South African Hydrostratigraphy: A conceptual framework

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Abstract

South African geology, geomorphology and climate are distinctly variable, resulting in a complex hydrological cycle superimposed on equally complex ground conditions. With fractured and karstic systems dominating the hydrogeology, thick vadose zones comprising soil and rock and at highly variable moisture conditions contribute to complex hydrostratigraphic systems comprising various confining and hydraulically connected units. This paper proposed standard terminology for basic concepts pertaining to the description of ground and water in the subsurface to eventually propose a hydrostratigraphic classification based on abiotic factors fairly constant over short periods of time (geology, geomorphology and climate), as well as those temporally highly variable (climate) and those introduced by human involvement (society). Ten major hydrostratigraphic units are eventually described, namely the Cape Fold Belt, Kalahari Desert, Witwatersrand Supergroup, Malmani Subgroup, Cenozoic Coastal Deposits, Saldanian Basement, Karoo Main Basin, Namaqua-Natal Metamorphics, Waterberg Group, and Archaean Granitoids.

Introduction

Hydrostratigraphy

Hydrostratigraphy is the classification of the subsurface into distinct hydrogeological units, each with defined areal extent, thickness and hydraulic parameters (Poehls & Smith, 2009, p.188). The hydrostratigraphic units may or may not overlap with geological stratigraphic units, such as formations and groups, and one hydrostratigraphic unit may include multiple geological units, and vice versa (Al-Aswad and Al-Bassam, 1997). For example, a generally arenaceous formation with extensive argillaceous beds may be classified into several aquifers, whereas multiple formations consisting of impermeable rock types may all be grouped into one mega-aquitard.

Generation of a credible hydrostratigraphic model requires a large amount of effort, including lithostratigraphic analysis, borehole logging, hydraulic testing and porosity calculation (Runkel et al, 2006), or construction of 3D models with ground truthing and iterative validation (Passadore et al, 2012). Thus, the information required to perform a hydrostratigraphic classification is not only the hydraulic parameters (e.g. K and S values) and hydrogeological nature of the rocks (e.g. porosity type, fracture distribution and orientations), but also the connectivity with other aquifers (Chesnaux et al, 2012).

Hydrostratigraphic classifications are not common and, although some ambitious attempts have been made, for example across the whole of Nigeria (Akujieze et al, 2002), usually they are limited to regional or local areas with well-defined geology and abundant data, such as for north-eastern Wisconsin

(Muldoon et al, 2001), the Salento Peninsula of Italy (Giudici et al, 2012) or the Upper Awash River basin in Ethiopia (Yitbarek et al, 2012).

A comprehensive aquifer classification system designed for implementation on maps was developed by Payne and Woessner (2010). They employed a 4-point system:

- aquifer flow class potential;
- geological setting;
- groundwater quality, and
- depth to groundwater and connection with surface water resources.

Each of these parameters had a grading system, requiring inputs from geological maps, hydraulic tests, water quality analyses and a host of other sources. The system is rigorous and has great potential in well studied areas, but suffers from a need for much input data and the difficulty of comparison when environments are different.

Given that South Africa has a wide range of environments and a shortage of data, especially published results, the hydrogeological profession has a great challenge to implement any hydrostratigraphic classification countrywide. This paper aims to provide the terminology and the means to using that terminology for the description of hydrogeological units, such that a more consistent approach is adopted by hydrogeologists. In the case of unquantified parameters, such as transmissivity, more fundamental information can be used as a proxy, such as rock type, stratigraphic thickness and water table depth. This is not to reduce the need for rigorous testing, but rather to encourage ways of filling data gaps. Fuller description of the hydrogeological environment will enable easier comparison between different studies and environments, and ultimately the development of a hydrostratigraphy for the region.

The South African challenge

Readers of this journal will likely be familiar with the spectacular geology of the country, but quick mention will be made to emphasize the point. In addition, the geomorphology and climate are also very diverse, as are the biological and cultural (although these are largely beyond the scope of this paper).

South Africa has a stratigraphic record spanning over 3.5Ga, including world class examples of Archaean granite-greenstones (Barberton), Archaean volcano-sedimentary sequences (Witwatersrand, Ventersdorp and Transvaal), Proterozoic metamorphic belts (Namaqua-Natal), the world's largest layered igneous complex (Bushveld), the Pan-African orogen (Gariep, Malmesbury, Kango and other Saldanian units), a Permo-Triassic fold belt (Cape), a Phanerozoic continental foreland basin (Karoo), a continental flood basalt (Drakensberg), and extensive inland (Kalahari) and coastal (Uitenhage, Zululand, West Coast, etc) Mesozoic to Cenozoic deposits. The landscape ranges from sea level to 3 500 m elevation, with minor coastal plains and vast inland plains, fold mountains, the Southern-African Great Escarpment, canyons, inselbergs and other landforms. The climate ranges from Mediterranean in the far south-western region around Cape Town, with rainfall in winter, including snow on the mountains, through cool to hot sub-tropical to tropical, with seasonal monsoon style thunderstorms, to desert in the far west. Perennial advective rainfall occurs from the south coast, up the east coast, and along the eastern and north-eastern sections of the Great Escarpment. Annual rainfall ranges from zero often in the deserts of the north-west to over 3 m in the Cape Mountains. Temperatures range from winter minimums below -5°C at high elevations to summer maximums exceeding 40°C.

The geology, geomorphology, climate and vegetation have influenced human development, resulting in quite different distributions of people and economic activities. Mining is largely confined to the central and northern regions of the country; forestry is mainly in the east; agriculture is throughout the country, but tends to be rangelands in the central and north-west, rainfed crops in the east and south, and irrigated farmlands along large, perennial rivers. People are clustered in cities along the coast from the south-west to the east, and in the central mining and agricultural regions. Interestingly, the population density is highest in the north-eastern to central portion of the country in Gauteng due to establishment of communities along the dolomite springs in what is now Pretoria, and the later discovery of gold in the Witwatersrand area to the south.

Concepts and context

Ground

Ground is used to imply all solid materials below the surface of the earth, and incorporates soil, rock, and – more recently – the entire suite of manmade materials (collectively called made ground, anthropogenic ground, or fill).

Rock is formed through igneous (plutonic, intrusive or volcanic), sedimentary (precipitation or cementation) or metamorphic processes, and can be found in various states from totally fresh to totally weathered. Bedrock or fresh rock is that which has negligible weathered material, usually only found along discontinuities (joints, faults and bedding planes) that act as conduits for groundwater flow. Saprock is slightly weathered rock where original minerals occur side by side with minerals that have weathered into new phases (usually clays or oxides). Saprolite is highly weathered rock where little of the original mineralogy remains (usually only the oxides and quartz), but the texture of the rock is largely unchanged - original mineral outlines are still evident. Through in-situ and altered stress conditions, resulting in brittle or ductile deformation, the properties of rock are altered with significant implications on its hydraulic behaviour.

Soil can include transported and residual material, as well as any pedogenic materials, but often has a requirement for the presence of organic activity or materials (roots, burrows and decaying plant or animal remains). Thus soil is part of the biosphere. Pore space is mostly governed by primary or interstitial porosity and with 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 (e.g. