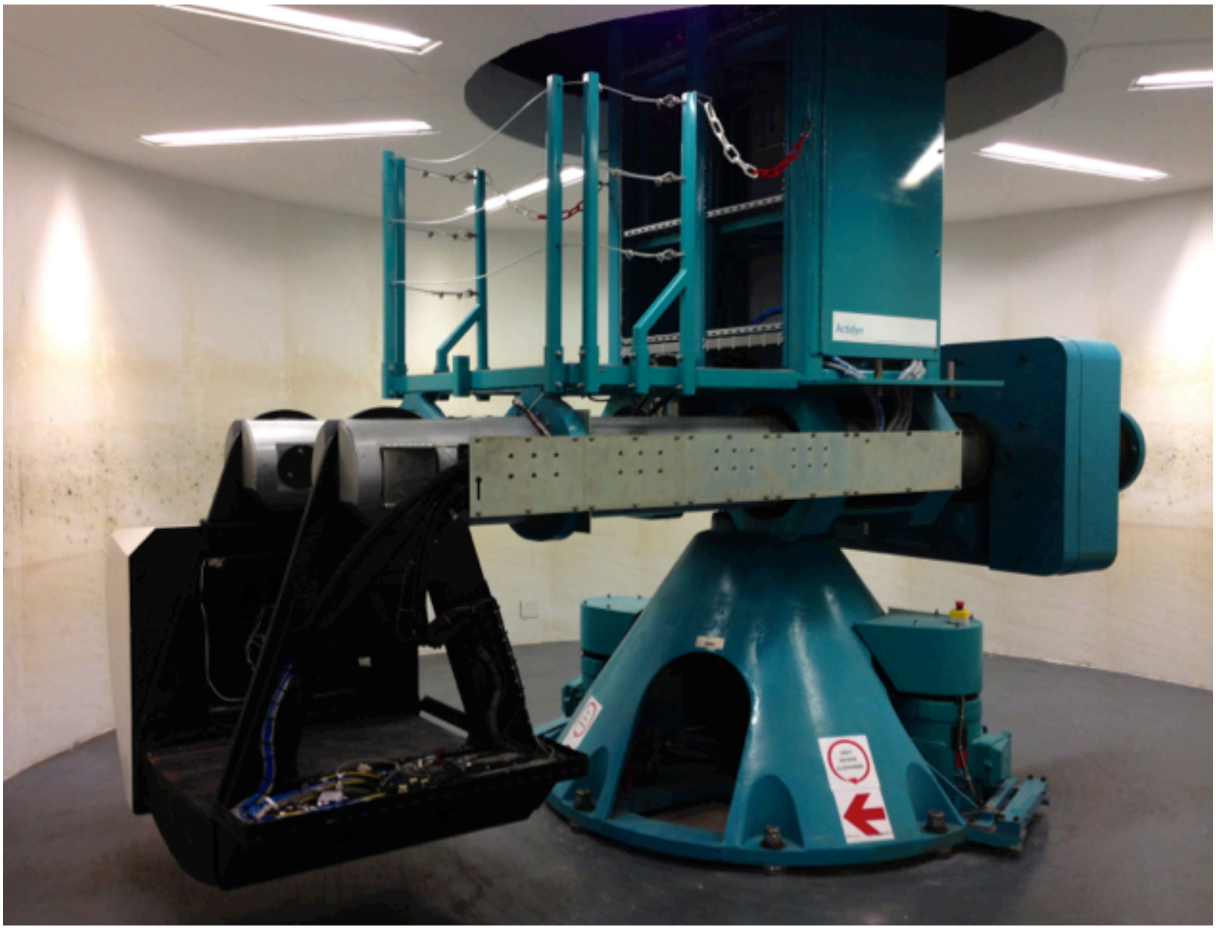


Figure 3-7. Geotechnical centrifuge of the University of Pretoria (© Jones 2014).

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 30) will govern the model's behaviour
- Artificial materials, pluviated samples or undisturbed samples can be used, provided that they mimic the natural material's stiffness, strength, and mechanical properties.

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

- Reynolds 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 considerations 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).

3.6. In-situ Methods

3.6.1. Percolation tests and infiltration tests

Various authors describe approaches to percolation testing from auger holes (e.g. Jenn et al. 2007c; Reynolds and Elrick 1986). In South Africa, one such a method is documented in SANS 10252-2 (1993) on drainage installations for buildings. Similarly, the double ring infiltration test (DRI) is a well-documented and widely applied method to estimate infiltration into the subsurface. The methods used in the percolation and DRI tests are described in Box 24. 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.

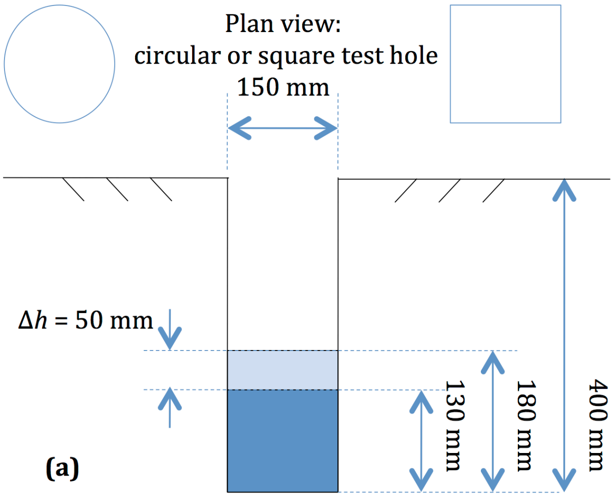
Finally, these tests are subjected to bias as they are typically conducted in areas that are open for installation of the DRI (e.g. non-vegetated patches or looser, flatter soil) or where hand auger penetration is easy for the percolation test. This intrinsically suggests the possible presence of granular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

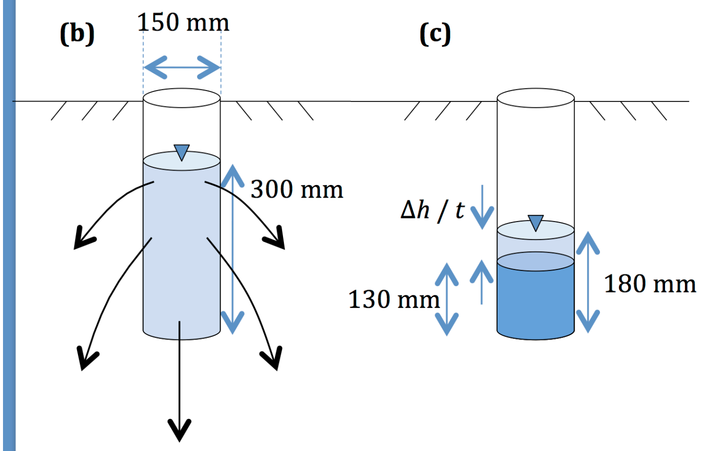
Box 24. Field Percolation and Double Ring Infiltration Tests.

PERCOLATION TEST SANS 10252-2 (1993)

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

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



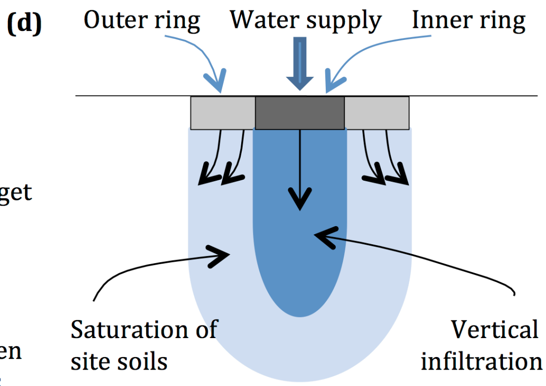


(b) Water is addedd to 300 mm from the base and allow to drain away completely three times or for at least 8 hours prior to conducting the test.

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

DOUBLE RING INFILTROMETER (DRI)

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



READ MORE & CITED FROM:

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

3.6.2. 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 3-8. Water from the measurement tube aims to equilibrate with soil moisture and the suction is detected using the pressure gauge.

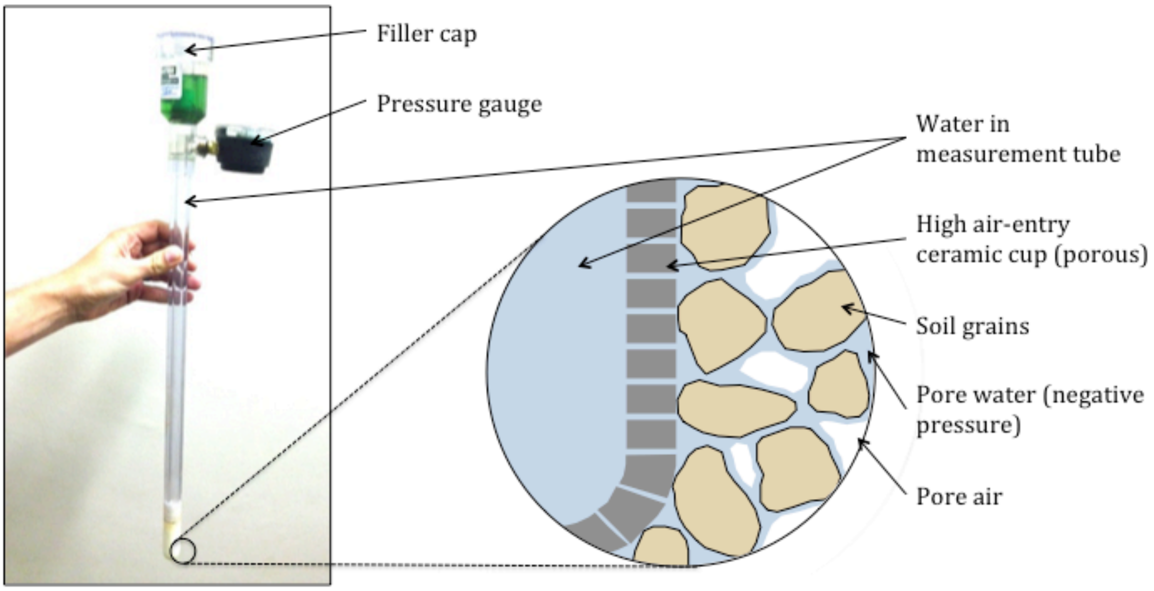


Figure 3-8. Irrometer moisture indicator (left; supplied by CalAfrica) and detail of the ceramic tip of the tensiometer (right; after Lu and Likos 2004).

3.7. Soil – Moisture Characteristic Curves

Although not applied in the accompanying case studies as the focus was on flow regimes, the geological materials and the intermediate vadose zone, characteristic curves are used to relate moisture content to matric suction as explained in Box 16. This can then be applied to estimate hydraulic conductivity for a medium at variable saturation, provided that the saturated hydraulic conductivity is known.

3.8. Modelling

Compilation of a model is dependent on a high quality initial conceptual model. The compilation of a quality conceptual model is discussed in §3.11, including the acquisition of proper material descriptions to ensure validity of the conceptual model. Assessment of modelling accuracy is not the intention of this study and has this been excluded.

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

3.9. 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 3-4. Note that values have been rounded to the nearest order of magnitude and the smallest possible ranges were used from the sources (Younger 2007; Karamouz et al. 2011 summarised from Domenicao and Schwartz 1990, Freeze and Cherry 1979, Fetter 1994, Narasimhan and Goyal 1984).

3.10. Supporting Methods

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

3.10.1. Foundation indicator tests

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

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

Table 3-4. Published saturated hydraulic conductivities for soil and rock material (collated from Younger 2007; Karamouz et al. 2011 summarised from Domenicao and Schwartz 1990, Freeze and Cherry 1979, Fetter 1994, Narasimhan and Goyal 1984).

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

3.10.2. Cation exchange capacity

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

3.10.3. X-Ray diffraction and X-Ray fluorescence spectroscopy

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

3.10.4. Toxicity characteristic leaching procedure

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

3.10.5. Acid-base accounting

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

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

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

3.11. Conceptual Models

Proper vertical and spatial material descriptions increase confidence in conceptual models through accounting for differing material properties (§3.1). Hydraulic data then are superimposed onto the conceptual model to deduce hydraulic behaviour. Variability of earth materials governs the hydrological behaviour. Examples of typical South African soil profiles from Limpopo, Gauteng and Mpumalanga Provinces shown in Box 25 (granite and gabbro-norite) and Box 26 (sedimentary and volcanic rocks), emphasising the variability in similar lithologies in similar climatic regimes.

3.11.1. Conceptual geological models

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

The important role of water in engineering is notable in pivotal position of fluid mechanics in the triangle of geomechanics, as well as the inclusion of groundwater under "composition" in the triangle of engineering geology as depicted in Figure 3-9 (Bock 2006).

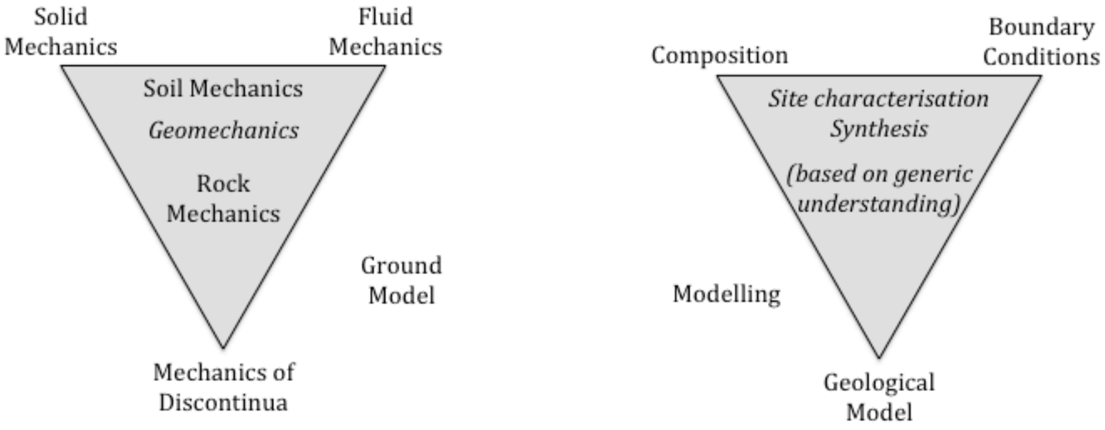
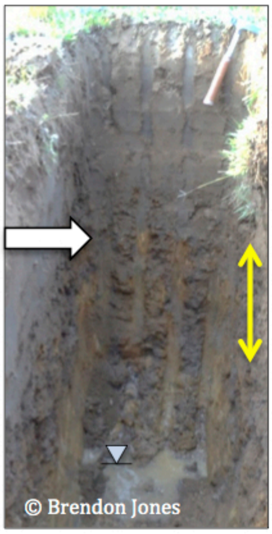


Figure 3-9. Triangle of engineering geology and geomechanics (not shown: geotechnical engineering) (after Bock 2006).

Box 25. Typical Intrusive Igneous Profiles from South Africa.

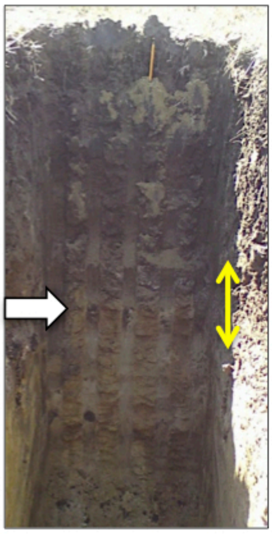

© Brendon Jones

Nebo Granite
(KwaMhlanga;
footslope)

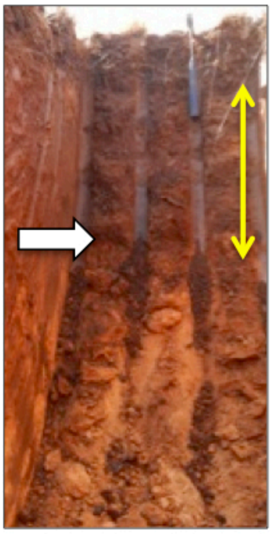

Nebo Granite
(Dennilton; crest)


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

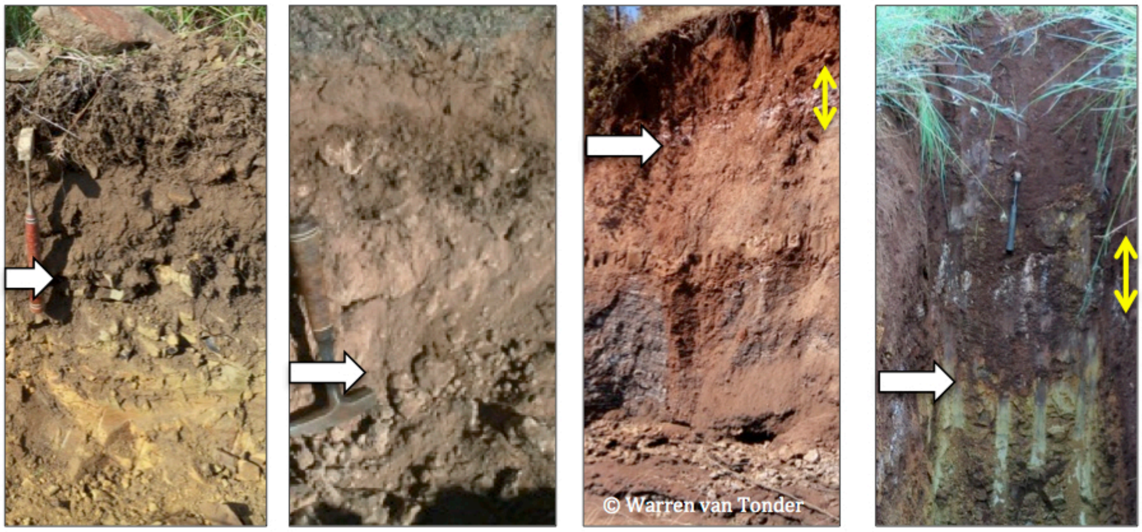
↔ Horizons subjected to distinct pedogenesis (varying degrees)

▽ Seepage/ perched water

READ MORE & CITED FROM:

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

Box 26. Typical Sedimentary and Extrusive Profiles from South Africa.

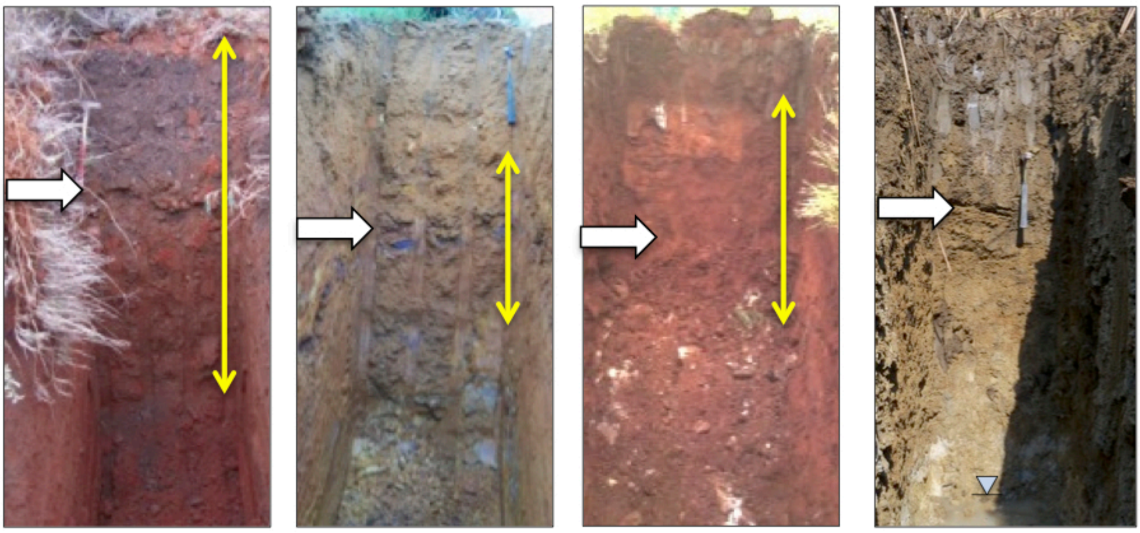


Machadodorp
Basalt
(Machadodorp)

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

READ MORE & CITED FROM:

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

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

3.11.2. Conceptual hydrostratigraphic models

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

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

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

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

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

3.11.3. Conceptual vadose zone models

A detailed review of three basement granite terrains in South Africa (Johannesburg Dome Granite, Goudplaats-Hout River Gneiss and Nelspruit Suite Granite) collating available hydraulic, hydrogeological and geotechnical data from numerous discipline-specific investigations accentuates the importance of incorporation of large multidisciplinary datasets in refinement of the conceptual model for application to the vadose zone. The review incorporates data from VZSA1 and deduces process-specific conceptual models for basement granite terrains in various climatic settings in South Africa (Figure 3-10). Similar conceptual models have been derived for VZSA1 and VZSA3, attached in Part 3 of this text.

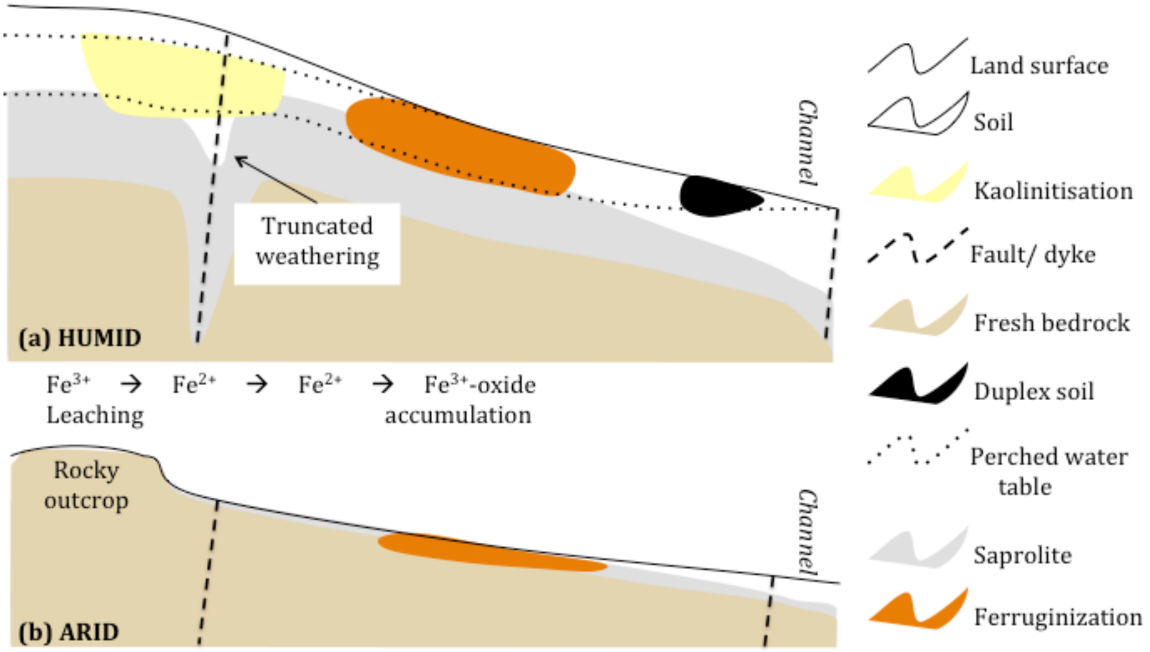


Figure 3-10. **Typical material successions and pedogenetic processes from a hillcrest (left) to drainage channel (right) underlain by basement granite in humid and arid settings (Dippenaar and Van Rooy 2014).**

Triangles of interaction in vadose zone hydrology and the compilation of the vadose zone model have been deduced based on the large datasets and is shown in Figure 3-11.

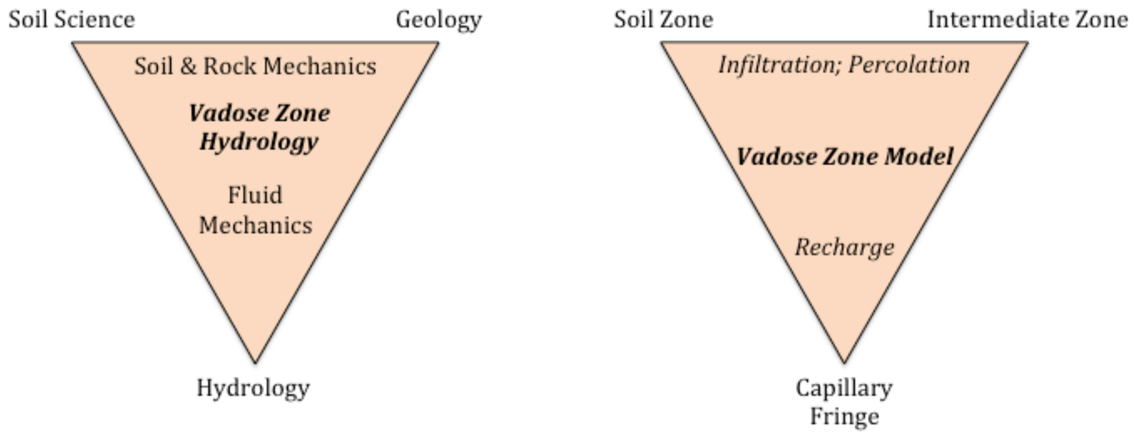


Figure 3-11. **Triangle of vadose zone hydrology (left) and the compilation of the vadose zone model (right) (Dippenaar and Van Rooy 2014).**

3.11.4. Provisional findings

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

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

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

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

4. VADOSE ZONE HYDROLOGY – APPLICATIONS AND GUIDELINES

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

4.1. Wetlands

4.1.1. *Defining wetlands*

Various definitions exist for wetlands. Some of these definitions, including the one used in South Africa according to the NWA (36, 1998), as well as the most common types of wetlands, are explained in Box 27.

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 4-1.

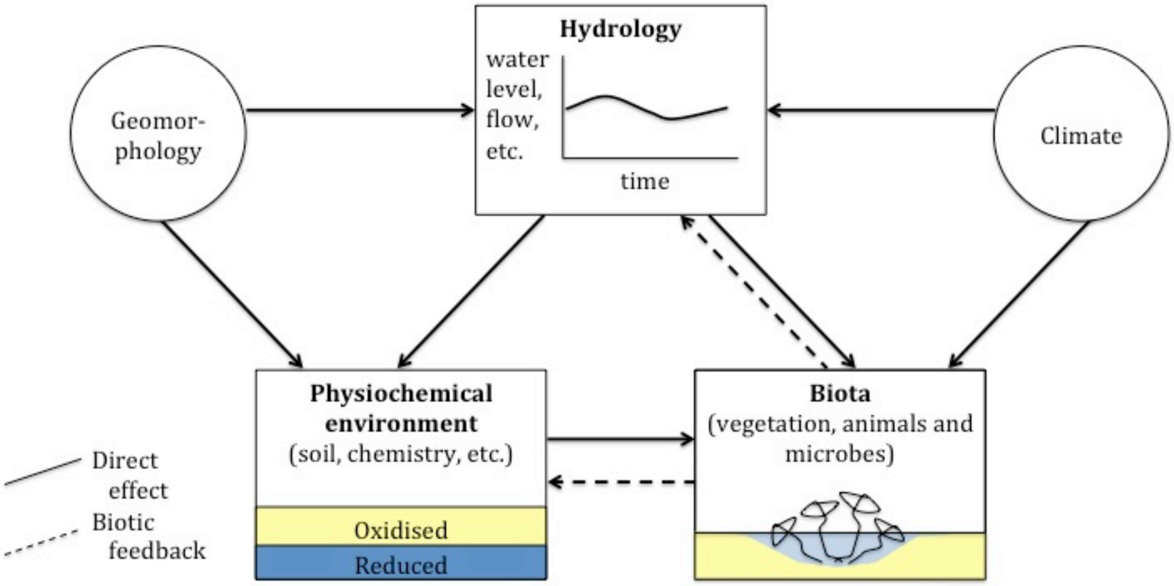


Figure 4-1. Defining wetlands based on hydrology, the physiochemical environment and biota (adapted from Mitsch and Gosselink 2000).

Box 27. Wetlands: Definitions and Types.

WETLANDS ARE:

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

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

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

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

TYPES OF WETLANDS (Ewart-Smith et al.)

Seeps and springs
(where rivers originate)

Floodplains
(areas flooded when a river exceeds its banks)

Marshes and swamps
(low-lying wetlands)

Lakes
(permanent bodies of fresh water)

Mangrove swamps
(tropical coastal swamps)

Estuaries
(tidal mouths of rivers)

TYPES OF WETLANDS (Semeniuk and Semeniuk)

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

READ MORE & CITED FROM:

DWAF 2005; Ewart-Smith et al. 2006; NWA 1998; RAMSAR 2006; SANBI 2009; Semeniuk and Semeniuk 1995

4.1.2. Wetland classification and delineation

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

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

Some approaches to wetland delineation and classification are discussed in Box 28. Wetland classification is usually based on the environmental driving functions and most notably on hydrology and, as discussed by Ewart-Smith et al. (2006), is based on its biophysical characteristics and is labelled the hydrogeomorphic classification (HGM). Landforms and hydrology are two fundamental features that determine the existence of all wetlands, both of which are included in the HGM approach.

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

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

The four indicators (terrain, soil form, soil wetness and vegetation) are mostly applied in wetland delineation. The first – the terrain unit indicator – relates to those parts of landscapes where wetlands are more likely to occur, but should not be used as a sole indicator of a wetland. Typical terrain units likely for wetland occurrence are valley bottoms and valley bottoms connected crests, midlopes and footslopes as per Figure 4-2 (DWA 2005). Alternative landform descriptions proposed by Venter (1986) for notably the igneous terrain in the southern and central Kruger National Park are shown for correlation.

Box 28. Wetlands: Classification and Delineation.

HYDROGEOMORPHIC (HGM) WETLAND CLASSIFICATION SYSTEM

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

WETLAND DELINEATION ACCORDING TO THE FOUR INDICATORS

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

ADDITIONAL INDICATORS

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

READ MORE & CITED FROM:

Day et al. 2010; DWAF 2005; Ewart-Smith et al. 2006; NWA 1998; RAMSAR 2006; SANBI 2009

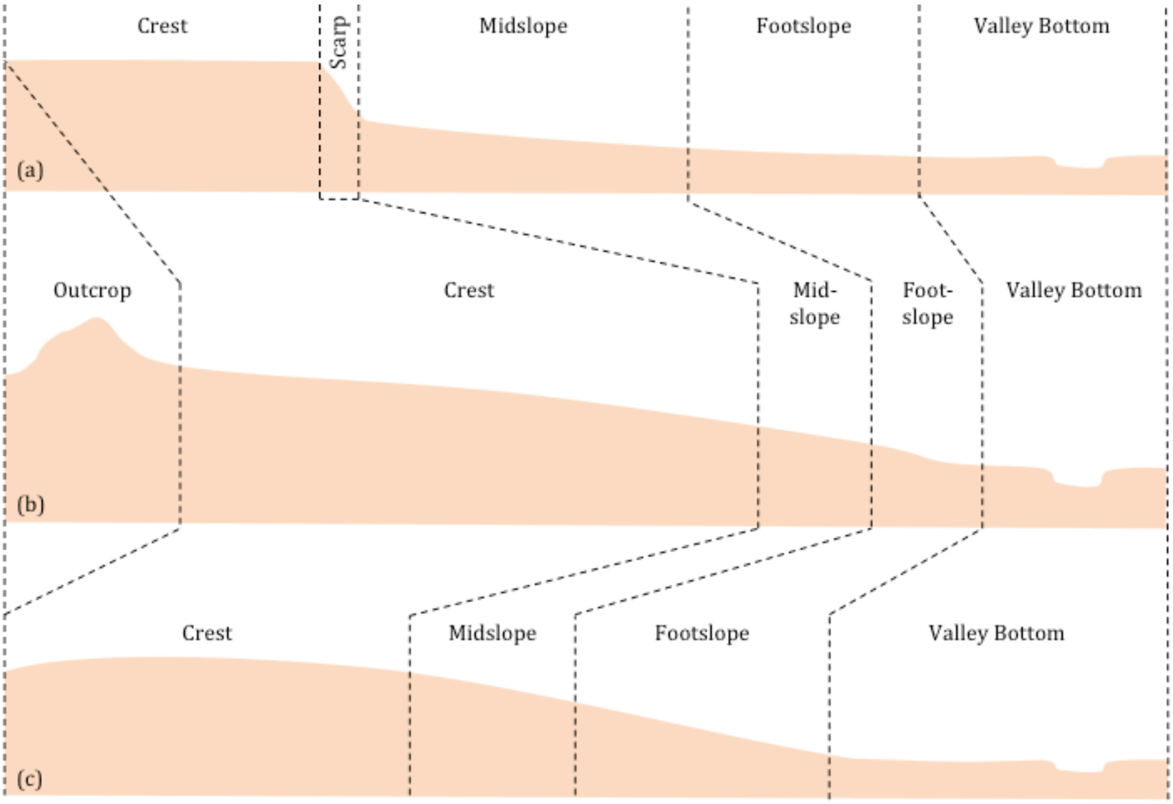


Figure 4-2. **(a) Typical terrain units of wetlands (after DWA 2005) correlated to typical alternative landform units used in South Africa and based on the (b) southern and (c) central Kruger National Park (Venter 1986).**

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. Due to the saturated conditions, plant roots cannot behave in its normal metabolic function and certain nutrients become unavailable to the plants, leading to certain elements being in elevated concentrations in the soil. Due to extensive morphological, physiological and/ or reproductive adaptation, these plant species are able to persist in these anaerobic soil conditions (ECA 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).

4.1.3. Provisional findings

Two notable wetland areas were investigated:

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

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

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

4.2. Cemeteries

4.2.1. Risk associated with cemeteries

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

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

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

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

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

The influence of infiltrating water is explained through Figure 4-3. Backfill material in graves may be less compacted than the in-situ material and may, therefore, act as preferential pathways. This may result in the graves being near water saturation, leading to anaerobic conditions for the breakdown of the organic matter. Interaction and interflow are possible between proximate graves, and/ or contaminated water may enter the vadose zone below the grave bottom if the water table is sufficiently deep. Natural attenuation of contaminants can occur through aerobic conditions in the aerated vadose zone. Shallower groundwater should be more vulnerable to contamination due to (1) the thinner vadose zone where natural attenuation can occur and (2) possible mounding of the water table, which can even result in a periodical contact between the grave bottom and the groundwater table.

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

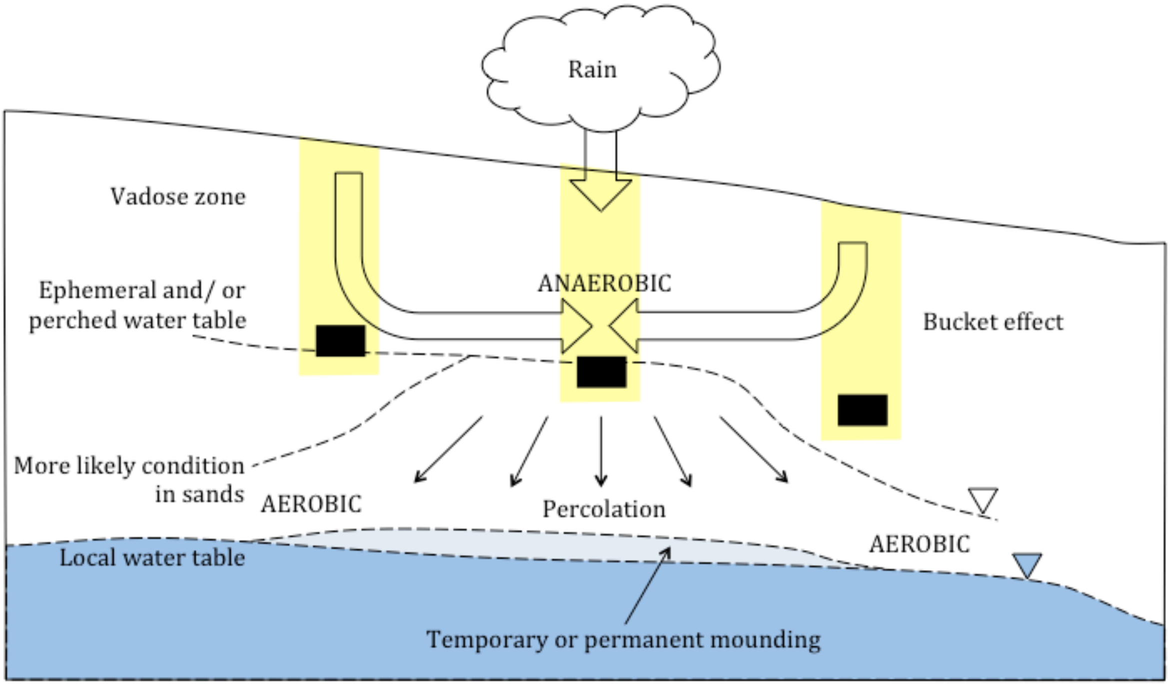


Figure 4-3. **Interaction between graves and the subsurface hydrology (adapted from Dent and Knight 1998).**

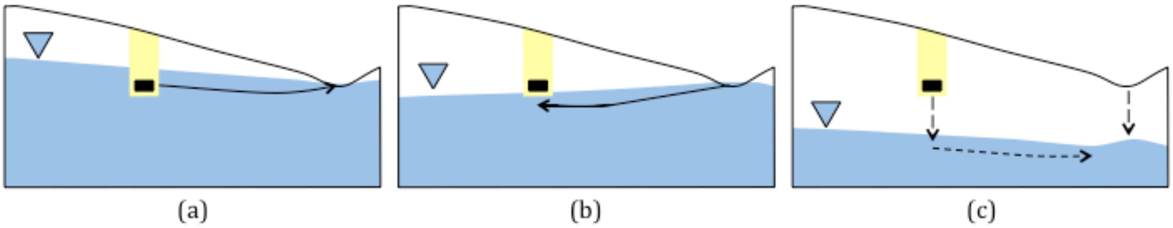


Figure 4-4. **Hypothetical interactions between graves sites and (a) a gaining stream at risk from contamination from gravesites, (b) losing stream possibly more protected and (c) deep groundwater table with possible contamination (arrows indicate likely flow directions).**

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

4.2.2. Site investigation for cemeteries

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

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

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

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

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

- The surface gradient should be between 2° and 6° (up to 9° in extreme cases) to ensure adequate drainage of the site, to minimise erosion and to promote mobility on site.
- The soil profile depth should be at least 1.80 m for ease of excavation.

- The soil consistency should be such that it ensures the stability of the grave walls for a few days.
- The underlying site soils should have a low permeability (10^{-5} to 10^{-6} cm/s) to prevent groundwater contamination.
- The site should be located at least 100 m from the 50-year flood line.
- The groundwater depth should exceed 4 m.
- A buffer zone of at least 2.5 metres should be present between the bottom of the grave and the top of the groundwater table.
- No drainage channels should intersect the proposed cemetery area.
- The site should not be underlain by dolomitic material.
- No borehole drinking water should be located closer than 500 m of the proposed cemetery.
- The cemetery should be large enough for future expansions at an estimated 3 000 graves per hectare.

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

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

community. Based on all such factors, a cemetery can be considered suitable or unsuitable.

A rating system, based on physical and sanitary aspects, was proposed by Hall and Hanbury (1990). The system is summarised in Box 29, resulting in final ratings of unacceptable, poor, satisfactory or very good.

4.2.3. Provisional findings

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

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

Changes in the water budget (due to, for instance, reduced or increased infiltration resulting from surface sealing or disturbance of surface materials, increased or reduced groundwater abstraction and variable backfill properties) will furthermore alter redox conditions which control the natural attenuation of the contaminants and their ability to be transported to groundwater or surface water bodies.

Land use planning with respect to cemeteries should exceed consideration of the cemetery alone, and should include some estimation of the impact of changing the proximate land use such as through increased development. This is addressed further in proposed guidelines in §5.4 and 6.1.

4.3. Construction and Engineering

4.3.1. The role of water in engineering geology

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

Box 29. Cemetery Site Investigation (Physical and Sanitary) where the final ranking is the sum of the six other rating scores.

EXCAVATABILITY	**Assessment**	**Rating Score**
Easy spade	Geological pick pushed in 50 mm with ease	15
Pick and spade	Geological pick causes slight indentation	10
Machine	Firm blows with pick cause 1 – 3 mm indentations	5
Blasting	Backactor refusal	0

STABILITY	**Assessment**	**Rating Score**
Stable	Little overbreak with safe excavation profiling	20
Overbreak	Overbreak between 1.3 and 1.8 m	15
Slightly unstable	Minor falls of material	8
Unstable	Collapse of excavation likely	1

WORKABILITY	**Unified**	**MOD AASHTO**	**Rating Score**
Excellent to good	GW. SW, GP	> 1 800 kg/m^3	10
Fair	SP, SM	< 1 800 kg/m^3	5
Poor	OL, CL, NL	< 1 700 kg/m^3	2
Very poor	OH. CH, MH	< 1 500 kg/m^3	0

WATER TABLE	**Water Table Depth (m)**	**Rating Score**
Deep water table	> 8	25
Intermediate water table	4 – 8	5
Possible perched water	0 – 4	5
Waterlogged soil	0 – 4	Fail

SUBSOIL PERMEABILITY	**Percolation Rate**	**Approx. Permeability**	**Rating Score**
Impermeable	Not measurable	$< 10^{-7}$ m/s	15
Relatively impermeable	10 – 15 mm/h	$10^{-6} – 10^{-7}$ m/s	20
Relatively permeable	15 – 50 mm/h	$10^{-5} – 10^{-6}$ m/s	10
Permeable	50 – 1 000 mm/h	$< 10^{-5}$ m/s	0

BACKFILL PERMEABILITY	**Unified Class**	**Rating Score**
Impermeable	OH, CL, CH	5
Relatively impermeable	GC, SC, MH	10
Relatively permeable	GP, SP, GW	7
Very permeable	SW, SP	0

FINAL RANKING	**Suitability**
> 90	Very good
75 – 90	Satisfactory
60 – 75	Poor – precautions required
< 60	Unacceptable

READ MORE & CITED FROM:

Hall and Hanbury 1990

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

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

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

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 due to, for instance, dissolution of cementing materials (Hencher 2012).

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

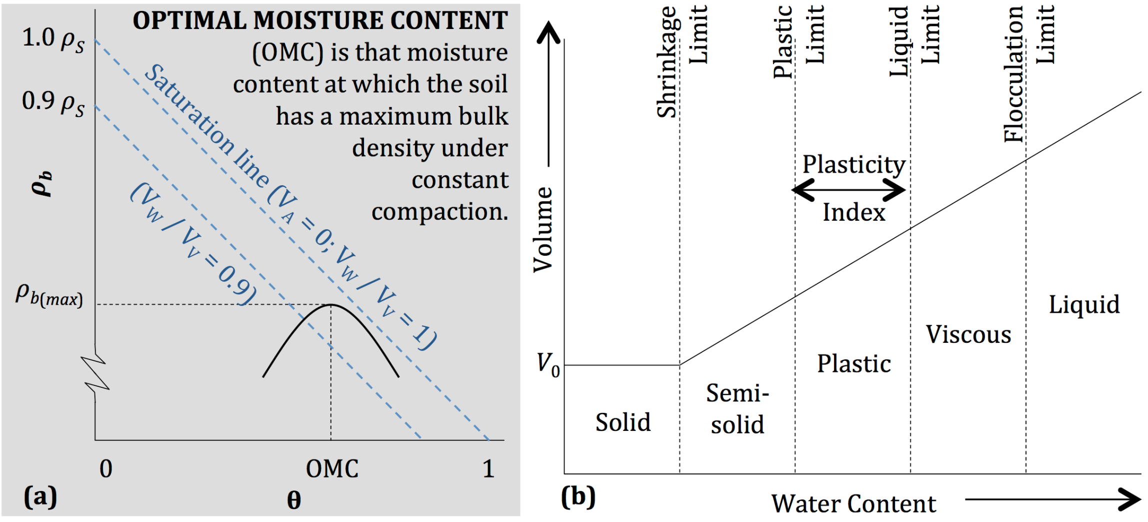
- Dissolution resulting in loss of material in soluble rocks and karstification, causing cavities, subsidence and/ or collapse
- Erosion or piping resulting in loss of material, sheetwash, internal erosion and gully erosion, causing subsidence, collapse, settlement, piping and/ or silting
- Chemical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

The influence of variable saturation in engineering is explained at the hand of the optimal moisture content, the Atterberg limits (relating soil consistency to moisture content in cohesive soils) and stress distribution in Box 30.

The optimal moisture content (OMC) refers to that moisture content at which the soil exhibits a maximum bulk density ($\rho_{b(\max)}$) under constant compaction and is especially important in defining the compactive effort required in road construction (Rose 2006). At lower moisture contents, soil tends to be difficult to compact due to its consistency and structure. With increasing moisture content, the soil becomes more workable until the OMC is reached. Beyond the OMC, the dry density decreases as more water is added and an increasing proportion of the soil becomes occupied with water. The relationship between these parameters is shown in Box 30.

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

Box 30. Geotechnical Engineering and Engineering Geology.



OPTIMAL MOISTURE CONTENT (OMC) is that moisture content at which the soil has a maximum bulk density under constant compaction.

ATTERBERG LIMITS

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

EFFECTIVE STRESS

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

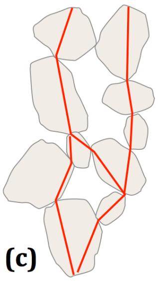
Then, effective stress = total stress – pore pressure:

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

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

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

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



READ MORE & CITED FROM:

Craig 1999; Das 2008; González de Vallejo & Ferrer 2011; Knappett and Craig 2012

4.3.2. Problem soils

Construction may involve problem soils (Box 20) where the soil may undergo volume change on changing load and/ or moisture content. Soil consistency, notably in cohesive soils, is linked to moisture content according to fixed Atterberg Limits. The plastic index is calculated as the difference between the liquid and plastic limits and is commonly used in estimations on the likelihood of expansive behaviour in soils.

4.3.3. Constructed fills and made ground

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

4.3.4. Drainage for infrastructure and excavations

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

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

4.3.5. Construction impacts on the water budget

Development inevitably changes the hydrological budget. Most aspects have been covered elsewhere, and include for instance (Box 31):

- 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 (e.g. 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.

4.4. Aquifer Susceptibility

4.4.1. Aquifer vulnerability

The vadose zone in groundwater-related studies serve fundamental purposes in protecting groundwater against potential contamination (as addressed in ***aquifer vulnerability studies***) and in transmitting surface water and precipitation downwards to add to the groundwater reservoir (as labelled ***groundwater recharge***), both summarised in Box 32.

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

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

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

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

Recharge can be direct, localized or indirect. In arid countries and/ or areas where groundwater is not in direct contact with the land surface or with surface water bodies, the vadose zone forms a fundamental component of the recharge process. This thicker vadose zone can serve as additional protection to the aquifer. Recharge is discussed in elaborate detail by, for instance, Xu and Beekman (2003) and Healy (2010).

Box 31. Examples of Possible Construction Impacts on the Vadose Zone.

INCREASED WATER SUPPLY DUE TO GOLF COURSE IRRIGATION

Golf Course underlain by Johannesburg Dome Granite

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

SURFACE SEALING AND IMPORTED FILL

Proposed Shopping Center underlain by Johannesburg Dome Granite:

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

CUT-AND-FILL AND LEAKING PIPELINES

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

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

CONFINED AQUIFER LEAKING AFTER DRILLING

Residential dwelling underlain by Johannesburg Dome granite

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

SWIMMING POOL EXCAVATION IN SHALLOW GROUNDWATER

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

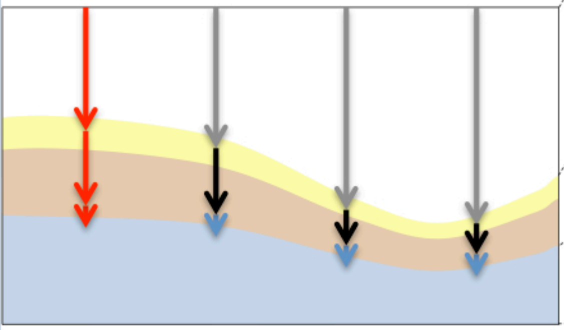
READ MORE & CITED FROM:

Box 32. Recharge and Aquifer Vulnerability.

BOX 35: RECHARGE AND AQUIFER VULNERABILITY

SPECIFIC VULNERABILITY

Risk exacerbated by specific contaminant:
- Contaminant properties/ toxicity
- Manner of contaminant disposition
- Persistence, bioaccumulation



INTRINSIC VULNERABILITY

ATMOSPHERE AND LAND SURFACE
Likelihood of infiltration:
- Precipitation (intensity/ duration)
- Topography/ slope
- Land use/ land cover

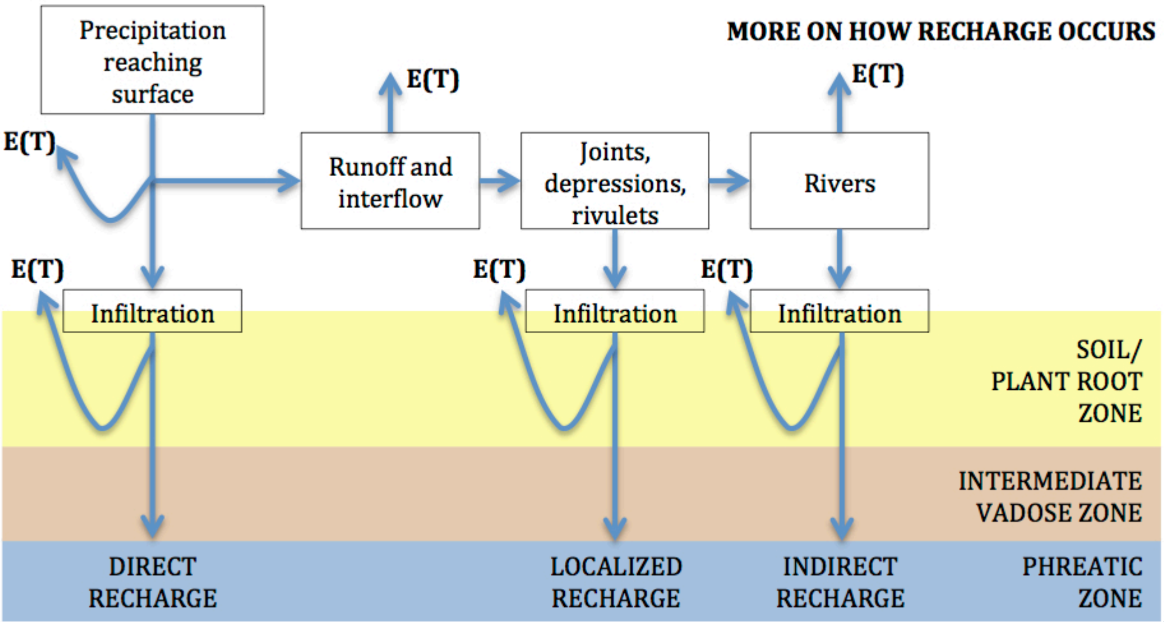
VADOSE ZONE
Likelihood of recharge:
- Distance (depth to water)
- Flow rate (K_{unsat})
- Confining layers

PHREATIC ZONE
Impact on aquifer:
- Recharge rate
- Aquifer media

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

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

MORE ON HOW RECHARGE OCCURS



READ MORE & CITED FROM:

Vulnerability: Foster 2002; Saayman et al. 2007; Sililo et al. 2001
Recharge: Lerner 1997 in De Vries and Simmers 2002

4.4.2. *Provisional findings*

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

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

4.5. Ground-based Sanitation

Ground-based sanitation options are numerous and generally fall within two broad types, viz. (1) pit latrines (such as the ventilated improved pit latrine or VIP) which are dry systems, and (2) on-site soakaway systems (such as septic tanks and french drains) where conditions are generally anaerobic. Investigation for the latter is well documented and prescribed in the field percolation test by SANS as per Box 24. The main considerations for such on-site groundbased sanitation systems are, however, similar to that off cemeteries, and should for sanitation specifically focus around:

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

4.6. Riparian Interaction and Groundwater Dependent Ecosystems

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

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

4.7. Agriculture

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

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

4.8. Urban Hydrology

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

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

- Increased surface sealing results in decreased infiltration as bulk of stormwater from sealed or paved surfaces are generally discharged in stormwater systems. The exception to this is where runoff is localised an directed to unsealed surfaces, resulting in forced preferential infiltration.
- Increased runoff subsequently results in reduced recharge and possible implications on urban drainage and stormwater
- Leaking pipes (drinking water mains and wastewater) contribute futher to the urban water balance and alter, for instance, interflow
- Some anticipated changes in soil properties due to changing land use include ploughing (loosening), compaction (densification), imported material or made ground (variable properties), cut-and-fill (interuption of flow paths), drying of wetlands (due to removal of source of water), creation of manmade wetlands (due to accidental or planned redistribution of water) and changes in the interflow processes and the associated movement of ions and fines.
- Connectivity between stream channels and wetlands may be lost due to interruption of the continuous water supply or through canalisation of such

channels. Downstream ecosystems are inevitably influenced, and groundwater recharge may be significantly decreased due to increased evaporation from sealed surfaces and removal of water through stormwater systems.

- Aquifer vulnerability becomes increasingly important given the high density of potential sources of contamination in urban areas. Allocation of groundwater polluters are difficult, as for instance in the example of organic contamination in areas where numerous petroleum storage facilities are present. Cognisance of the vadose zone may aid in understanding the subsurface flow paths and subsequently in addresseing deteriorating urban water quality.

5. FINDINGS

Main findings have been published around three central themes, each incorporating background on methods employed, description of applications and implications of vadose zone hydrology, and summarising of critical findings. These three themes overlap and are:

- Conceptual models and their importance, contained in §5.1 (Dippenaar and Van Rooy 2014) and §5.2 (Dippenaar and Van Rooy, in print)
- Applications to important case studies, including wetlands in §5.3 (Dippenaar 2014b) and peri-urban cemeteries in §5.4 (Dippenaar, in print)
- Guidelines for improved investigation contained in §5.4 (Dippenaar, in print).

Additional findings are documented in the relevant sections of fundamental concepts and methods in Dippenaar (2014c) and Dippenaar (2014d).

5.1. Review of Engineering, Hydrogeological and Vadose zone Hydrological Aspects of the Lanseria Gneiss, Goudplaats-Hout River Gneiss and Nelspruit Suite Granite (South Africa)

Numerous authors have evaluated basement aquifers in southern Africa (e.g. Botha and Van Rooy 2001; Dippenaar et al. 2009; Holland and Witthüser 2011; Titus et al. 2009; Witthüser et al. 2010). However, as a critical component of understanding the hydrological cycle, one needs to consider the behaviour of earth materials in all aspects of the hydrological cycle, which includes not only saturated conditions, but also the vadose zone, aquicludes and barriers. These all relate to the formation of the earth materials and are highly dependent on the mineralogy of the host rock, the tectonic influences causing subsequent deformation, weathering of the in-situ rock, prevailing and historical climatic conditions, geomorphological processes governing landscape development, and the intrusion of younger lithologies.

Three distinct basement granite settings have been selected based on ten years' detailed investigation in these areas and the subsequent abundance of data specifically relevant to the phreatic hydrology (behaviour as aquifers), soil properties (and shallow vadose zone hydrology) and geochemistry. These areas are:

- Lanseria Gneiss of the JGD (Gauteng Province)
- Goudplaats-Hout River Gneiss (Limpopo Province)
- Nelspruit Suite (KNP, Mpumalanga Province).

The purpose of this paper is to review and collate the data from a variety of studies within these basement granite areas, with the emphasis on addressing bulk of the important variables as envisaged in the triangle of geomechanics and the triangle of engineering geology by Bock (2006) as shown in Figure 3-9. The eventual aim is to address the vadose zone properties of the different basement granites in South Africa.

5.1.1. Basement granites and weathering

5.1.1.1. Basement granite

The term basement rock applies to any hard, crystalline or recrystallised, igneous or metamorphic rock associated with Precambrian Age, including ancient Archaean cratonic rocks (granites, gneisses, greenstones), metamorphic rocks associated with mobile belts (usually deformed and of Proterozoic age) and anorogenic intrusions of variable age (Arcworth 1987; Jones 1985; Key 1992; Wright and Burgess 1992).

Granite, from a geological point-of-view, can be considered any intrusive or hypabyssal, felsic, igneous or metamorphic rock composed of predominantly quartz and feldspar (orthoclase and plagioclase). Igneous granites (granites s.l. or granitoid rocks) typically comprise alkali feldspar granite, granite (s.s.), granodiorite and tonalite.

Basement granite (for the purpose of this study) therefore comprises the variety of rock types as shown in Figure 5-2.

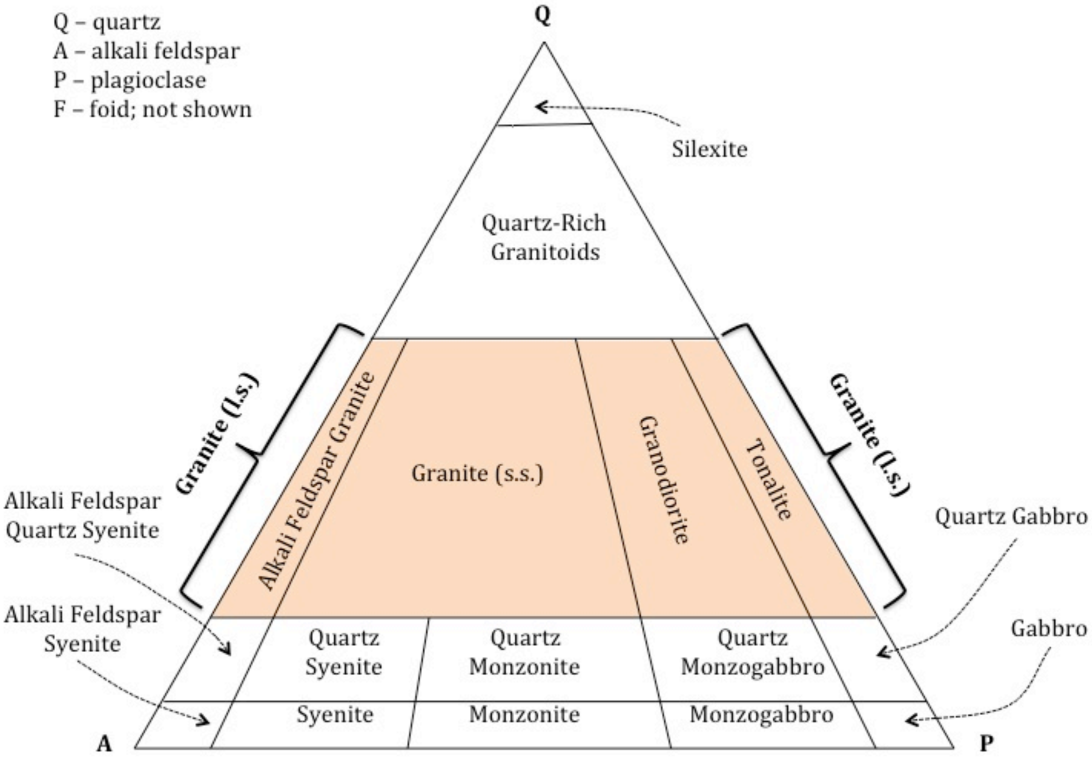


Figure 5-1. Upper portion of QAPF diagram indicating the plutonic igneous rocks commonly referred to as "granites" (s.l.).

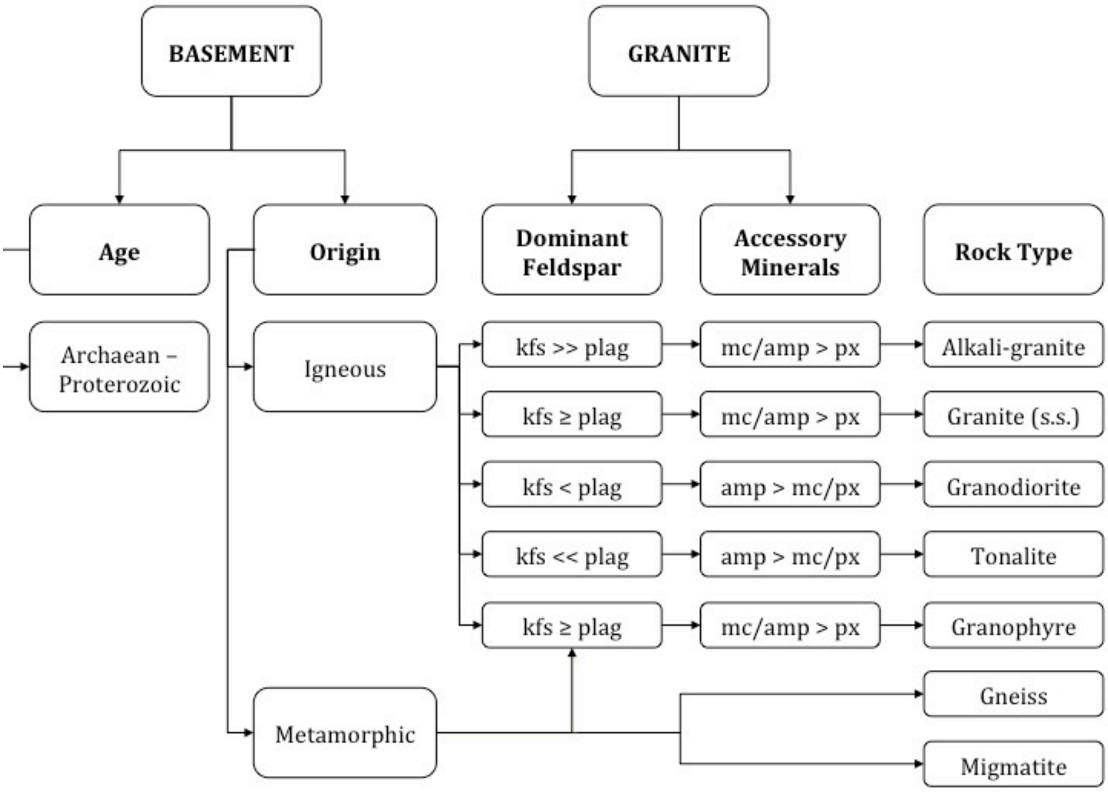


Figure 5-2. **Classification of basement granites (kfs – potassium feldspar; plag – plagioclase; mc – mica; amp – amphibole; px – pyroxene).**

5.1.1.2. Granite weathering

A number of authors have investigated typical weathering patterns associated with granitic bedrock. Dewandel et al. (2006), for instance, considered rock mineralogy, climatic conditions (notably rainfall) and long periods of stable tectonic conditions as requirements to form thick weathering profiles. Additional to this they found that flat topography was required to enhance water infiltration and to minimise erosion of the weathering products. For areas with predominating chemical decomposition, they subdivided a basement aquifer system into:

- Laterite at surface (the possible presence of an iron/ bauxite crust)
- Saprolite (clayey material due to the in-situ chemical alteration of bedrock)
- Fissured layer (densely horizontally fissured rock)
- Fresh Basement (locally permeable bedrock).

Scarciglia et al. (2005) focused on the physical disintegration of granite in Italy rather than the chemical decomposition, placing the emphasis on climatic interpretation and an assessment of the age of the soil. Weathering processes and landforms were considered important factors, but the key roles were assigned to petrographic and mineralogical controls.

Kirschbaum et al. (2005) evaluated the granite weathering profiles in Argentina, stating that weathering "… consists of thermodynamic readjustment of these [outcropping] rocks to surface conditions." Their results showed distinct corestone development (as was also found to some extent by Scarciglia et al. (2005)) and the formation of blocks of rock due to intense fracturing. The profiles were summarised as a horizon where leaching predominates; a second where accumulation, eluviation and alteration occurs; and a third closer to the protolith characterised by fracturing and fragmentation.

Ceryan et al. (2008) investigated the influence of weathering on granitic rocks in Turkey, specifically addressing the P-wave (primary seismic wave) velocity as an indicator of the engineering properties. In their study, they specifically also compared the percentage secondary minerals and the percentage micro-cracks and voids to discern between the different stages of weathering. Drainage conditions were found to determine the type and abundance of the different clay minerals; viz. 1:1-types in a well-drained environment and 2:1-types in poorly drained environments. This latter statement was confirmed by Sequeira Braga et al. (2002), whereby 2:1-type clays occurred more frequently under present-day wet climates, whereas the 1:1-type was more common in present-day temperate climates.

Sequeira Braga et al. (2002) evaluated the arenization (weathering leading to the sandy granite saprolite) in Portugal. They found that the weathering profiles showed vertical and horizontal heterogeneity regardless of the granite composition with corestones occurring sporadically. Sodium and calcium were found to be the most-leached elements from granitic saprolite and were ascribed to the complete alteration of plagioclase. In summary, they concluded on the importance of distinguishing between climatic versus non-climatic influences, as well as between present-day climates versus palaeoclimates.

Based on the approaches followed in international studies, soil profile development depends on historical controls (geomorphology, geotectonics and palaeosoils), present-day controls (relief and landforms, microclimate and younger soils) and the interaction between these controls as shown in Figure 5-3.

Clearly one of the major determinants in the weathering profile – apart from those mentioned in Figure 5-3 – is the influence of rock mineralogy. Accessory minerals occur in small quantities and can be considered to have significantly less influence on the weathering products than the main minerals. Quartz typically weathers physically to smaller grain size, as it is fairly inert chemically. However, feldspars can weather differently depending on the mineralogy, which is either the potassic end-members (orthoclase, microcline) or the calcic-sodic end-members (plagioclase).

5.1.2. South African basement landscapes and its development

5.1.2.1. Geomorphological development

The South African soil profile is fairly characteristic in that (a) transported soils are typically present, (b) a pebble horizon typically separates the transported and residual soil cover and (c) different stages of ferruginization are often present. This is mostly due to the long exposure to weathering and erosion cycles, leading to different conditions regarding water movement in the soil profile, ion movement and concentrations, and the formation of pedocretes.

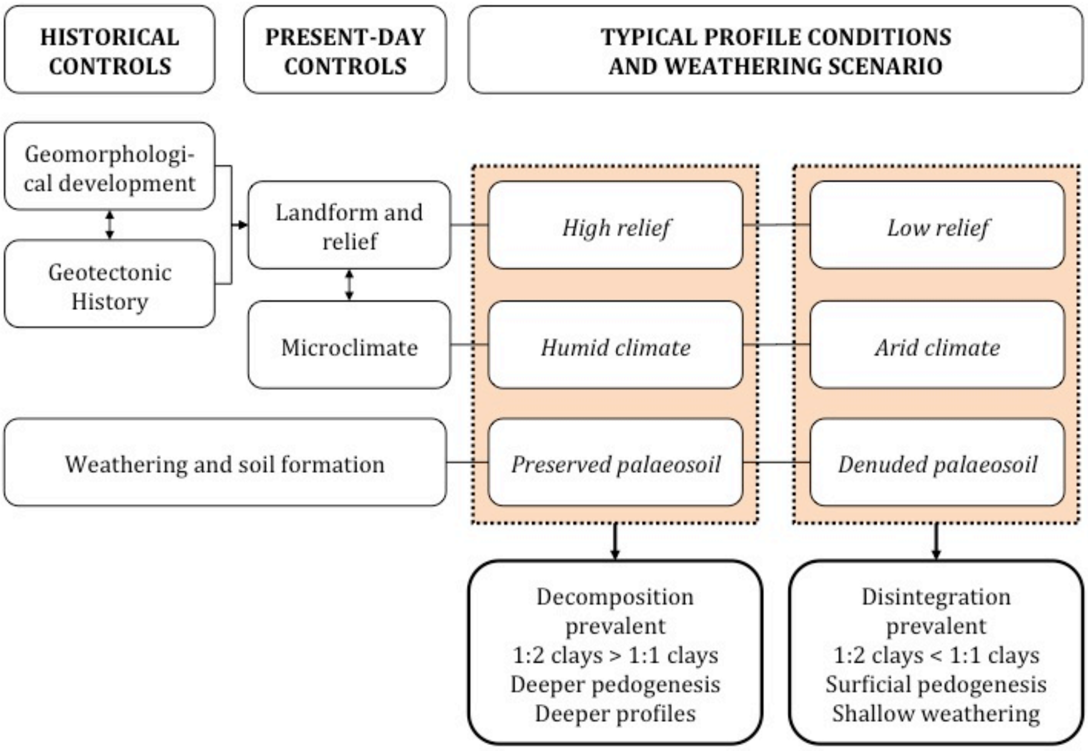


Figure 5-3. **Historical and present-day influences on soil profile development.**

Intensive work were done by Partridge and Maud (1987) and King (1975) to identify these erosion cycles due to tectonic movements, sea-level changes and changing climate. After each of six recognised erosion cycles (each representing long periods of weathering and erosion), a new set of base levels was formed. The six cycles identified by King (1975) are the following:

- Gondwana planation, ca. 190 Ma
- Post-Gondwana cycle, ca. 135 Ma
- African cycle, ca. 100 Ma
- Post-African I cycle, ca. 20 Ma
- Post-African II cycle, ca. 5 Ma
- Quaternary cycle, ca. 2 Ma.

Typical landforms for granitic terrain are discussed by Venter (1986) for the central and southern KNP (Figure 4-2b, c). The main distinction is based on climate and these subdivisions will be applied henceforth.

5.1.2.2. Tors and inselbergs

Following extensive periods of weathering, erosion and denudation, the granite landscape in South Africa formed as it exists today with rock outcrops being typically of two broad types, viz. (Figure 5-4a and b):

- Tors which form as bare rock outcrops with free faces on all sides due to differential weathering and mass wasting commonly governed by jointing (e.g. Keary 2001); very often chemical weathering is induced in well jointed rock, followed by mechanical erosion of the debris, resulting in remaining corestones on surface to form the tors (e.g. Sparks 1971)
- Inselbergs which are large steep-sided outcrops forming due to parallel retreat of the bedrock slopes or resulting from deep weathering, resulting in distinct landforms surrounded by pediments (e.g. Keary 2001; Marshak 2005).

Vegter (1995) addresses regolith development in granite terrains where tors exist (Figure 5-4c). Tors and possibly to a lesser extent inselbergs are influenced by jointing where the more jointed part of the rock denudes to form lower lying areas between the outcrops. Inselbergs that are loaf-like and circular are termed bornhardts, as opposed to other varieties with peaked or table top crests. Large flat inselbergs are commonly termed whalebacks, with the very steep bornhardts often referred to as tortoise rocks or elephant rocks, depending on geometry.

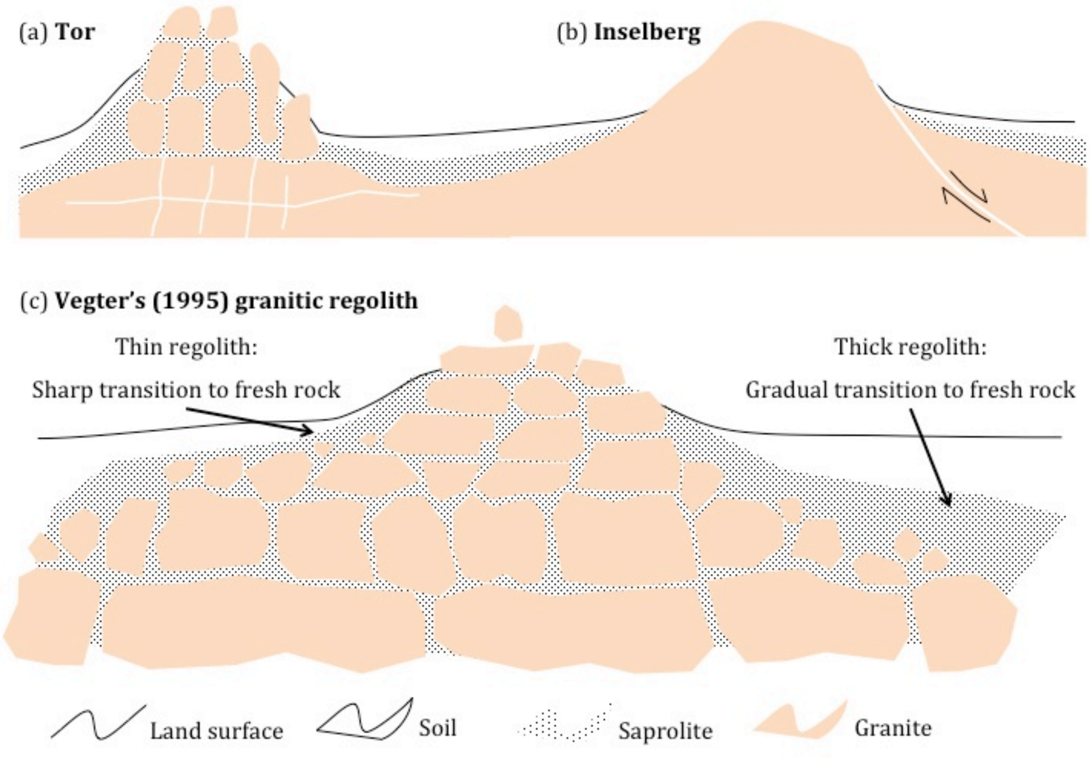


Figure 5-4. **(a) Tor and (b) inselberg with typical pediment cover (shaded area) and white lines denoting joints or faults where movement is indicated; (c) Vegter's (1995) conceptual regolith development on granite.**

5.1.2.3. Slope hydrology and associated processes

Fine colloids (e.g. clay minerals) and dissolved ions (depending on its solubility) are commonly mobilised in soil profiles for deposition or precipitation at another position vertically displaced in the profile or laterally downslope. Two broad categories are defined in this, namely (i) translocation or the mobilisation (leaching; eluviation) of clay minerals and its deposition elsewhere (illuviation) and (ii) pedogenesis or the movement of dissolved ions in water until its later precipitation on drying in more oxidizing environments.

The slope on granitic bedrock can be subdivided into a truncated weathering profile on the hillcrest and pediment with iron being leached from higher areas and accumulating as iron oxide on the lower slopes and pediments (Righi and Meunier 1995). This formation of ferricrete is fairly common in the more arid portions of South Africa underlain by granites and generally represents a seasonal perched water table. In international context, laterite is noted more typically and is the pedogenic material formed from aluminium sesquioxide. In South Africa, iron rather tends to mobilise to form ferricrete (Weinert 1980).

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

An important aspect (notably when considering bedrock as a constant and climate as a variable) is the change in hydrology due to minerals weathering differently under chemical (decomposition) and mechanical (disintegration) processes. This may results in some sort of a snowball effect where more moisture leads to more clays forming, resulting in more perching of groundwater during wet seasons, then further weathering and transformation of minerals to clays with more pedogenesis, and so forth. This is supported by Brink (1981), stating that the degree of weathering is known to influence the permeability of rocks and varies between 10^{-7} m/s in completely weathered granitic rock and 10^{-5} m/s in the slightly weathered zone. Unweathered granite is typically considered to be practically impervious.

Similarly, clay minerals (with the notable emphasis on kaolinite as a common weathering product of potassium feldspar) may filtrate depending on the flow velocity. A study by Alem et al. (2013) found through tracer tests that increasing flow velocities result in further transport of clay particles and that larger particles are retained at the entrance to the medium. Kaolinite was identified as the main weathering product followed by mica in residual granitoid soils from Portugal (Viana da Fonseca et al. 2006) and is generally anticipated as the most likely clay mineral to form.

Resulting from these slope hydrological processes, a number of subsurface water – surface water interactions can exist. These are notable in the common occurrence of ephemeral hillslope wetlands or seepage lines and typical catena sequences in many of the South African Basement granite terrains. Catena elements comprise that specific combination of plant cover, soil, slope characteristics and slope position thought to cause and result from a relatively homogeneous water budget, and are often associated with savannah landscapes underlain by granitoid rocks in the KNP. These catenas form due to mobilisation and eluviation of clay particles and dissolved weathering products from porous upland areas, through transport under gravity and deposition on footslopes to form impermeable clay horizons, which eventually form groundwater out on surface (Cullum and Rogers 2011; Schaetzl and Anderson 2005; Venter 1986).

5.1.3. Basement aquifers

Basement aquifers comprise the whole suite of rocks as defined earlier and which furthermore can fulfil the important function of economic water supply. Its formation and age intrinsically make these rocks – notably the granites – secondary aquifers due to the low primary porosity, the long history of tectonic and geomorphological influences and the likelihood of metamorphic textures such as gneissosity.

5.1.3.1. Basement aquifers and groundwater

Basement aquifers form a fundamental component of water supply in sub-Saharan Africa with the notable emphasis on rural domestic water supply. This has been addressed by numerous authors, including for instance Adams (2009 in Titus et al. 2009) and Witthüser et al. (2010), with further recent evaluation of groundwater supply and demand for a Basement aquifer in Malawi by Robins et al. (2013). This latter paper notes that basement outcrops in approximately 33% of South Africa, making it a very important potential groundwater supply. Conceptual block diagrams are additionally available in Vegter (1995). Further work has been conducted on water supply from the Nebo Granite in South Africa (Botha and Van Rooy 2001), but is not included in this review given the significantly younger age of the Bushveld Igneous Complex.

With respect to the Southern African Developing Community (SADC, and including South Africa, Lesotho, Swaziland, Namibia, Botswana, Zimbabwe, Angola, Zambia, Malawi, Democratic Republic of Congo and Tanzania), the Basement granites in north-eastern South Africa depicts very low to low aquifer productivity and moderate to high recharge potential, coupled with low to very high groundwater dependence (Villhoth et al. 2013). This dependence makes proper understanding of these aquifers important in ensuring sustainable water supply given the scarcity of perennial drainage features in South Africa.

Groundwater resource potential depends on the type of hard-rock formation, structural geology, geomorphological evolution and present-day groundwater recharge and discharge (Foster 2012), highlighting the importance of a multidisciplinary approach to data acquisition and interpretation. Optimal drilling localities are adjacent to intrusive dykes where fracturing and deep weathering prevails, as opposed to within fresh granite (Figure 5-5; Vegter 1995).

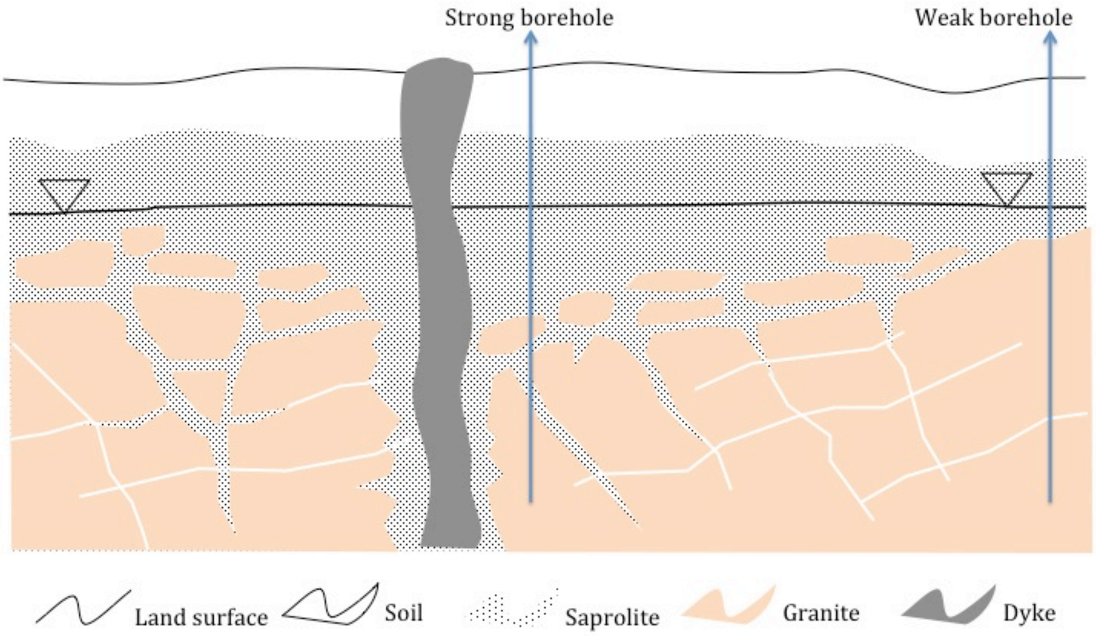


Figure 5-5. **Influence of dykes in optimal siting of water supply boreholes in granite terrain (simplified from Vegter 1995).**

5.1.3.2. Hydrostratigraphy

Hydrostratigraphy as discussed in §3.11.2 will henceforth be slightly redefined to include regional variation of earth materials to include the complete phreatic and vadose zones, as well as all forms of aquitards, aquicludes and aguifuges, as well as all components of the rock cycle. However, the focus will henceforth be on understanding the vadose zone component.

5.1.4. Materials and methods

5.1.4.1. Study areas

The study areas are selected to address three major basement granite areas in the temperate areas of South Africa (Figure 5-6). Smaller plutons, localised variations in lithologies and surrounding rock types are not shown. Sampling positions are indicated by means of towns, cities or regions (e.g. W-L and E-L denoting western and eastern regions of Limpopo Province).

The Johannesburg Dome underlies a vast area in South Africa's economic node, Gauteng. Urban development in this area emphasises the importance of understanding water behaviour, notably given the urban infrastructure that can easily be influenced by water. The Goudplaats-Hout River Gneiss is included as an equally important rural development node where groundwater is often the sole water supply. The Nelspruit Suite is included as undisturbed study areas within the KNP, as well as the densely developed Bushbuckridge area.

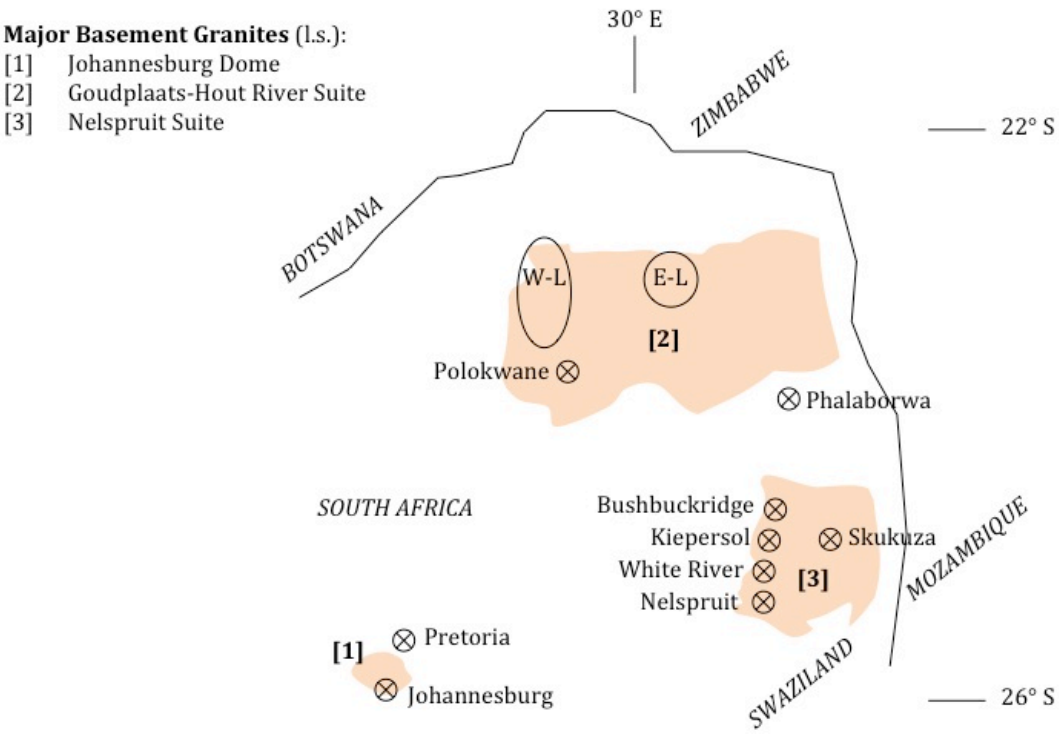


Figure 5-6. **Some major basement granites of Gauteng, Limpopo and Mpumalanga Provinces in South Africa, excluding younger intrusive plutons and smaller inliers (adapted from Johnson et al. 2009).**

For simplification, the study areas will be labelled as follows:

- Lanseria Gneiss – of the Johannesburg Dome, underlying Midrand and the northern suburbs of Johannesburg
- Goudplaats-Hout River Gneiss – subdivided into W-L (Western Limpopo in the vicinity of Vivo) and E-L (Eastern Limpopo in the vicinity of Giyani)
- Nelspruit Suite – in the area of the SGRS, KNP.

5.1.4.2. Investigation approach

This study is the culmination of approximately 10 years' work – some published in journals and others in research or consulting reports – focused solely around Basement granite terrains in the north-eastern portions of South-Africa. Historical and new data from a variety of geological, engineering geological, hydrogeological and vadose zone hydrological investigations have been collated to deduce common behaviour for different basement granites in different climatic-geomorphological settings in South Africa. The data do not always represent the exact same parameters; however, incorporation of different data sets may supply new knowledge to the understanding of these systems in different climatic and geological settings and may reduce bias resulting from the interpretation of small, localised datasets.

The case studies are presented in four sub-sections: (1) geology, (2) soil profile and indicator test results, (3) geomorphology and landforms, and (4) hydrostratigraphy, incorporating available literature, published data and selected additional data collected from a variety of recent studies.

5.1.4.3. Investigation techniques

Standard geotechnical, hydrogeological and vadose zone assessment techniques were applied for the respective study areas. The methods detailed below were employed to varying degrees in some or all of the instances and supply an informative bulk database. Given the elaborate methodology applied to all study areas, standard guidelines were used with minimal deviation to ensure replication of results. Short summaries of the methods are supplied and elaboration can be obtained from the cited references.

Soil profiles were recorded according to moisture, colour, consistency, soil structure, soil type (texture) and origin as per SANS 633 (2009a) with the original engineering geological investigations conducted according to SANS 634 (2009b) or the generic specification by the National Department of Housing (2002).

Foundation indicator laboratory analyses are conducted to determine the particle size distribution and the Atterberg limits of selected samples. The prior depicts the percentage abundance of different particle sizes on cumulative distribution plots, whereas the latter relates the engineering behaviour of soils to moisture contents. In many instances, the Unified Soil Classification System's (USCS's) soil class is also supplied.

XRF and XRD analyses were conducted to address the chemical and mineralogical compositions of different horizons for comparative purposes, notably with respect to composition of the granite bedrock, alterations due to weathering and changes in composition due to translocation and leaching processes.

Where available, photographs were taken of thin sections under petrographic or reflecting light microscopes. Limited additional samples were photographed and interpreted by means of scanning electron microprobe.

Limited double ring infiltration (e.g. Jenn et al. 2007; Reynolds and Elrick 1986) or auger hole percolation tests (SANS 1993) were conducted in some of the areas to infer saturated vertical hydraulic conductivities for site materials. In both instances, late-time steady state time-drawdown data are used to calculate an infiltration or percolation rate in distance per time. Under the assumption that the soils are saturated when steady state conditions are encountered, and under an assumed hydraulic gradient (i) of unity, the rate of infiltration or percolation (q) equals the hydraulic conductivity (K) according to $q = Ki$.

5.1.5. Results: geology

Available XRD and XRF data are shown in Dippenaar and Van Rooy (2014; Appendix A) and are discussed for each area.

5.1.5.1. Lanseria Gneiss

Five distinct varieties exist within the JDG, including the Lanseria Trondhjemite Gneiss (ca. 3 340), which forms the focus point of this study and makes up the northern half of the dome. The southern half of the dome comprises four smaller outcrops, is marginally younger in age and varies in composition between tonalitic gneiss, granodiorite and porphyritic granodiorite (Robb et al. 2006). Eight samples analysed for highly weathered to fresh granite from Midrand (Gauteng) show approximately 29-51% (37.3%) qtz, 27-40% (33.3%) plag, 5-39% (19.0%) kfs and the remainder accessory muscovite or kaolinite. This classifies the Lanseria Gneiss, on average, as granodiorite in composition.

5.1.5.2. Goudplaats-Hout River Gneiss (G-HRG)

The G-HRG Suite range in age from 3 600 to 3 200 Ma and comprise a wide range of granitoid gneisses. The gneisses are massive to layered, leucocratic to dark grey and vary in grain-size from fine-grained to pegmatoidal. The area of interest – around Polokwane – is underlain by homogenous, light grey, medium-grained biotite gneiss (syenogranitic in composition) with occasional distinct leucocratic bands resulting from local incipient anatexis. Younger granitic intrusions into but not forming part of the G-HRG include the Duivelskloof Leucogranite, Shamriri Granite, Turfloop Granite, Matok Granite, Moletsi Granite, Matlala Granite, Utrecht Granite and Mashashane Suite (Robb et al. 2006).

5.1.5.3. Nelspruit Suite

Granitoid rocks in the KNP include, from the most recent to the oldest (Robb et al. 2006; Barton et al. 1986) include:

- Phalaborwa Complex; syenite (ca. 2 050 Ma)
- Muscovite-bearing Pegmatites; granite (s. s.; ca. 2 200 Ma)
- Granodiorite Plutons; granodiorite, granite, trondhjemite (s. s.; 2 650 ± 50 Ma)
- Nelspruit Suite/ Nelspruit Granite-Migmatite Complex; granodiorite, granite, migmatite (s. s.; ca. 3 200 Ma)
- Tonalitic and Trondjemitic Gneisses; tonalite, trondhjemite (ca. 3 500 Ma).

The Stevenson Hamilton Southern Granites Research Supersite (SGRS, one of four identified as per Smit et al 2013) falls in the Nelspruit Granite-Migmatite Complex, which is also known as the Nelspruit Batholith or Nelspruit Suite. This forms part of the Mesoarchean intrusion emplaced ca. 3 200 – 2 800 Ma with at least one pluton (Cunning Moor Tonalite pluton, although not yet identified in the KNP) emplaced around 2 800 Ma. The Nelspruit Suite has distinctive textural varieties such as gneiss, porphyritic granite (s. s.) and two other smaller plutons with the coarse-grained, strongly porphyritic predominantly granodiorite or quartz monzonite being most prevalent. These granites are generally greyish to pinkish in colour and comprise quartz, plagioclase, microcline perthite and biotite where the K-feldspar forms phenocrysts. Particularly along the margins of the batholith one finds the gneiss to be migmatitic that rarely shows regional orientation (Barton et al. 1986; Robb et al. 2006).

XRD and XRF results from the SGRS are available in Dippenaar and Van Rooy (2014). The flatter areas of the batholith have much higher quartz content (granite s.s.) than the outcropping tors and inselbergs. Four such major outcrops were sampled and analysed and have localised varying composition of the greater batholith as follows:

- Matekenyane (inselberg) is composed of a coarse-grained massive leucogranite phase as well as darker bands of melanogneiss. In terms of composition, the leucogranite (SG15F) is granite (s.s.) comprising approximately a third each of microcline, plagioclase and quartz in its fresh state. The darker melanogneiss bands (SG15W) comprise muscovite and plagioclase with lesser kaolinite (potentially due to weathering of feldspar) and accessory microcline and hornblende. The outcrop forms a large flat inselberg ("whaleback") with a circular form and rising from the flat peneplains. Texturally it appears to be migmatitic.
- The outcrop at the Stevenson Hamilton memorial (SG03) is much more pronounced as a bornhardt inselberg with steep sides as the major landform with evidence of joint controlled tor formation around the major outcrops. Mineralogically it comprises quartz, plagioclase and microcline with accessory biotite and is classified as granite (s. s.).
- The outcrop in the southeast of the study area (SG73) also resembles a bornhardt with joint controlled tor formation around the major inselberg. The granite here is distinctly foliated into gneiss with a tonalitic to trondjemitic composition, the latter referring to the absence of mafic minerals in the general composition. Plagioclase followed by quartz is the major constituent with accessory biotite and microcline.
- The tor along the western boundary of the study area comprises a number of suboutcrops. This tor possibly contains chemically and texturally distinct granite. Also distinctly foliated, it is composed of (SG80) quartz and plagioclase with lesser microcline and accessory biotite and diopside and therefore has a generally granodioritic composition.
- The batholith underlying the flatter portions of the site is composed roughly of more than 50% quartz, 20 – 25% microcline, 15 – 20% plagioclase and possible accessory muscovite. The Nelspruit batholith is therefore granitic (s. s.) in composition.

5.1.6. Results: soil profile and indicator test results

Available indicator test results are shown in Dippenaar and Van Rooy (2014) and are discussed below.

5.1.6.1. Lanseria Gneiss

Typical profile successions for the Lanseria Gneiss are as follows (summarised in Table 5-1):

- Silty sandy colluvium (topsoil) from surface, often pinholed and well-leached if not vegetated; this often grades into a thicker silty sandy colluvium, often yellowish grey to pale brown, and which typically exhibits collapsible soil fabric (typically absent to < 1.00 m thick)

- Various amounts of gravel, pebbles and cobbles, typically comprising quartz and weathered granite, in a matrix of silty sand, forming a characteristic pebble marker (occasionally absent or poorly defined to < 0.50 m thick)
- Reddish brown to yellowish brown, slightly clayey silty sandy residual granite, structure more intact although occasionally pinholed to voided, and characteristically mottled to ferruginized (typically < 0.50 m thick)
- Ferricrete, if present, forming typically within the pebble marker or residual granite with the origin of the soil being unclear when encountering hardpan stages of formation (absent to < 0.40 m; thickness often undetermined due to impenetrability by means of backhoe)
- Pinkish to yellowish white or white, often streaked, stained or mottled black, completely weathered granite with gravelly silty sandy texture and often with distinct foliation and/ or remnants of Fe-stained joint surfaces (typically < 1.00 m grading gradually into highly weathered bedrock)
- Fresh jointed bedrock.

Table 5-1. Thicknesses of typical horizons per profile type for the JDG per landform (from Van Rooy and Dippenaar 2008) and for an ephemeral hillslope wetland.

Type	Population *n*	Colluvium	Pebble Marker	Residual Granite	Completely Weathered	Granite Bedrock
Hillcrest	8	0.59	0.15	—	—	—
Upper slope	41	0.42	0.24	—	—	—
Midslope	15	0.33	0.23	—	—	—
Lower slope	40	0.36	0.23	—	—	—
Floodplain	2	—	—	—	—	—
Wetland	6 - 13	0.56	(0.71)	1	>1.15	

44 residual granite samples were addressed in terms of its indicator properties (Dippenaar et al. 2006). An additional 107 transported and ferruginized soil profiles from historical engineering geological investigations on the Johannesburg Dome were evaluated in terms of the landform on which the profiles were described, as well as the typical index properties (Van Rooy and Dippenaar 2008, shown in Dippenaar and Van Rooy 2014).

5.1.6.2. Goudplaats-Hout River Gneiss (G-HRG)

Soil profiles in the G-HRG are more variable given the aerial extent of the gneiss, as well as distinct local variations, climatic influences and intrusions. No laboratory testing formed part of the study.

5.1.6.3. Nelspruit Suite

Five typical soil profiles (excluding alluvium) were identified and are labelled according to the characterising surface material. All data are contained in Table 5-2 and in Dippenaar and Van

Rooy (2014) and are discussed below. The number of profiles described per type is supplied in brackets (n) and the materials are labelled according to the characteristic shallow materials.

Type 1: brown sandy colluvium (n = 15). All horizons are sandy with the pebble marker and residual granite tending more towards gravel-sand. Clay contents are very low for all horizons with a harmonic mean of 4.9%. Plasticity indices calculated are very low for all horizons, ranging between zero (not plastic) to 6%. Colluvium is classified as SM (silty sand) according to the Unified Soil Classification System (USCS), followed by SW-SM (well-graded sand/ silty sand) for the pebble marker and mostly SM for residuum and weathered granite. Typical material succession is as follows:

- Colluvium – slightly moist, light to dark brown (speckled orange)/ (light) orange or reddish brown/ occasionally greyish brown, (pinholed; with krotovinas), gravelly or clayey silty SAND
- Pebble Marker – slightly moist, orange brown, pinholed with open root channels, gravelly silty SAND with scattered fine to medium quartz gravel
- Residual Granite (occasionally reworked) – slightly moist, (yellowish) brown, (gravelly) silty SAND with abundant, fine to medium, subangular quartz and feldspar gravel
- Completely Weathered Granite – slightly moist, (yellow or light) brown/ light whitish grey, silty sandy GRAVEL with angular, fine to medium feldspar and quartz gravel
- Highly Weathered Granite – slightly moist, light brown speckled white and orange, silty SAND or sandy SILT with quartz and feldspar gravel.

Type 2: grey sandy colluvium (n = 11). The exception here is SG12b where colluvium is 1.15 m in thickness, changing colour from grey to greenish grey, and underlain by calcrete developed in leached residual granite. No laboratory analyses are available for this material. The typical material succession is as follows:

- Colluvium – slightly moist, (light or brownish) grey, (voided; open; pinholed), silty gravelly SAND or (clayey or gravelly) silty SAND; occasionally with mixed gravel
- Pebble Marker – slightly moist, light grey, silty SAND with abundant fine to medium, subangular quartz and feldspar gravel or granite gravel
- Residual Granite (occasionally reworked) – slightly moist, (yellowish) brown, (gravelly) silty SAND with abundant, fine to medium, subangular quartz and feldspar gravel
- Completely Weathered Granite – slightly moist, light brown/ white speckled grey and orange, silty sandy GRAVEL (gravel occasionally ferruginized)
- Highly Weathered Granite – slightly moist, light brown speckled white and orange, silty SAND or sandy SILT with quartz and feldspar gravel.

Table 5-2. **Thicknesses of typical horizons per profile type for the SGRS near Skukuza.**

Type	Profile	Colluvium	Pebble Marker	Residual Granite	Completely Weathered	Granite Bedrock
1 Brown Sandy Colluvium	SG08	0.2	X	0.45	X	> 0.60
	SG12	0.69	X	0.69	> 0.79	—
	SG13	> 0.15	—	—	—	—
	SG20	> 0.40	—	—	—	—
	SG24	0.13	0.2	X	X	> 0.20
	SG25	> 0.14	—	—	—	—
	SG34	> 0.35	—	—	—	—
	SG43	0.42	> 0.52	—	—	—
	SG44	0.4	X	0.7	> 0.70	—
	SG45	0.4	0.46	X	X	> 0.50
	SG46	0.2	X	X	> 0.51	—
	SG70	0.05	X	X	1.3	> 1.30
	SG74	0.05	> 0.12	—	—	—
	SG81	0.32	0.42	> 0.51	—	—
	SG86	0.45	0.95	> 1.15	—	—
	SG87	0.31	0.65	1.06	X	> 1.15
	SG88	X	X	0.48	1.1	> 1.52
2 Grey Sandy Colluvium	SG09	0.09	0.36	X	> 0.47	—
	SG10	0.05	> 0.10	—	—	—
	SG12b	1.15	X	> 1.30	—	—
	SG16	0.28	0.4	0.4	> 0.47	—
	SG17	0.15	> 0.30	—	—	—
	SG25	> 0.14	—	—	—	—
	SG30	0.05	X	X	X	> 1.50
	SG31	> 0.05	—	—	—	—
	SG69	0.31	0.36	X	> 0.46	—
	SG74	0.05	> 0.12	—	—	—
	SG83	0.3	X	X	0.5	> 0.65
3 Grey Clayey Colluvium	SG32	> 0.05	—	—	—	—
	SG33	0.1	X	> 0.20	—	—
	SG56	> 0.31	—	—	—	—
	SG59	0.43	> 0.50	—	—	—
	SG60	0.12	X	> 0.90	—	—
	SG82	0.94	X	> 1.43	—	—
	SG89	X	0.17	X	X	> 0.50
4 Ferruginized Profiles	SG05	0.2	X	0.51 **	0.67	> 0.96
	SG07	0.08	> 0.21 **	—	—	—
	SG11	0.3	0.50 **	> 0.60 **	—	—
	SG23	0.52	0.70 ?	—	—	—
	SG28	0.43 *	> 0.65	—	—	—
5 Duplex Soils	SG01	0.15	0.5	0.7	> 0.90	—
	SG02	> 0.05	—	—	—	—
	SG04	> 0.45	—	—	—	—
	SG47	> 0.32	—	—	—	—
	SG48	> 0.05	—	—	—	—
	SG49	> 0.39	—	—	—	—
	SG50	> 0.05	—	—	—	—
	SG51	> 0.21	—	—	—	—
	SG55	> 0.05	—	—	—	—
	SG61, SG64, SG72, SG77, SG78			Surface description only		

—	Hole terminated prior to possible occurrence of horizon
X	Horizon distinctly absent
>	Final depth represents end of profile due to hand auger refusal or other reasons
?	Underlying material contradicting anticipated sequence
**	Extensive ferruginization;
*	slight ferruginization

Type 3: grey clayey colluvium (n = 7). The exception here is SG60 where colluvium grades into calcified residual granite. With the obvious exception of the more gravelly pebble marker, surface soils are generally clay-silt SAND becoming gravelly SAND with depth. Clays easily reach 20% by mass and up to 40% in surface horizons when considering all cohesive particle sizes (clay and silt) together. Soils generally exhibit very high plasticity with plasticity indices ranging between 15% (pebble marker) and 25% (colluvium). All soils are classified as SC (clayey sand) according to USCS. The typical material succession is as follows:

- Colluvium – dry to slightly moist, dark (brownish) grey (speckled orange), (pinholed), (very stiff), silty sandy CLAY/ clayey SAND
- Pebble Marker – slightly moist, black, clayey gravelly SAND with abundant quartz cobbles and pebbles
- Residual Granite – moist, dark grey speckled orange, clayey gravelly SAND
- Highly Weathered Granite – slightly moist, (dark or orange) brown, silty gravelly SAND becoming silty to sandy GRAVEL

Type 4: ferruginized soils (n = 5). These profiles showed ferruginization, notably of the pebble marker and residual granite. No laboratory analyses are available for this material. Profile SG23 does not completely comply with the typical succession as a sand lens in which ferruginization is evident underlies the pebble marker. The typical material succession is as follows:

- Colluvium – dry to moist, pale or light brown (mottled orange)/ light grey, (loose), (voided and pinholed), (gravelly) silty SAND
- Pebble Marker – dry, light brown, silty SAND with abundant fine to medium, subangular quartz and feldspar gravel; matrix-supported (with abundant Fe and Mn nodules)
- Residual Granite – moist, yellowish white speckled orange, loose, open, silty gravelly SAND with scattered Fe and Mn nodules and fine quartz gravel; ferruginized
- Completely Weathered Granite – wet, brown speckled orange blotched black, loose, clayey silty gravelly SAND
- Highly Weathered Granite – wet, light olive brown mottled orange, loose, silty gravelly SAND with Fe and Mn nodules.

Type 5: duplex soils (n = 10). The sodic duplex soils are generally characterised by dark grey to black surface soils of distinct clayey texture. The deeper in-situ (not transported) soils resemble typical granitic soils, being white to reddish brown in colour and mainly of sandy texture. Due to the dry state of the clayey soils during investigation, excavation was difficult in stiff to very stiff clays and exposed profiles are, therefore, generally shallow. Only one profile was sampled to represent duplex profiles (SG01). Clay content varies between 8% and 26% with recorded plasticity indices between moderate 11% (colluvium) and very high 22% (pebble marker). Regardless, sand still makes up the bulk of all horizons, accounting for more than 50% by mass of all samples analysed. All soils are classified as SC according to the USCS. 15 such profiles were noted of which 10 were profiled as follows:

- Topsoil – dry to slightly moist, light grey, silty gravelly SAND with scattered fine gravel, leached topsoil

- Colluvium – slightly moist pale grey speckled orange/ dark (brownish) grey, (very stiff), (shattered; slickensided; voided), (silty) clayey SAND
- Pebble Marker – slightly moist, dark grey becoming black, (shattered; desiccated; voided), clayey gravelly SAND with gravel
- Residual Granite – slightly moist, grey, silty gravelly SAND; reworked
- Completely Weathered Granite – slightly moist, light brown, silty gravelly SAND with scattered gravel

Type 6: alluvium. Alluvial profiles vary slightly based on stream order. For this sake, distinction is made between Type 6-1 first order, 6-2 second order and 6-3 third order alluvium. First order streams generally form through seepage from sodic sites (profile 5: duplex soils) and are characterised by slightly moist, dark grey speckled orange becoming orange brown speckled white, silty gravelly SAND (e.g. SG84). Second order streams are characterised by bedrock at shallow depth, commonly outcropping in stream channels. Side banks generally comprise slightly moist becoming moist, grey to white-orange, medium dense, often desiccated at surface, (silty) clayey SAND. Granite or amphibolite underlies these materials at shallow depths (e.g. SG57, SG57B, SG58). Third order valley floors are wide with unconsolidated sandy alluvium described as slightly moist, light brown, very loose becoming medium dense, slightly pinholed, slightly gravelly slightly silty SAND (e.g. SG06, SG71, SG79). The confluence of second and third order streams is influenced by the materials from second order streams which are commonly more clayey than in the third order streams (e.g. SG58). Surface materials here comprise slightly moist, dark grey becoming orange brown, medium dense to dense, open, clayey silty SAND underlain by more gravelly sandy materials at depth. No laboratory analyses are available for this material.

Additional data from outside of KNP and covering the Nelspruit Suite in the Kiepersol, White River and Bushbuckridge areas are summarised by Van Rooy and Dippenaar (2008) and Dippenaar et al. (2006). Interestingly, potentially due to the proximity to the escarpment and somewhat higher annual precipitation, the soils in these areas are more clayey and more plastic than those encountered in the KNP.

5.1.7. Results: geomorphology and landforms

Local variations exist, but typical material successions for basement granites in temperate regions north-eastern South Africa (broadly labelled, within context, as humid and arid) are shown in Figure 3-10. The more humid areas (such as JDG and E-L portion of G-HRG) exhibit deeper weathering profiles associated with distinct kaolinitization on the upper slopes (likely due to chemical decomposition of feldspars), ferruginization on midslopes to lower slopes and often the formation of duplex soils on footslopes. More arid regions, however, lack the deep soil profiles and ferruginization is more common on or near surface with typical barren outcrops forming hillcrests.

5.1.7.1. Lanseria Gneiss

Figure 5-7 shows a photographic exposé of an excavated hillslope wetland underlain by Lanseria Gneiss.

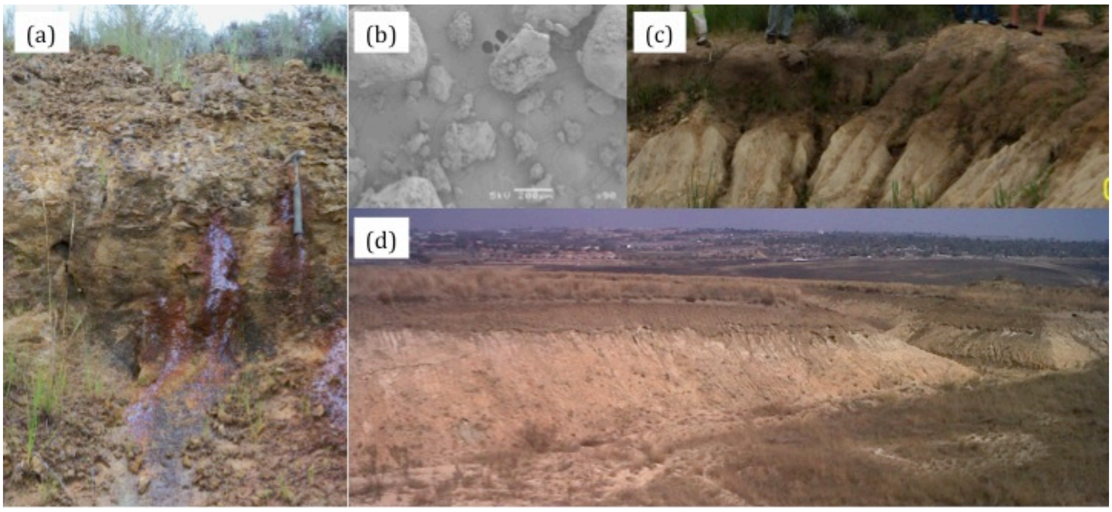


Figure 5-7. (a) Seepage from ferricrete on the midslope; (b) kaolinite covering quartz (1 500 μm across); (c) dispersive/ erodible behaviour; and (d) view of excavation in Lanseria Gneiss.

The geomorphological development of the Midrand area (between Johannesburg and Pretoria) resulted in three distinct soil profiles (McKnight 1999):

- Above 1 600 mamsl, transported and residual soils are typically thick, collapsible, very kaolinitic and with deep bedrock.
- Between 1 500 and 1 600 mamsl, corestones and variable weathering troughs are evident on the exposed land surface.
- Remnants of the ferricrete cap of the old African land surface are exposed in certain areas of the East Rand and differential weathering is present adjacent to intruded dykes.

The Lanseria Gneiss forms typical weathering profiles with variable bedrock topography and characteristic positions of kaolinitization (kaolinite-enrichment) and ferruginization (iron-enrichment) associated with a truncated weathering profile on the upper slope and perched water tables forming on midslopes. Intrusive dykes, melanogneiss bands or faults typically occur at drainage features and near hillcrests, forming the characteristic truncated weathering in the latter. Given the low permeability of granite bedrock, perched water tables typically form overlying bedrock, resulting in the translocation of kaolinite and the formation of ferricrete. Wetland-conditions are common overlying the ferruginized areas, often with the honeycomb ferricrete serving as the horizon in which interflow occurs (Figure 5-7a). Given the plagic composition of the trondhjemite, the soils are somewhat dispersive in places.

5.1.7.2. Goudplaats-Hout River Gneiss (G-HRG)

Figure 5-8 shows a photographic exposé of the E-L and W-L study areas underlain by G-HRG.

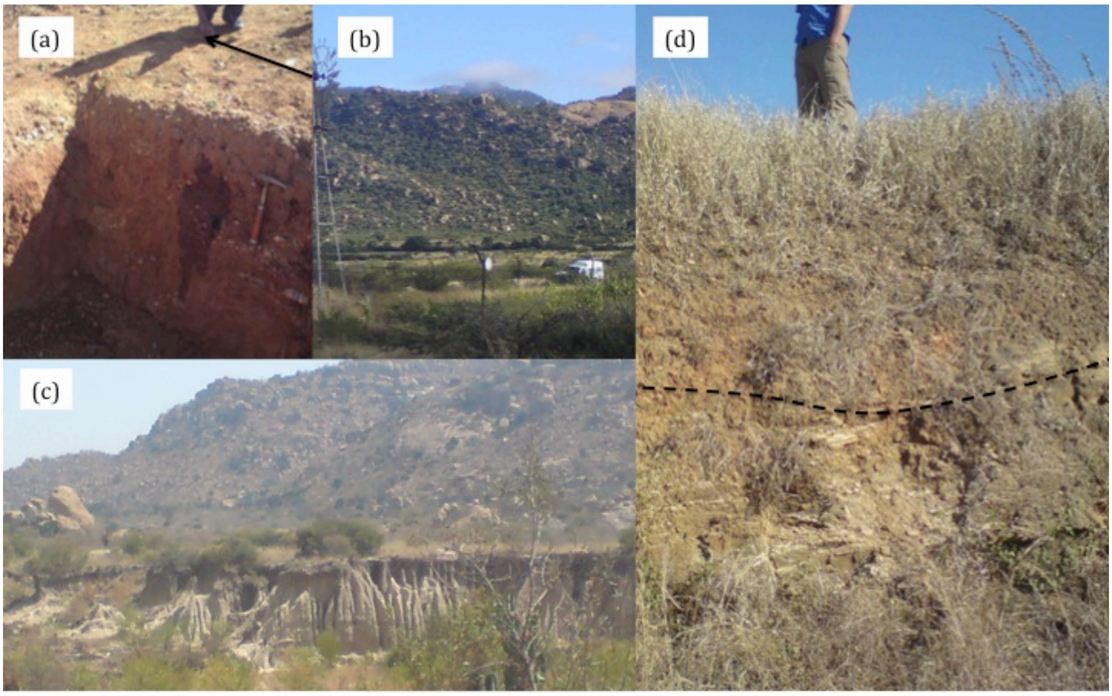


Figure 5-8. (a) Lateral seepage due to preferential flow from a percolation test conducted 400 mm below surface at the arrow in E-L; (b) rocky outcrop in W-L; (c) dispersive/ erodible behaviour in W-L; and (d) soil underlain by weathered bedrock (E-L).

Preferential flow is commonly associated with the well-leached upper soil horizons and is often exacerbated by insect or animal burrows, plant roots and historical land use practices such as encountered in ploughed land. This can also be ascribed to the high feldspar content resulting in kaolinitic clays forming and materials being subject to erosion or dispersive behaviour.

In the more humid areas (e.g. study area E-L), the profiles resemble those in Figure 3-10, although ferruginization may be less evident and, although soils show mottling and discolouration, hardpan ferricrete is less common. The more arid regions, however, exhibit near-outcrop conditions on the crests and slopes with ferruginization near surface on the midslopes.

5.1.7.3. Nelspruit Suite

Figure 5-9 shows a photographic exposé of the Nelspruit Suite in the Stevenson-Hamilton Southern Granites Research Supersite (SGRS), Kruger National Park (KNP).

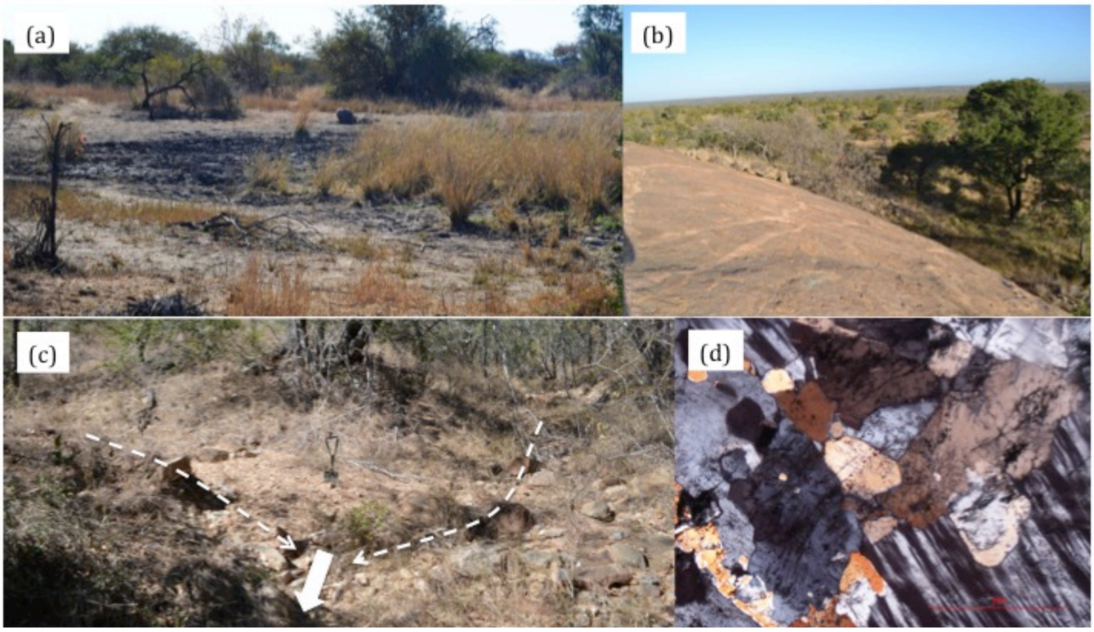


Figure 5-9. **(a) Typical duplex soils on footslopes; (b) view from Matekenyane inselberg; (c) confluence of two first order channels to form a second order; (d) polarised-light thin section of fresh granite (3 mm across) of the Nelspruit Suite in the SGRS, KNP.**

The area now outlined as the SGRS falls within the Renosterkoppies Land Type of the Skukuza Land System and has hillslopes with or without footslopes, depending on the ability or inability of the drainage features to incise their drainage channels. Large seasonal (third and fourth order) and small seasonal (first and second order) drainage channels are present with the latter lacking a prominent footslope. The third and fourth order drainage features subsequently influence relief more with the site sloping towards these features. Leaching appears to have a greater effect on midslopes than on hillcrests, creating so-called duplex sites at the transition area from the hillcrest to the midslope or on the midslope in the event of first order drainage features (Venter 1986).

The granite landscape is characterised by gently to moderating undulating topography with scattered inselbergs, often in clusters, forming due to locally higher resistance against weathering (Venter and Bristow 1986).

A summary of more than 80 data points described for the SGRS provide three typical profile successions towards various drainage channels (Figure 5-10). The numbers indicate typical engineering geological material descriptions as detailed in §5.1.6.3.

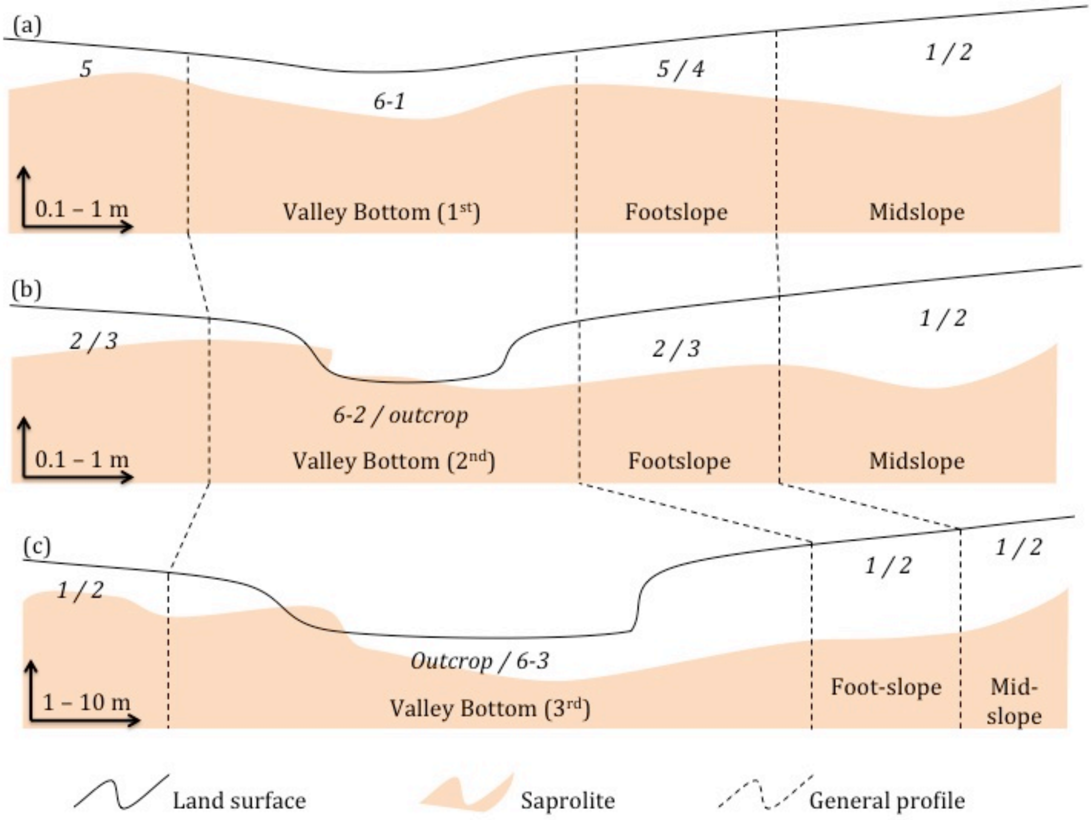


Figure 5-10. **Typical material successions and landforms approaching (a) first order, (b) second order and (c) third order drainage channels in the SGRS, KNP.**

5.1.8. Results: hydrostratigraphy

5.1.8.1. Lanseria Gneiss

Groundwater is not commonly used for large-scale abstraction in the Gauteng area. Johannesburg is mainly supplied by the Vaal River and Rand Water Board, with Pretoria being supplied extensively by the Rand Water Board and springs in the Chuniespoort Group dolomite to the north of the Lanseria Gneiss (DWAF 2002; Dippenaar 2013). The Lanseria Gneiss, therefore, is mostly used as a rural supply or for local irrigation.

Groundwater is generally deeper than 10 m and a thick soil and fractured intermediate zone exists. Limited (14) field percolation tests yield vertical saturated hydraulic conductivities ranging between 2.60 x 10^{-4} m/s and 1.5 x 10^{-5} m/s.

5.1.8.2. Goudplaats-Hout River Gneiss (G-HRG)

A study characterising a large volume light non-aqueous phase liquid (LNAPL) spill found gneisses in the central and western portions of the G-HRG Suite to have preferential flow directions associated with the dip direction of the gneissosity, as well as to be influenced by significant geological structures such as faults and intrusions such as diabase dykes (Dippenaar et al. 2005).

Further work in other areas of the same lithology evaluated the most important influences on anticipated borehole yield and found that certain structural and intrusive features distinctly promote or reduce transmissivity. Based on location (eastern and western parts of the Limpopo Province), present-day climate (arid versus humid) and directions of major structural features, more than 1 000 constant discharge and more than 1 000 step-drawdown tests were analysed and superimposed on climatic, geomorphological and tectonic settings. The findings can be summarised as shown in Table 3 where "high" represents $T > 100$ m^2/d, "moderate" $T > 10$ m^2/d and "low" below (Dippenaar et al. 2009).

The vadose zone also typically comprises a soil zone and a fractured intermediate zone. Field percolation and double ring infiltration tests yield vertical saturated conductivities of 1.4 x 10^{-3} m/s to 5.00 x 10^{-5} m/s (Dippenaar et al. 2010).

5.1.8.3. Nelspruit Suite

The groundwater type associated with the Nelspruit Suite is predominantly Na-HCO$_3$ and was discussed for the entire KNP by Leyland and Witthüser (2008) based on data from the National Groundwater Archive (NGA) maintained by the Department of Water Affairs (DWA). The authors ascribe this as the assumed long-term equilibrium between groundwater chemistry and underlying acidic igneous lithology.

No field percolation or infiltration tests were conducted for the Nelspruit Suite and no groundwater data are included in this review.

5.1.9. Findings

5.1.9.1. Weathering profiles

Basement granites in South Africa vary based on mineralogy, igneous or metamorphic textures and younger structural influences. This, together with climatic variations, result in distinct geomorphology and landforms with characteristic soil successions both vertically and between crests and drainage channels. Variable bedrock topography is associated with most such granitic terrains in temperate to humid areas in South Africa and ferricrete or duplex soils are commonly found on midslopes to footslopes.

Ferruginization is common, notably in the Lanseria Gneiss (JDG) and to a lesser extent in the Goudplaats-Hout River Gneiss Suite (G-HRG). Perched water tables form overlying bedrock and result in ferricrete which serve as a zone of interflow when nodular to honeycomb, and which becomes an aquitard when in the hardpan stages of formation. Ferricrete occurs to a lesser extent in the Nelspruit Suite and the translocation of clay minerals is more common, forming so-called duplex soils. These duplex soils also sometimes exist on the footslopes in the JDG.

Most of these granite profiles are characterised by some degree of translocation of clay minerals, mostly comprising kaolinite. This often results in collapsible surface horizons, which may also be dispersive when the granite contains significant amounts of albite.

Bedrock depths vary, notably based on climate (which influences the depth of chemical weathering) and landform.

5.1.9.2. Engineering geology

Bulk of the residual and weathered granites depicts – as anticipated – low plasticity and low potential expansiveness. Kaolinite, although often present in abundance, remain inactive. Active clays may, however, be present in the duplex soils where these transported materials often form zones of low water infiltration and high water retention.

Apart from collapsible soil fabric and possible dispersive behaviour, the main identified geotechnical constraints are shallow bedrock, granite boulders or hardpan ferricrete which affect excavatability. Additionally, seepage lines, hillslope wetlands and seepage problems have to be anticipated given the low permeability of bedrock and the altered hydrology of the profile resulting from leaching and translocation.

5.1.9.3. Surface and phreatic hydrology

Groundwater occurrence is mainly governed by significant structures such as shear zones and faults, as well as contacts with younger granitic plutons. The influence of the orientations of these structures determines whether they are open for the transmission of water and also commonly govern the directions of major drainage features.

The South African basement granites discussed in this paper comply with the general definition of a catena and more often than not form pedocretes or duplex soils. This results in yet further interflow and commonly this water forms seepage lines or ephemeral wetlands on the midslopes and lower slopes. These are typically dry, but contribute to the flow in higher order streams. These wetlands, however, do not always fall within the classical definition of a wetland, requiring areas that are periodically or permanently saturated and sustains growth of plants requiring waterlogged conditions (e.g. NWA 1998).

5.1.9.4. Vadose zone hydrology

In both the G-HRG and JDG, saturated vertical hydraulic conductivities of surface materials are typically between 1 x 10^{-4} and 1 x 10^{-5} m/s with local anomalous values due to preferential flow, fractured rock, or other influences.

Interflow is almost always of notable importance on the granite terrains. Low permeability bedrock, coupled with ferruginization and clay translocation result in water in the unsaturated zone being forced downslope, often to daylight in the form of seepage lines or ephemeral hillslope wetlands. The connection with the regional groundwater table is, therefore, not always direct and recharge may only occur in very specific recharge zones such as drainage channels.

In assessing vadose zone conditions, the need for a multi-disciplinary effort is clear. In understanding the basics of the science, at least soil science, geology and proper understanding of the hydrological cycle and all associated disciplines are required as per the proposed triangle of vadose zone hydrology. To compile, understand and interpret the vadose zone model for any application, more detail is required on the soil zone, intermediate zone and the capillary fringe, as well as any associated processes of infiltration, percolation, recharge, interflow, throughflow or evapotranspiration from the subsurface (Figure 3-11).

5.2. Conceptual Geological Models, its Importance in interpreting Vadose Zone Hydrology and the Implications of being excluded

5.2.1. Conceptual models

Perspectives regarding the vertical succession of earth materials and the classification of soils vary between disciplines. Albeit based on different intentions, an all-encompassing multi-disciplinary approach may significantly improve information gained from soil profile descriptions (e.g. Dippenaar 2012; §2.2).

Additional to the vertical variation discussed previously, the spatial variation and subsurface hydrology can best be simplified by the catena concept, which has been well-documented (e.g. Schaetzl and Anderson 2005).

The importance of conceptual models is also well documented, e.g.:

- The importance thereof in groundwater models (Izady et al. 2013)
- The lack of proper understanding in conceptual hydrological models on land (Lahoz and de Lannoy 2013)
- The special circumstances in karst settings (Bakalowicz 2005)
- Incorporation of multidisciplinary data and different scales of observation (Dewandel et al. 2005)
- Considerations of different potential conceptual models in assessment of aquifer vulnerability (Seifert et al. 2007)
- Inclusion of subsurface flow in shallow saprolite and deep bedrock (Banks et al. 2009)
- Challenges and trends in geological visualisation and modelling (Turner 2006)
- The inclusion of historical data to potentially replace the conceptual model (Royse et al. 2009)
- The influence of alternative conceptual models on predicting beyond calibration base of the flow model (Troldborg et al. 2007)
- The concept of hydrostratigraphy contributing to proper conceptual modelling (Allen et al. 2007; Angelone et al. 2009; Heinz and Aigner 2003)

- The incorporation of geology, engineering geology, hydrogeology and geomorphology in advancing conceptual model quality (e.g. Dippenaar and Van Rooy 2014; §5.1).
- Urban development induces changes to the vadose zone, which is readily overlooked in compilation of a conceptual model prior to development. Made ground is of different grading and compaction than in-situ materials, saturation is increased by irrigation or leaking pipelines, and surfaces are sealed as land is being developed. These are just come factors contributing to the already complex vadose zone.
- The importance of proper vadose zone conceptualization, notably in urban settings, is explained at the hand of five case studies underlain by Lanseria tonalite gneiss of the Johannesburg Dome. Granites in South Africa are – given its age – highly variable due to an intricate tectonic and geomorphological history. These case studies illustrate the importance of conceptual vadose zone models, as well as the implications of exclusion.

5.2.2. Case studies

For the purposes of explanation, geology and climate are kept as constant parameters and all case studies presented as situated on tonalite gneiss (Lanseria Gneiss, Johannesburg) within the Midrand and Johannesburg areas of South Africa.

5.2.2.1. Pedogenesis and ephemeral hillslope wetlands

Randjesfontein, situated on tonalite gneiss of the Archaean basement complex in Midrand (RSA), was investigated during two subsequent stages. During the first, vegetation was absent due to veldt fire in the dry winter months. During the second, the geotechnical investigation noted marshy areas at the site and deduced that the ferricrete in the profiles represents a periodically perched water table system. These markers were overlooked and, using only the absence of wetland vegetation indicators as proof, the site was excavated for construction. With changing seasons, the wetland wetted up again and water influx into the excavation resulted in cessation of construction as water collected at the excavation floor and wetland conditions regenerated on barren bedrock.

Of interest in the conceptual understanding of this study area are the following (Figure 5-11):

- Ferricrete appears much more heterogeneously and anisotropically as anticipated. Given the 150 x 50 x 10 m excavation, the varying thickness, as well as the localized absence, of ferricrete can clearly be seen. Important for the conceptual model is to properly infer the vertical and spatial extent of the pedocretes.
- In the instance of this study site, the ferricrete changed its role in the subsurface hydrology. With initial perching probably on low permeability bedrock, the process of pedogenesis progressively resulted in varying stages of ferruginization in residuum and the pebble marker. In the stages before nodular/glaebular and in the hardpan stage, the ferricrete is of low permeability and porosity with water perched

above. However, in the honeycomb phase, the porosity is low due to the cementation, but the calculated porosity of 0.15 as opposed to the overlying 0.21 exists as large connected pore spaces where parent soil has been washed out. The perching, therefore, occurs localized within the ferricrete, and not above.

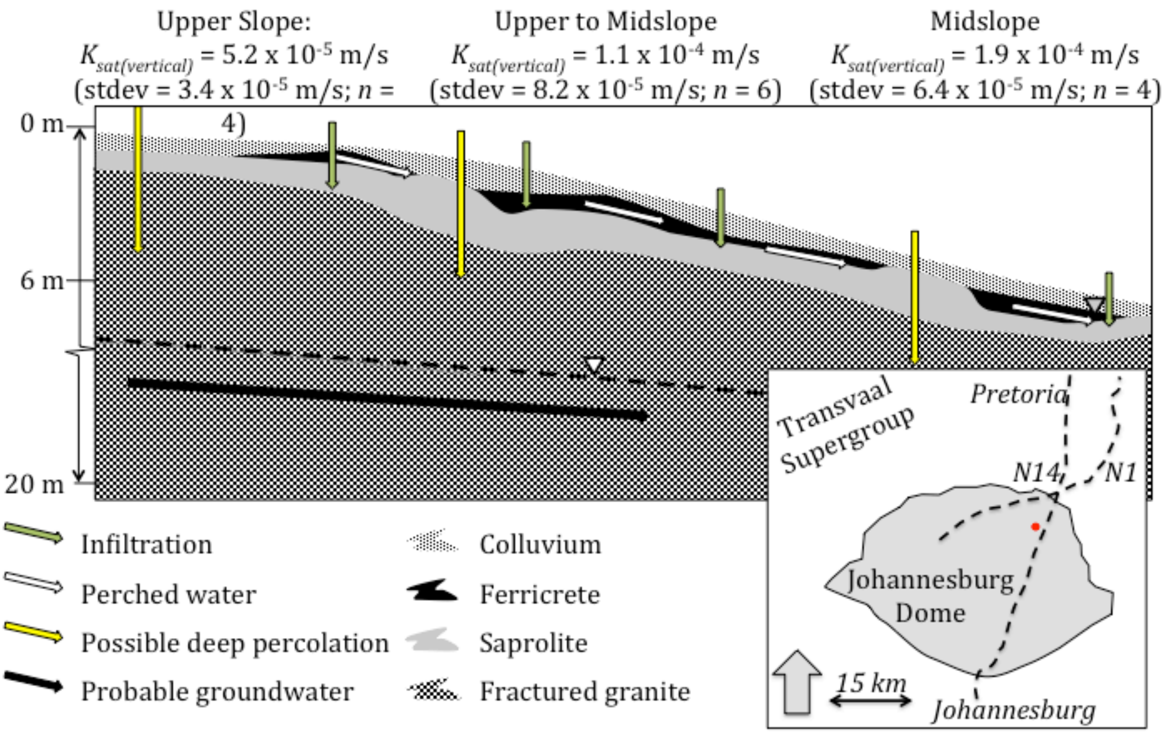


Figure 5-11. Shallow interflow through glaebular to honeycomb ferricrete resulting in the formation of an ephemeral hillslope wetland on Archaean tonalite gneiss (Midrand, RSA).

5.2.2.2. *Made ground and variably compacted fill*

Urban hydrogeology has an increased variable: that of anthropogenic materials. These include a wide variety of materials of variable compaction and grading (e.g. uncompacted imported fill), as well as variable composition (e.g. contaminated land). In two separate studies in the suburbs of Alexandra and Linbro Park respectively, the following was found:

- Cut-and-fill operations have to be included as significant impacts on shallow interflow. This is notable in all three studies and the excavation through illuviation zones result in water being subjected to other lateral pathways and not necessarily deeper percolation. Compaction of imported materials may have higher porosity and/ or permeability, fill for drainage systems may interrupt flow paths in unsaturated materials and induce imbibition rather than drainage, and retaining wall systems may become unstable and exhibit seepage through faces.
- Non-uniform building rubble and fill material may influence downslope properties and may create periodical waterlogged conditions in poorly compacted fill materials.

This is notable in the central urban portions where old buildings are demolished for the construction of high rises, requiring deeper foundations and basements.

5.2.2.3. Increased infiltration and interflow

Increased water addition can be explained at a case study in Fourways (residential golf course). Significant additional volumes of water was released, resulting in the following:

- The natural systems were in hydrological equilibrium where water infiltrated and sporadic small wetlands occurred in Fourways. These areas were developed as the golf course and the residential areas on the perimeters and downslope.
- Increased golf course irrigation resulted in the formation of a perched water system where the high saturation of surface soils induced interflow on the bedrock interface.
- The main damage is with water imbibing into porous plaster and mortar, resulting in extensive damage to buildings.

5.2.3. Discussion

The geological model should include the vadose zone and all variability, whether natural or induced, in material properties and moisture contents. Urban development notably exacerbates the uncertainty in the vadose zone due to, for instance, surface sealing, disruption of natural structure and compaction, inducing increased flow, and diverting flow paths.

The variation in properties between the soil zone and intermediate vadose zone, and between the soils, saprolite and bedrock should be understood properly to ensure optimal construction. Damage to infrastructure on-site and off-site, drainage of wetlands, generation of waterlogged conditions, and weakening of retaining structures are just some of the significant results of proper understanding of the vadose zone.

The importance of the vadose zone exceeds vulnerability assessments and optimizing irrigation practices. It should be seen as a fundamental component of all hydrological and geotechnical assessments and should be included as a detailed component of any conceptual model.

5.3. Towards Hydrological and Geochemical Understanding of an Ephemeral Palustrine Perched Water Table "Wetland" (Lanseria Gneiss, Midrand, South Africa)

As most other arid to semi-arid countries, South Africa is characterised by low rainfall, limited surface drainage features and fairly deep groundwater tables. Subsequently, formal wetlands complying with the identifiers of soil wetness, soil form, land form and vegetation, together with the required shallow water table, may be limited due to the depth of the groundwater and the absence of distinct drainage features. A number of "wetlands" do, however, form following prolonged and intense rainfall events and are possibly associated with seep faces, catenas and temporary perched water tables.

The main objectives of this section are to address the driving hydrological processes in the formation of these systems through the application of field and laboratory data, as well as to highlight the need for refined methodology to identify such temporary "wetland" systems that may very easily be overlooked during single investigations based on the landform, soil form, soil wetness and vegetation alone. Finally, recommendations are made regarding the possible inclusion of these systems as a special type of wetland, regardless of the absence of a shallow groundwater table, to ensure protection of these sensitive systems that are playing a vital part in biodiversity and water quality. Whether they are termed temporary hillslope wetlands, perched water table wetlands, wet grasslands, a type of isolated or ephemeral wetlands or paluslopes are not clearly defined in the wetland terminology, but the need for protection requires their formalised inclusion in the literature to ensure early identification.

5.3.1. Background

Wetlands have been discussed extensively in §4.1 However, a number of authors have recently considered inter-disciplinary influences on the occurrence of wetlands and, notably, referring to inland, isolated and/ or ephemeral wetlands. Siegel (1988) evaluates the influence of disturbance on a number of bogs, fens and mires, with precipitation being the main water contribution to these systems with possible influence of groundwater in fens. Although generally occurring in flatter areas, the concluding remarks accentuate the lack of hydrological understanding of the functioning of these wetlands. Richardson (2003) considered the classification of pocosins (swamps on hills), concluding that they may not be completely isolated, but it fact contribute to adjacent ecosystems. Zedler (2003) focussed specifically around vernal pools, which form in basins or flatter areas, but are also considered isolated from the regional hydrological system and are ephemeral. Gasca and Ross (2009), for instance, include proper regional hydrogeology to better understand the wetland system and the implications of groundwater abstractions thereon, whereas Steube et al. (2008) focus around the importance of collaboration between ecologists, hydrogeologists and geochemists. Lane et al. (2012) address the loss of wetlands due to agriculture and development, notably with respect to isolated wetlands. What are notable are the issues of lost wetlands and the need for incorporation of proper understanding of the subsurface hydrology.

The possible absence of distinct vegetation and disruption of natural surface soils are significant omissions in classical wetland delineation. With regards to what is termed temporary perched water hillslope wetlands in this study, these indicators are rarely all simultaneously present and are often absent altogether for prolonged periods. These wetlands form typically due to perched water tables occurring annually or less frequently, notably dependent on prolonged high intensity precipitation events in these upper hillslopes. Wetland biota resurface directly following waterlogging.

Attempts at characterising temporary wetlands are limited. Wise et al. (2000) considered the importance of quantifying the interaction between isolated wetlands and the deeper aquifers (which – although not necessarily temporary systems – addresses the importance of deeper investigation). Warwick and Brock (2003) evaluated duration and season of flooding with respect to germination, establishment of wetland plants and completion of life cycles. Espinar and Clemente (2007) related seasonal cracks and dispersion of topsoil during dry periods to different diaspores at different depths in Mediterranean temporary wetlands in Spain. Herrero and Castañeda (2009) evaluated the importance of wetlands in arid areas with specific reference to the variability from perennial to temporary, fresh water to hypersaline and in size from less than 1 km^2 to more than 9 000 km^2. Additionally, they specifically mention the highly variable interannual and seasonal rainfall patterns and biota adapted to extreme environments. Roshier and Rumbachs (2004) applied AVHRR satellite data to map temporary wetlands in the arid regions of Australia. Bagella et al. (2010) evaluated plant assemblages within nine temporary wetlands in the Mediterranean biogeographical region, which are dependent on the groundwater depth and the period of flooding. Although most of these studies consider temporary wetlands related to distinct drainage features, isolated wetlands, or the biotic markers of temporary wetlands, it relates to these poorly studied yet extremely important components of the hydrological cycle.

5.3.2. Materials and methods

5.3.2.1. Study site

The site is situated in the Midrand area (Johannesburg) of Gauteng Province at the junction of the N1 motorway and Olifantsfontein Road between Pretoria and the Johannesburg, South Africa (Figure 5-12(a) and (b)). The topography ranges between 1 561 mamsl in the northeastern corner of the site to 1 493 mamsl where the drainage features exits the site at the western boundary, amounting to an average gradient of 3° (from Google Earth © imagery). The study site is underlain by Archaean Lanseria Gneiss of the Johannesburg Dome Granite (Figure 5-12 (b)), comprising essentially tonalite, granodiorite and trondjemite (Robb et al. 2009).

The upper reaches of the site were excavated for development in 2008. Figure 5-12 (c) depicts the site prior to excavation in 2006 and Figure 5-12 (d) directly following excavation in 2009. Note the extent of the wet conditions as visible from the satellite imagery and the nearest drainage feature approximately 800 m downslope of the excavation (© Google Earth 2013). Distinct biota were absent during the dryer winter months when the environmental investigations were being conducted, which was followed by a field fire destroying whatever vegetation remained. Subsequently, construction commenced and a 200 m long profile is now exposed from the upper slope to the lower slope, giving valuable insight into the anatomy of the hydrological system.

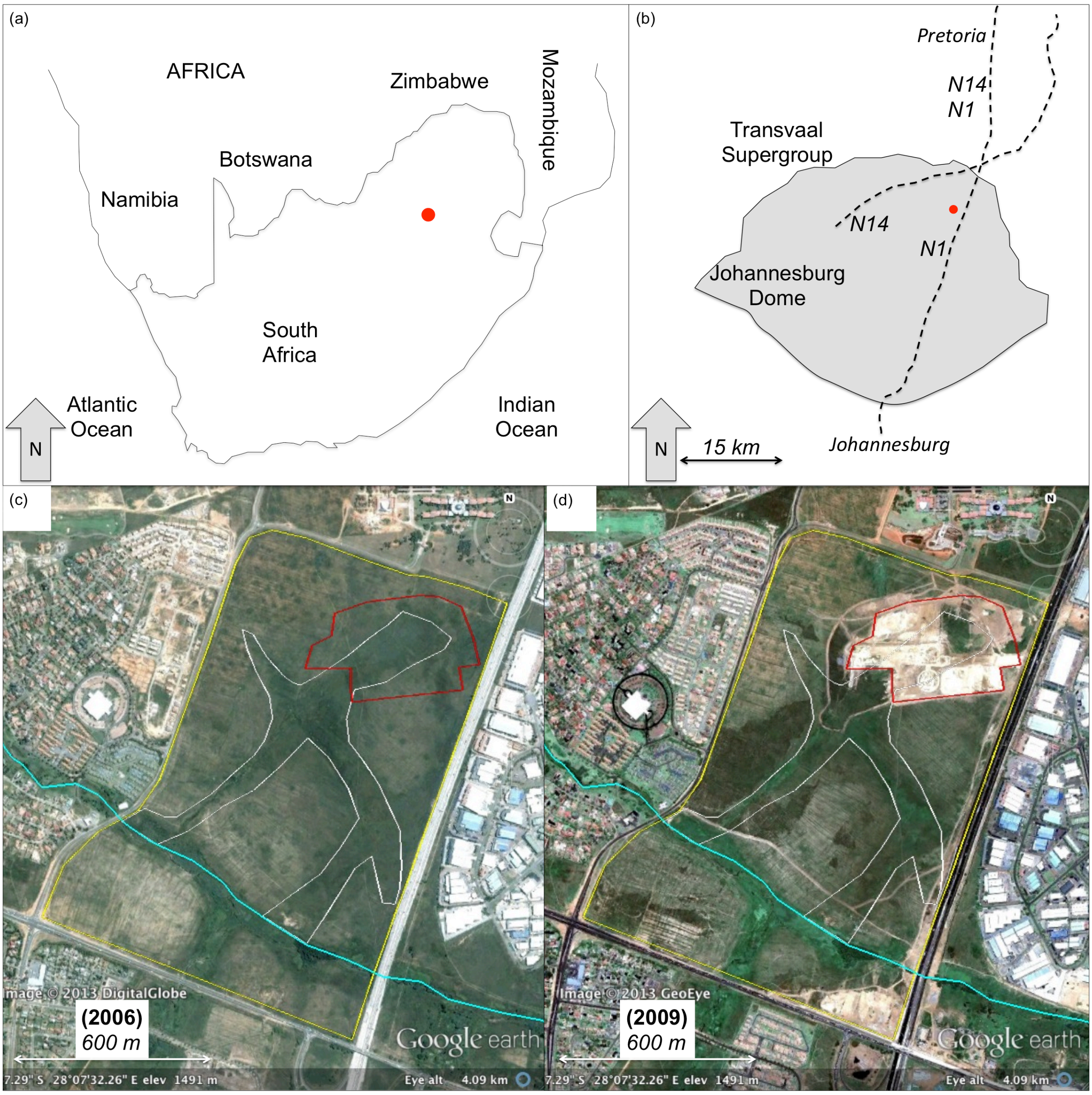


Figure 5-12. **(a) Locality, (b) regional geology with Johannesburg Granite Dome indicated, and (c) and (d) satellite imagery before and after excavation indicating the boundaries of the site, the nearest surface drainage feature and extent of the wetness (© Digital Globe/ Google Earth 2013).**

5.3.2.2. Methodology

Three piezometers were installed following excavation with depths varying between 3 m and 6 m. Seepage water appears between surface and approximately 2 m below surface following intense periods of rainfall and is practically absent in the dryer months and years. The regional groundwater is expected to occur within fractured granite and the depth has not been confirmed on the site, although it is assumed to be deeper than 6 m (the depth of the deepest piezometer which is occasionally dry).

The perched water table occurs shallower than 1 m below surface (when present) and is expected to be connected to the stream forming the southern perimeter of the site.

Sixteen soil profiles were described according to the draft South African National Standard on soil profiling for engineering purposes (SANS 2009a), of which seven have been extensively sampled and included in this study. The seven profiles were sampled in each visually differing horizon (based on origin, viz. colluvium, ferricrete in pebble marker and residual granite, residual granite, completely weathered granite and highly weathered granite bedrock). 39 samples in total were submitted for X-Ray Diffraction (XRD), X-Ray Fluorescence Spectroscopy (XRF), soil grading and hydrometer, and Atterberg limits determination. The latter were used to determine porosity based on density relationships (Equation 18).

5.3.3. Results

5.3.3.1. Material succession and soil profiles

Figure 5-13 shows a panorama viewing southward to the east – west section in the excavation (profile VP01 was described at the left hand of the excavation and profile VP06 just outside of the photograph on the right hand side). Note the distinct seepage from the ferricrete and the apparent regeneration of the wetland conditions on the bedrock forming the excavation floor.

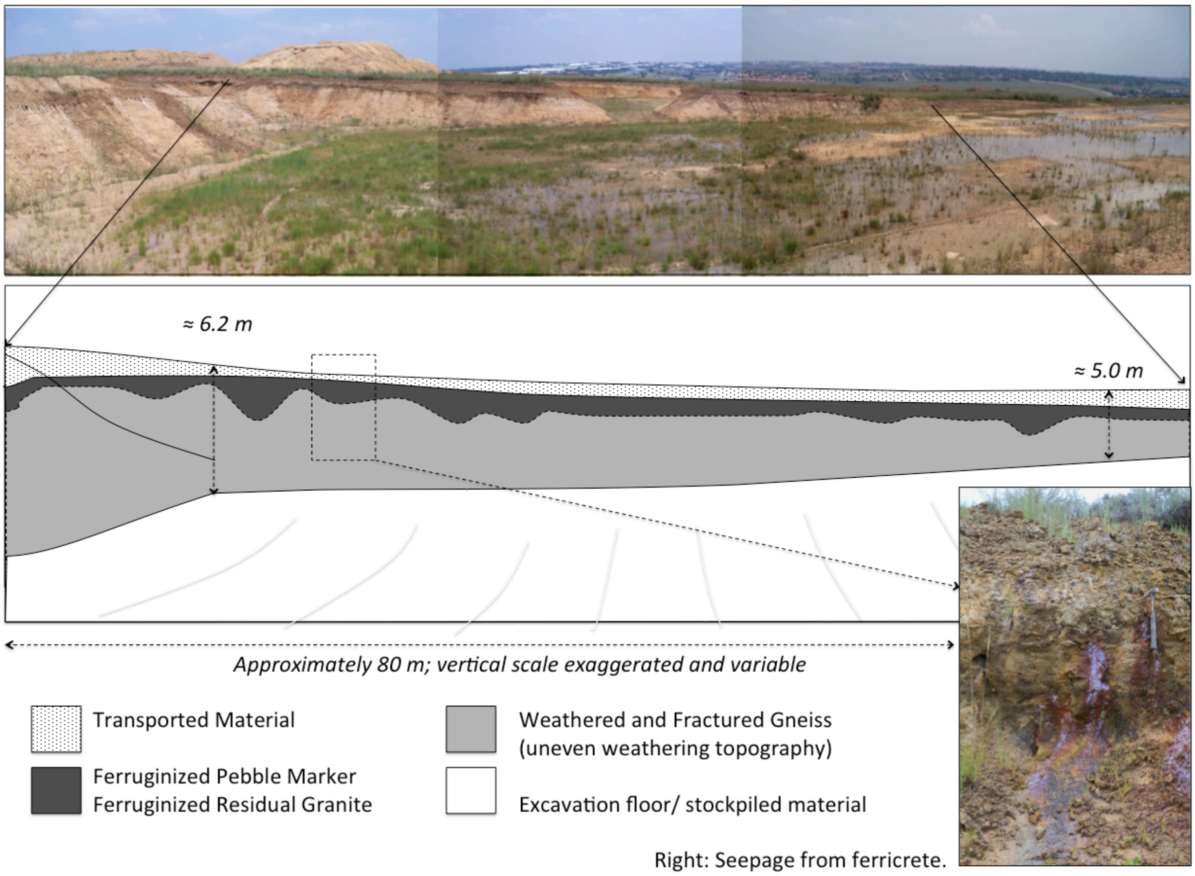


Figure 5-13. Existing excavation of the site under investigation.

Four typical soil profiles along the slope are shown in Figure 5-14, representing the upper slope (VP07), upper-midslope (VP01), midslope (VP03) and mid-lower slope (VP06). Note the distinct absence of ferricrete in VP03 (although some discolouration is evident), as well as the pinholed structure in all the upper soil horizons. Bulk of the surface soils grade as silty sand with bedrock becoming progressively less weathered and less fractured with depth. Figure 5-15 shows the soil mineralogy for different horizons in the seven sampled soil profiles. The absence of ferricrete is supported by the absence of goethite in VP07 on the upper reaches of the slope and VP03 in the central portions.

5.3.3.2. Porosity

The highest porosities were calculated for the open textured colluvium and residual granite (Table 5-3). The ferruginized horizon exists in the pebble marker and/ or upper parts of the residual granite and shows lower porosity. However, this lower porosity is characterised by large voids with visible water seepage as opposed to the smaller pores in the other materials. The large pores in the ferruginized horizons allow entry of water from the shallower voided horizons. On entry, due to lower adhesion and apparent lateral interconnectivity, water is allowed to move down gradient in this ferruginized horizon as is evident in the excavation where water seeps out of ferricrete. Where ferricrete is absent, infiltrating or interflow water may be forced to percolate deeper under gravity and possibly result in groundwater recharge. The ferricrete is thus not an aquiclude, but a conductive zone with large interconnected pores.

Table 5-3. Porosity values calculated for each soil horizon based on bulk densities and XRD.

Horizon	η (average)	Standard Deviation	Count
Colluvium	0.22	0.04	3
Ferruginized Horizons	0.15	0.05	3
Residual Granite	0.23	0.08	8
Completely Weathered Granite	0.15	0.06	3
Fractured Granite	0.15	0.02	5

5.3.3.3. Hydraulic conductivity

Field percolation test results are shown in Table 5-4. Average saturated vertical hydraulic conductivity according to this method generally varies within one order of magnitude between roughly 5 x 10-5 m/s in the upper-midslope to 6 x 10-4 m/s in the mid-lower slope. In all instances, this represents surficial colluvium with ferricrete or residual granite near the base of the trial hole. As the surface materials are tested, the test constraint of determining a vertical conductivity is acceptable, as infiltrating water will probably move in this direction until the ferruginized horizons where interflow commences.

0.00	Slightly moist, light brown speckled light orange, medium dense, pinholed, silty SAND. Transported (Colluvium) with abundant roots.
0.85	Dry, light orange mottled and blotched black, very dense, honeycomb FERRICRETE in sandy gravel with abundant quartz pebbles. Residual Granite.
2.48	Dry, light brown mottled yellow and orange stained black along joints, dense, jointed, silty SAND. Completely Weathered Granite.
3.26	

VP07

0.00	Dry, greyish brown, medium dense, slightly pinholed with open root channels, clayey silty SAND. Colluvium.
0.46	Dry, brownish orange mottled and blotched black speckled red, very dense, intact. Honeycomb Ferricrete formed in Pebble Marker (with scattered quartz gravel).
0.75	Dry, brownish orange blotched black speckled red, very dense, intact. Honeycomb Ferricrete formed in Residual Granite.
1.90	Dry, white to grey patched yellowish grey, medium dense, intact, silty sandy GRAVEL. Completely Weathered Granite.
3.20	Dry, dusky red speckled yellow and white stained black on joint surfaces, foliated with moderately spaced joints becoming widely spaced with depth, coarse-grained, highly weathered, soft-rock GRANITE.
6.20	

VP01

0.00	Slightly moist, greyish brown with reddish orange speckled, medium dense, pinholed, silty clayey SAND. Transported (Colluvium) with abundant roots.
0.84	Slightly moist, orange brown speckled and blotched orange, medium dense, pinholed, silty clayey SAND. Transported (Colluvium).
1.27	Dry, dark yellowish grey blotched orange, dense, (intact), silty SAND. Residual Granite.
2.20	Dry, dark yellowish grey blotched orange, very dense, (intact), gravelly SAND with subangular quartz pebbles. Completely Weathered Granite.
3.40	

VP03

0.00	Slightly moist, dark brown mottled reddish orange, medium dense, pinholed, silty SAND. Transported (Colluvium) with roots.
0.45	Slightly moist, light brown blotched reddish orange, loose, (intact), silty clayey SAND. Transported (Colluvium) with roots.
1.14	Slightly moist, light reddish orange mottled black and white, very dense, honeycomb FERRICRETE in sandy gravel. Residual Granite.
2.49	Slightly moist, light grey mottled black and red stained black on joints, dense, (jointed), silty SAND. Completely Weathered Granite.
3.83	Light orange brown stained black on joints, moderately jointed, highly weathered, soft-rock GRANITE.
4.97	

VP06

Figure 5-14. Profiles logs on the upper slope (VP07), upper-midslope (VP01), mid slope (VP03) and mid-lower slope (VP06).

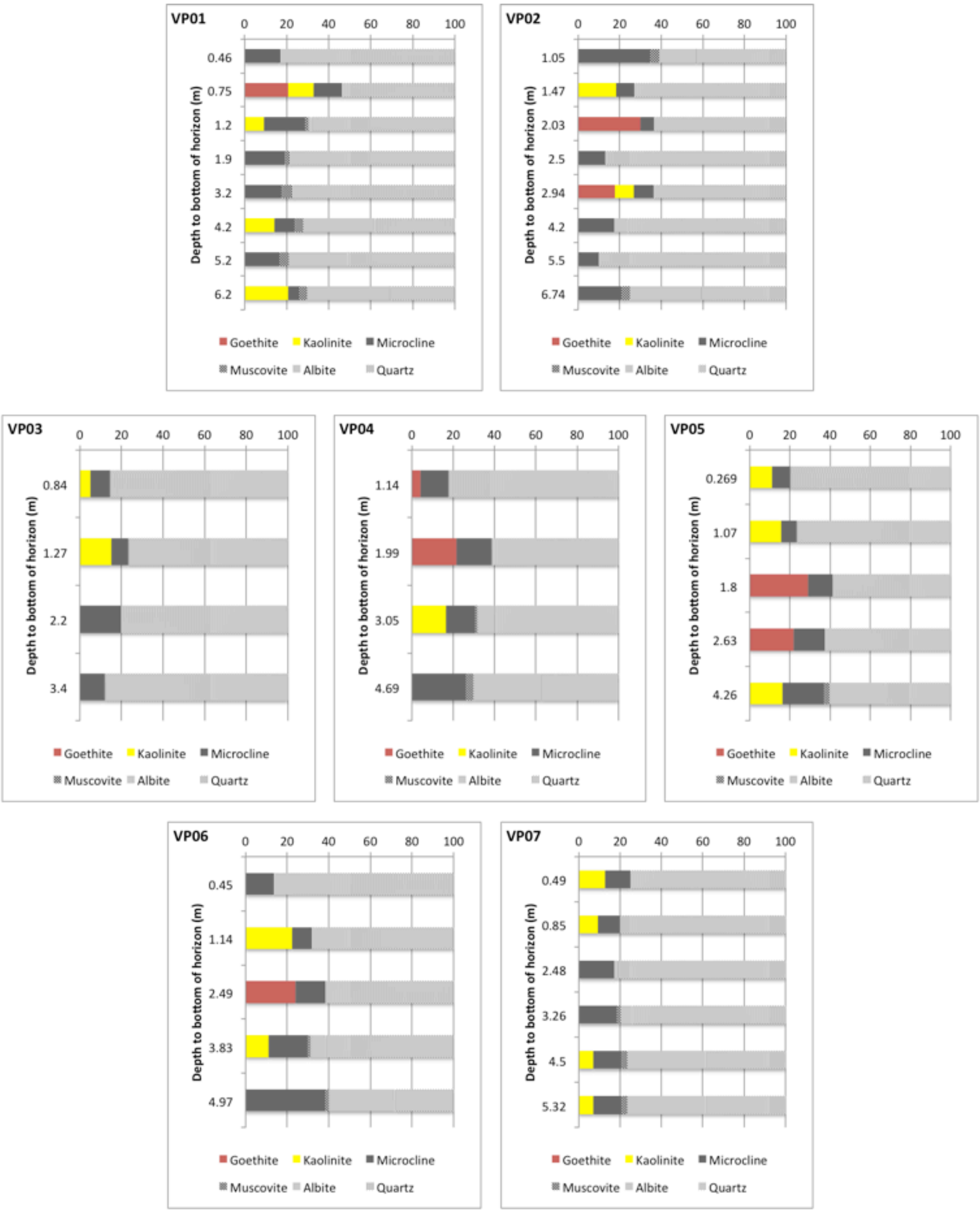


Figure 5-15. **Mineralogy (quantitative XRD) by soil horizon for seven sampled soil profiles.**

Table 5-4. Percolation test results.

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

5.3.3.4. Conceptual model

Figure 5-11 depicts a conceptual cross-section incorporating soil type and mineralogy descriptions at four representative positions along the slope. Hydraulic conductivities derived from percolation testing under presoaked conditions are noted for three positions along the slope. Major anticipated infiltration, recharge and interflow directions are inferred based on visual evidence and interpretation of the data (profile descriptions, K-values, soil texture).

High porosity together with small pore size and low connectivity in the upper transported soil horizons result in water retained by adhesion with excess water gradually draining under gravity. The underlying ferricrete is less porous but with larger pores and better connectivity, resulting in cohesion between water molecules and subsequently drainage under gravity. However, as the saprolite underlying the ferricrete is once again porous but with much smaller pores and more clogging due to clay minerals such as kaolinite and mica, adhesion retains moisture with interflow in the overlying ferricrete being easier than percolation into the saprolite. This results in surface infiltration, interflow in the perched water table in the ferricrete, and limited deeper percolation in ferruginized portions (Figure 3-2).

5.3.4. Conclusions and Findings

Transported soil horizons (notably upper colluvium) are pinholed with porosity in the order of 0.22. Ferricrete has larger pore sizes with average porosity in the order of 0.15 and is underlain by residual granite with porosity of 0.22. Vertical near-saturated hydraulic conductivities (which represent infiltrating water derived from precipitation on land surface) for these materials vary between 7 x 10-5 m/s on the upper to midslope to 1.8 x 10-4 on the midslope to lower slope.

Ferricrete underlies colluvium on the upper-midslope and the mid-lower slope and is distinctly absent just below the midslope and on the upper reaches of the slope. Yellow, orange and red discolouration of residual soil and weathered rock is much more pronounced than the discolouration in the colluvial materials, suggesting that leaching may occur in the upper horizons followed by precipitation in the deeper horizons. As visual evidence of seepage and distinct large connected pores are present in the ferricrete, it is expected that water infiltrating will enrich in mobile ions. Thereafter, enriched water will move as interflow within the ferricrete or alternatively may be sourced from interflow further upslope or from the bedrock below. The ferricrete is therefore expected to form upward, hence the distinct absence of some significant identifiers (such as soil mottling and wetness) in the upper horizons.

The residual granite underlying the ferricrete (or the colluvium, where absent) is once again more porous, stained with goethite and possibly resulted from the weathered bedrock (porosity 0.15 and lower) serving as a local aquitard. Fractures within the lesser weathered granite may serve as flow paths, although the same structures in the completely weathered granite appears to be more clogged with goethite and kaolinite.

Kaolinite forms from the weathering of the feldspars and may be sources from bedrock further upslope. This clay mineral, albeit not expansive, aids in clogging of porosity and may play an important role in the formation of the perched water table.

The flow in the ferricrete results as the larger pores promote cohesion between water molecules rather than adhesion to mineral surfaces. The direction and degree of interconnectivity govern the flow rate and direction. Vertical percolation will result where the ferricrete pinches out or where the void space is directly connected to that of the deeper horizons, although imbibition into smaller pores in the residuum may be less pronounced given the large void spaces within the ferricrete. The importance of pore size (scale of porosity) as opposed to volumetric porosity is accentuated in this process where the path of least resistance is the larger pores in the ferricrete, resulting in interflow rather than deeper percolation.

The weathered bedrock forms a fractured vadose zone. The ferricrete forms due to alternating reducing and oxidizing conditions, the latter supplying opportunity for precipitation of goethite. The system – which mimics a temporary wetland – is not related to the permanent groundwater table, therefore making classification of the site as a wetland (s.s.; sensu stricto or in the strict sense as defined in the National Water Act, DWA 1998) impossible. However, its behaviour as such in a region where groundwater is not shallow results in ecosystems flourishing in this area following long and intense rainfall events.

In areas where groundwater is generally deep and where rainfall is erratic, intense and concentrated within short periods, perched water tables form, which may result in waterlogged conditions supporting wetland vegetation. As the groundwater or surface water itself does not form the system, classification as a wetland is presently not possible and these sensitive systems are being zoned for development. This adversely impacts biodiversity, water quality and influences the development as water later affects foundations and underground services.

Importantly, the identification of these systems is limited and often contradicts wetland identification. Firstly, groundwater and surface water do not always directly influence these systems and they might appear isolated and are – as in the case of this study – supplied by precipitation or interflow only. Secondly, waterlogging occurs from depth or from upslope, often leaving soil wetness indicators in upslope or underlying soil horizons and not in the shallow soils where identification is evident. Thirdly, as these systems are highly ephemeral, the likelihood of identification during one field visit become limited as waterlogging and wetland vegetation occur only following long and intense rainfall, which might occur seasonally or less frequently.

Systems such as these should not be considered exceptions to the rule. As wetlands (s. s.) are not common in these terrains, the hydrological and ecological systems that depend on these temporary or perched systems are not presently protected. Whether these systems are perched water table wetlands, temporary hillslope wetlands, intermittently waterlogged slopes, paluslopes or wet grasslands, a need arises to classify them as a special type of wetland also requiring preservation and cognisance. This may require something as basic as awareness of these systems and the implications of development, to the level of incorporation as a distinct type of wetland to ensure future protection.

5.4. Towards a Multi-faceted Vadose Zone Assessment Protocol: Cemetery Guidelines and Application to a Burial Site located near a Seasonal Wetland (Pretoria, South Africa)

Burial or interment is a basic social need and, to many extents, a moral practice depending on culture. However, siting of cemeteries and grave sites lose focus of the environmental implications at the expense of these cultural needs. Although necessary and an important aspect, the issue is not interment per se, but rather the oversight of scientifically sound investigation techniques of this activity which does influence the environment. Issues are generally fourfold, in the opinion of the author, and include (1) social matters, which fall outside of the scientific regime, and include communities requiring specific placement of burial sites (e.g. on hills or in floodplains) and the growth of these sites; (2) environmental or sanitary issues such as resulting water contamination; (3) engineering issues which contribute to the social and environmental aspects, including, for instance, stability of the grave and ease of excavation of the site materials; and (4) the lack of an enforced document collating principles and approaches employed in South Africa.

Risk associated with and existing investigation approaches for cemetery sites are documented in §4.2.

5.4.1. Materials and Methods

5.4.1.1. Study area

The Temba Cemetery is shown in Figure 5-16 and is situated in Temba, approximately 40 km north of Pretoria in the City of Tshwane Municipality (Gauteng Province, South Africa). As a peri-urban node developed in the mid to late 1900s, the cemetery presently has 13 673 adult graves and 4 695 child graves amounting to a total of 18 368. Apart from fairly high density peri-urban development around the cemetery, the site itself is covered by grass veldt which has possibly been somewhat disturbed through historical agricultural practices.

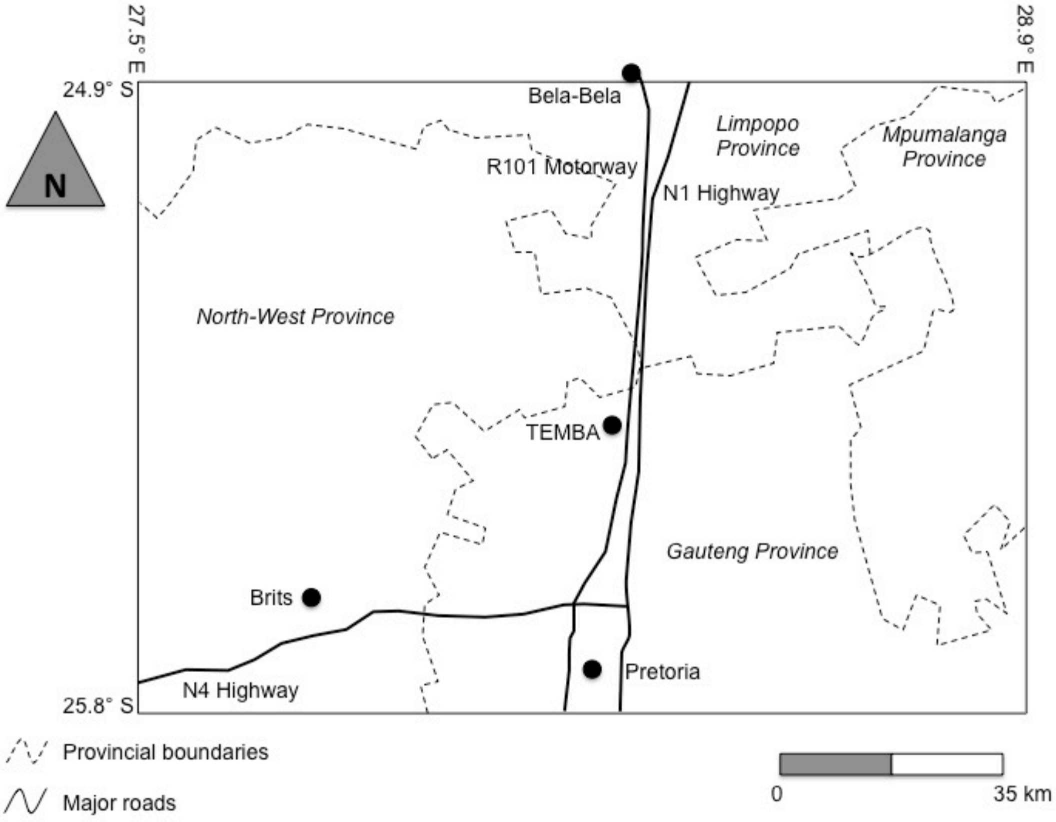


Figure 5-16. **Locality of the Temba Cemetery.**

Interments have ceased since the detection of water seepage into newly excavated graves. Expansion of the cemetery was towards a wetland feature to the southwest until detection of water seepage into new burial pits (Figure 5-17).

5.4.1.2. Topography and hydrology

Temba Cemetery is situated in the A23F quaternary catchment of the Crocodile/ Marico (West) Water Management Area (WMA3). Surface drainage is towards the southwest into the Apies River, located approximately 2.5 km away.

The site itself slopes fairly shallowly at an approximate gradient of 1:60. The surface gradient is roughly to the east in the western portions of the site and to the south in the northern portions of the site. A wetland forms on the slope, eventually forming a small non-perennial stream draining towards the southwest. The wetland is believed to be seasonally waterlogged.

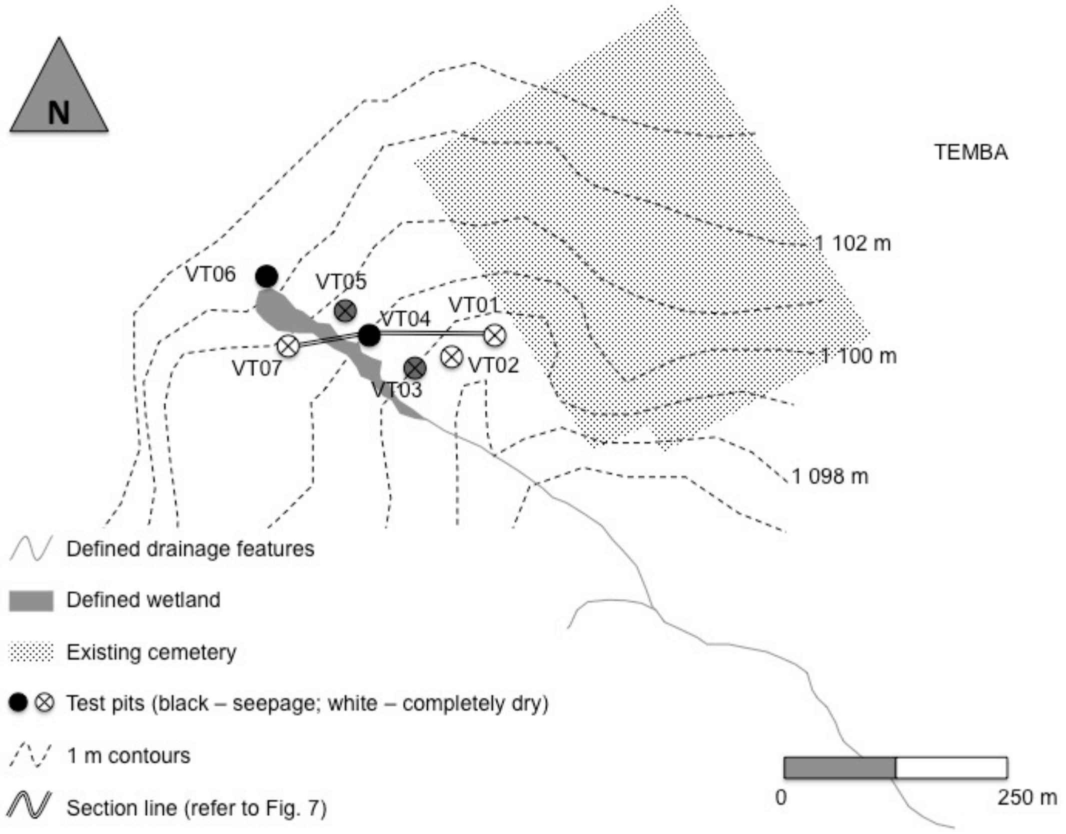


Figure 5-17. **The existing Temba Cemetery (yellow shading), wetland, surface drainage and excavated test pits depicted on one-meter surface contours.**

According to a series of Hydrogeological Maps of South Africa (published jointly by the DWA and the Water Research Commission in 1996), the electrical conductivity of groundwater is between 70 and 300 mS/m, groundwater recharge is 50 – 110 mm per annum, groundwater depth vary between 20 and 30 m (standard deviation 25 m) and groundwater is of the (Ca,Mg)(HCO3)2-type. Nitrate concentrations are noted as exceeding 10 mg/l in more than 20% of historical samples analysed.

5.4.1.3. Geology

The extensive deposits of the Karoo Supergroup generally vary between arenaceous to argillaceous sedimentary rocks with localised coal beds. Additional to this are also the intrusive dolerite dykes and extrusive mafic to ultramafic lavas marking the later stages of the stratigraphy, although these are not generally identified in the Pretoria region. The combined Karoo Supergroup ranges in age between 290 and 190 Ma and – in the area under consideration – are characterised by the Ecca Group deposited after southward polar migration and the subsequent warmer climate within the Springbok Flats Basin. Proximate to Pretoria, the Springbok Flats Basin of the Karoo Supergroup overlies the Dwyka Group with the Hammanskraal Formation being the most common in the area. At the site itself, bedrock comprises intercalated shale to siltstone or fine sandstone with eventual pale brown to orange brown fine sandstone at depth (Brink 1983; Johnson et al. 2009).

5.4.1.4. Investigation techniques

The investigation comprised excavation of seven test pits by means of a backactor (backhoe). Excavation was ceased on refusal or end of reach, ensuring to reach a maximum possible depth. Test pits were spaced to address geological and pedological variation along the drainage, as well as perpendicular thereto.

Representative samples were submitted for grading and hydrometer analyses, as well as to determine the Atterberg limits.

5.4.2. Findings

5.4.2.1. Geological and pedological characterisation

The land cover subdivides the site into a number of characteristic zones (Figure 5-18). From the slopes at the existing cemetery, the succession of materials change to distinct duplex soils (enrichment in clay minerals downslope due to translocation of clay particles by moving water) with clayey surface horizons (grass covered), followed by clayey soils overlain by sandy topsoil where precipitation of salts on surface is indicative of high evaporation (barren land). The wetland itself is also clayey and waterlogged and characterised by reeds and grasses adapted to waterlogged conditions.

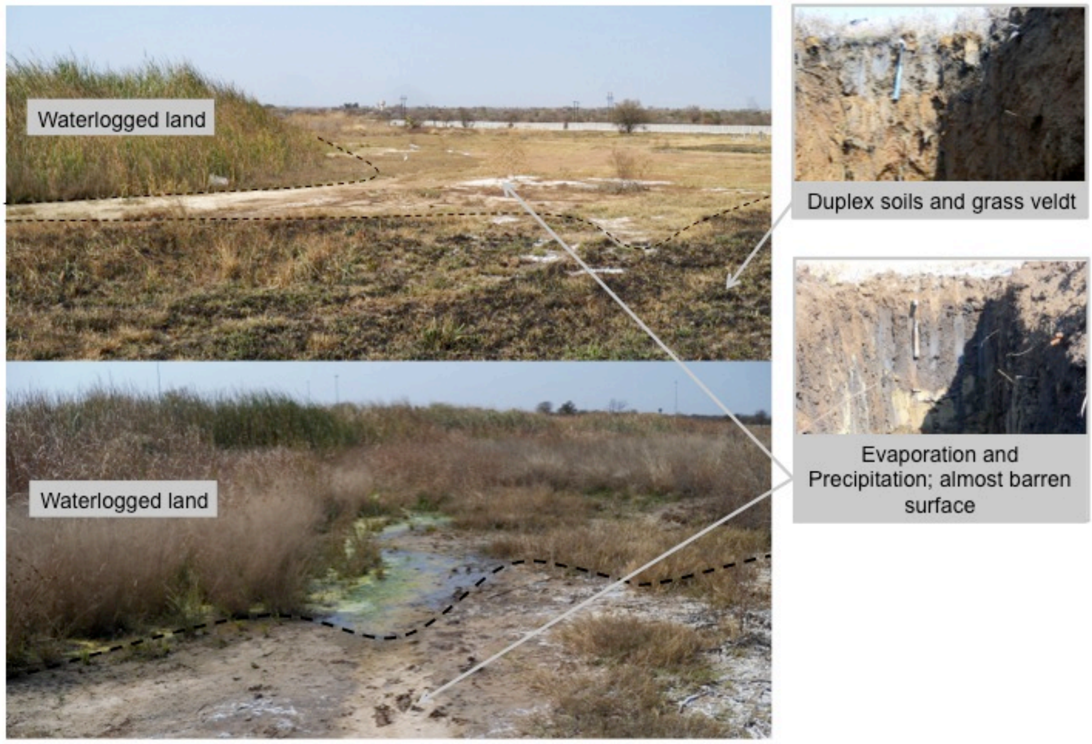


Figure 5-18. **Characteristic changes from flat upper slopes through clayey duplex soils, evaporation and precipitation zones with thin sandy topsoil, to waterlogged land.**

The test pit positions are shown in the site plan (Figure 5-17) and are summarised in Figure 5-19. Photographs of selected test pits prior to significant water influx (i.e. immediately following excavation) are also shown. Typical material descriptions are as follows:

- Colluvium – moist to wet, dark brown or grey, soft to firm, shattered and slickensided, silty clay near drainage feature, becoming slightly moist, dark reddish brown (streaked grey speckled olive), dense, shattered, clayey silty sand or firm, pinholed, sandy clay or clayey silt with increasing distance
- Residuum – moist, orange brown blotched olive or (light) olive blotched orange and grey, very soft, slightly slickensided to shattered, silty clay; occasionally with calcrete nodules
- Bedrock – moist, grey to olive grey stained orange and white, soft, laminated (in places), clay-silt to sandy in places; completely weathered shale, siltstone and sandstone becoming dull pale brown stained white, orange and black, laminated and jointed, intercalated fine-grained shale, siltstone and sandstone.

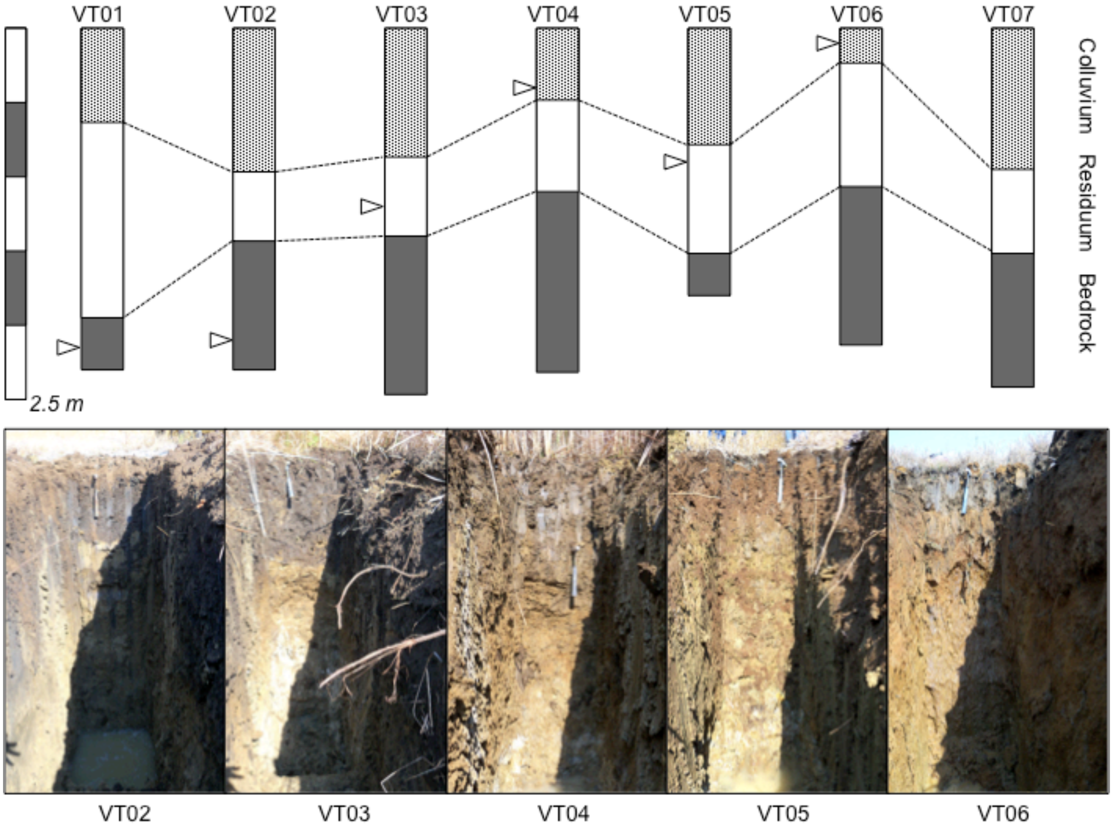


Figure 5-19. **Schematic depiction of soil horizon thickness and depth of water seepage (if any) denoted by triangles, as well as photographs of selected profiles prior to significant water influx.**

VT01, VT02, VT05 and VT07 show a thin open-structured and granular sandy topsoil whereas VT03, VT04 and VT06, which are situated closer to the wetland area, have more cohesive and plastic clayey topsoils. Below this sandy colluvium, all profiles show a similar succession of varying thicknesses of dark brown to black clayey alluvial and colluvial soils grading into orange brown clayey residual sandstone and silstone. Weathered bedrock generally occurs at depths greater than 1.50 m.

The topsoil variations are expected to be a function of transport and pedogenetic processes. Colluvium is generally more sandy and more porous with material originating from upslope, whereas alluvium transports fine clayey sediments to be deposited along the wetland. Lateral and vertical leaching of clays result in the distinctive duplex soils forming along the brim of the wetland.

5.4.2.2. Hydrological characterisation

Water seepage was encountered in all test pits with the notable exception of VT07. Although situated adjacent to the waterlogged area, interflow appears to be accentuated to the east of the wetland and possibly excluding the western side. A throughflow system is likely, or alternatively the position where VT07 was excavated may be more likely to serve as a highly evaporative zone (as is evident by the surface precipitation of salts). A third possibility is the likelihood that VT07 would eventually have shown seepage but that subsurface permeability is too slow for rapid water influx.

5.4.2.3. Geotechnical characterisation

Excavation is soft to depths exceeding grave depth (1.80 m) and all sidewalls are stable. However, water seepage and the occurrence of excessively clayey horizons highlight the likelihood of water influx into graves. Backfilling of graves with in-situ material may result in poor permeability and difficulty in compaction of highly cohesive soils, notably during drier seasons when the clays may be stiff and possibly dessicated. The likelihood of selective backfilling, i.e. using only the granular fractions due to better workability, may furthermore create preferential pathways for water from surface.

5.4.2.4. Conceptual model

A cross-section was constructed based on detailed soil profile descriptions and transects the wetland along VT07-VT04-VT01 (Figure 5-20). Water originates from upslope (in the vicinity of VT06) and collects in the wetland system from where interflow appears to predominate towards the southeast. In this instance, the system is considered a losing stream not in direct contact with the phreatic surface (which is expected to be well below 10 m depth, based on the afforementioned map series). Additionally, the system appears to behave as a throughflow system with water sourced from upslope and moving through the wetland rather than out of it in all directions.

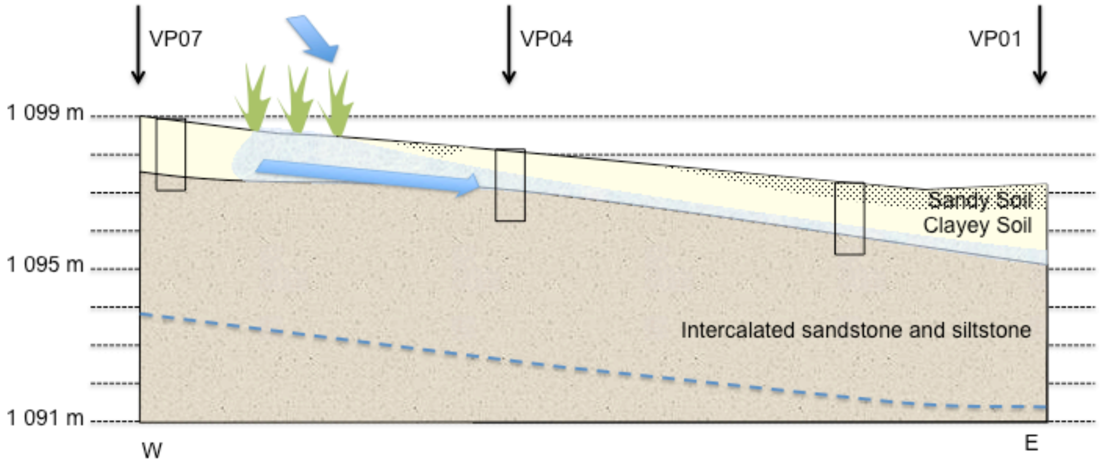


Figure 5-20. **Conceptual model depicting flow through the wetland obliquely through the streamflow direction (200 m across); note a regional groundwater table is inferred and local variations or multiple water tables may exist.**

The distinct presence of duplex soils followed by evaporation/ precipitation zones towards the wetland insinuates unsaturated interflow resulting in intermittently or seasonally waterlogged conditions between the wetland and the duplex soils. This water may represent yet a shallower perched water table moving within or just below the soil zone, which may or may not be in distinct contact with the deeper perched water table occuring on the bedrock head (Fig. 7). This scenario may be driven either from upslope as detailed above, or may alternatively be associated with the same losing stream system through which the wetland feeds this evaporative zone with the duplex soil forming as the moisture is lost to the atmosphere and clays become immobile.

5.4.3. Conclusions

5.4.3.1. Provisional findings and way forward

Basic geological characterisation techniques have been employed to conceptualise the hydrological interaction at a cemetery site developed near a seasonally waterlogged wetland. The phreatic surface is deep (in excess of 10 m) and subsequently the seepage detected in the trial holes are not in direct contact with the regional groundwater table.

Slopes terminate in duplex soils (plastic clayey topsoil) followed by evaporation/ precipitation zones (porous, open-structured sandy topsoil) and finally the wetland. The upper slopes are generally drier to greater depth with water being on surface in the wetland and at shallow depth in the evaporation/ precipitation and duplex soil zones to the east of the wetland. The distinct absence of seepage in the only western profile may suggest throughflow, although confirmation through additional profiling to the west is required for definitive clarification.

Fine-grained site soils induce surface ponding and very slow infiltration, which can enhance the waterlogged status of the site during wet seasons, which may be exacerbated when using this same material as backfill. More recent processes resulting from this primary low permeability are evident through clay translocation and evaporation.

A losing stream system is suggested whereby the wetland is fed from the upper reaches of the small catchment and water enters the proximate vadose zone from the wetland. The implications are important as this suggests that interflow water may not flow towards the wetland and subsequently that surface water is likely protected against possible contamination. The same does not necessary hold for groundwater and the thickness and properties of the vadose zone will govern this.

Even in dry months, the excavation and proper interpretation of soil profiles would have highlighted the likelihood of shallow seepage into grave pits. Although the proximity of the wetland should be a clear indicator, such processes are common in South Africa without any real connection to surface drainage features. Low precipitation and high evapotranspiration commonly result in perched water table systems and limited intrusive investigation is key in identifying such scenarios.

Excavation to the west of the wetland and water quality comparison for the wetland, seep water and groundwater are underway. This will aid in validating the conceptual model and in addressing possible existing contamination of water at the site.

5.4.3.2. Provisional guidelines

The final phased of the project entails guidelines for investigations for cemetery sites. Provisionally, a two-fold system is proposed. These correlate to those discussed extensively in §6.1. This multi-faceted Vadose Zone Assessment Protocol aims to incorporate strengths of a range of separate disciplines in proper characterisation of the complete vadose zone (including, for instance, the fractured vadose zone and secondary porosity, both of which are not clearly addressed in existing guidelines). This correlates to the addressed existing approaches, which are based on geotechnical and sanitary aspects, but with more distinct specification and for use in any vadose zone assessment and not solely cemeteries.

Following such a hierarchical approach will ensure detection of possible problems prior to extensive efforts and costs and will also direct future investigation towards the most likely issues. For cemetery sites, all stages are recommended although D2 and E1 can be solely at conceptual level. In the event that the site is waterlogged or adjacent to seasonal or intermittent water bodies, cemetery development should not proceed.

6. CONCLUSIONS

6.1. Standard Guidelines for Vadose Zone Assessment

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

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

6.1.1. Development-dependent investigation

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

6.1.2. Cost-ease-benefit screening

Relative cost and effort are shown in relation to increasing data accuracy in Figure 6-1. This indiscrete approach is to be configured for each study, incorporating the bulk of the sampling and analyses (where and how required) as one cost, one estimate of the ease of the approach followed, and yielding one result of data certainty. This will aid in selecting the best methods based on available accuracy data and is probably most effective in smaller investigations.

Based on this, the tiered approach (§6.1.4) can be applied depending on data requirements with increasing effort and cost associated with higher accuracy data., and with cognisance of the identification of competent persons for relevant tiers, and with decision-making incorporated into the process.

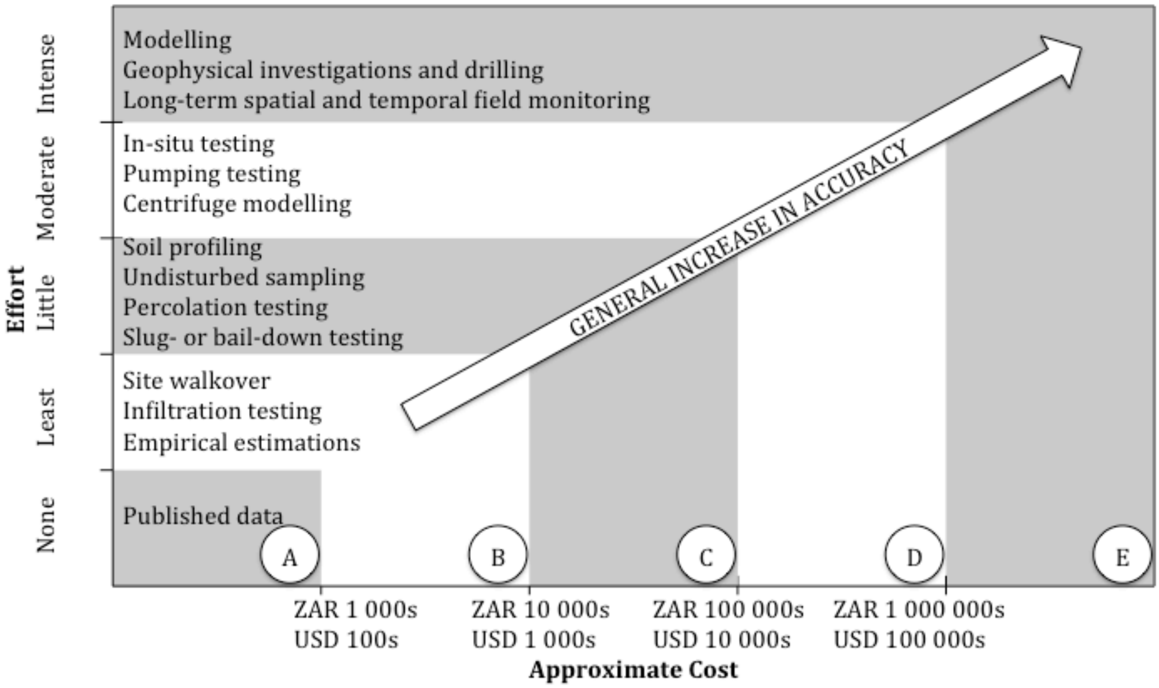


Figure 6-1. **Relative cost-effort screen related to tiers of investigation.**

6.1.3. Deducing the comprehensive earth system model

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

6.1.3.1. Stage 1: Define the settings

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

6.1.3.2. Stage 2: Superimpose the scenarios

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

6.1.3.3. Stage 3: Define the conceptual models

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

6.1.4. Multi-faceted vadose zone assessment protocol

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

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

Increasing effort and cost generally result in an increase in accuracy and validity of results obtained. Straightforward as this may seem, certain analyses or tests at certain stages of investigation will ensure adequate data input for the requirements. A recommended outline of a 5-tiered approach to increasing detail is shown in Box 33.

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

In order to do this, it is proposed that a fixed sequence of activities is employed correlating roughly to the five tiers outlined in the minimum requirements. Progressing towards the higher tiers, investigation become more focused for a specific purpose with the benefit of being able to apply lower-tier input to different applications. This can be summarised as per Box 34 with elaboration in Table 6-1. It is recommended to start at A1 and move downwards until the required level of detail is reached based on the risk posed by the required development. Omissions of certain stages or requirements are at the prerogative of the competent person conducting the investigation.

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

6.1.5. Decision-making and competent persons

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

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

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

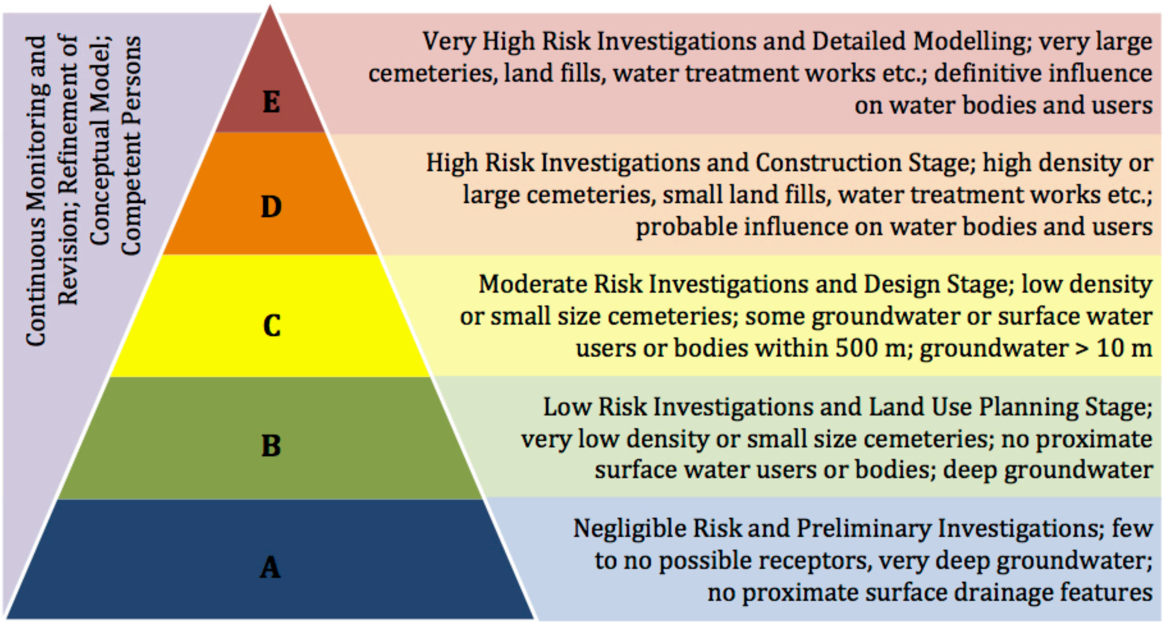
Competent persons should be defined based on academic qualification, professional registration and vocational experience within the specific water-related field required for the relevant tier. More experience should also be required for the higher tiers where a certain level of expertise is required,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

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

Box 33. Minimum Requirements for Vadose Zone Assessment (VZA).

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

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



Very High Risk Investigations and Detailed Modelling; very large cemeteries, land fills, water treatment works etc.; definitive influence on water bodies and users

High Risk Investigations and Construction Stage; high density or large cemeteries, small land fills, water treatment works etc.; probable influence on water bodies and users

Moderate Risk Investigations and Design Stage; low density or small size cemeteries; some groundwater or surface water users or bodies within 500 m; groundwater > 10 m

Low Risk Investigations and Land Use Planning Stage; very low density or small size cemeteries; no proximate surface water users or bodies; deep groundwater

Negligible Risk and Preliminary Investigations; few to no possible receptors, very deep groundwater; no proximate surface drainage features

MINIMUM REQUIREMENTS BASED ON THE 5-TIERED APPROACH

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

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

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Box 34. Multi-faceted Vadose Zone Assessment Protocol (VZAP).

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

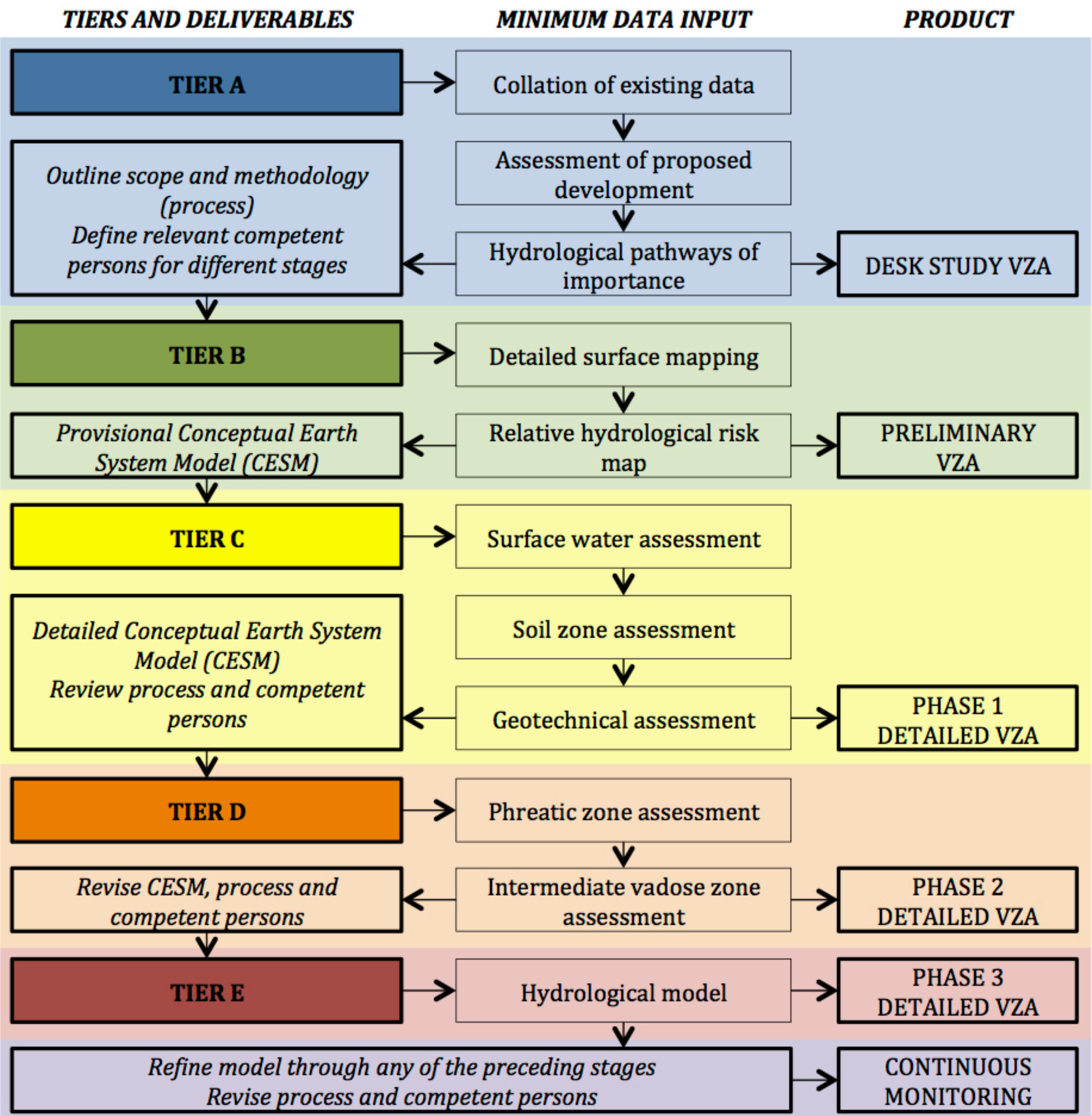

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Table 6-1. Minimum input requirements (where applicable) for a tiered Vadose Zone Protocol.

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

6.2. Contributions to the Understanding of Multi-disciplinary Vadose Zone Hydrology

The thesis elaborates on a number of aspects pertaining to vadose zone hydrology and is applied to relevant case studies in South Africa where protection of water resources, urban development and densification, and social responsibilities are key. These include incorporation of case studies related to ephemeral inland wetlands in urban areas and peri-urban cemeteries, as well as applications associated with groundwater vulnerability and water impacts on infrastructure.

Improved investigation and cognisance of data generated through other disciplines' efforts will significantly contribute to the understanding of the unsaturated system under investigation. Improved guidelines for cemetery investigations and distinct incorporation of interflow and unsaturated flow in the delineation of ephemeral wetlands are required for safer development and environmental protection. Similarly, understanding the effects of impacts on urban water budgets will reduce damage to infrastructure, prevent deterioration of aquatic ecosystems and improve the land use planning process.

Regarding cross-disciplinary dialogue and multi-disciplinary interaction, the need for better communication between technical disciplines is highlighted. Although it is believed that each individual specialisation has its own importance and should not be integrated, improved understanding of other disciplines will be beneficial to the promotion of vadose zone hydrology. It is for this reason that terminologies and methods have been outlined clearly.

Methods have been evaluated, and include bulk of presently utilised empirical, laboratory and in situ methods with additional mention of physical and numerical modelling approaches. Improved results are associated with increased effort and cost, and subsequently the choice of method will be dependent on the anticipated risks inherent to the investigation and/ or proposed development. Additionally, methods can be used between various earth scientific disciplines to the benefit of all and has the ability to become independent of the purpose of investigation. Subsequently, data gathered via a given method can be employed for a wide range of applications, including (but not limited to) those incorporated as case studies.

Presently, distinct vadose zone hydrological assessments are based on client needs and do not form a vital minimum requirement in environmental studies for any purpose. The proposed vadose zone assessment protocol aims to highlight the need for such investigations and to urge developers, engineers, managers and other scientists to include this at early stages already. This protocol allows for the contributions of various earth scientists while promoting data sharing and better cross-disciplinary understanding of findings.

Although the emphasis was placed on contributing to a multi-disciplinary audience related to vadose zone hydrology, certain aspects are still lacking. These include, for instance, the importance of proper input data for numerical models; adequate understanding of the constraints of physical models such as used in geotechnical centrifuges; effects of evapotranspiration; unsaturated flow through fractured vadose zone; etc. It is hoped that the findings of this thesis will promote enquiry into some of these aspects.

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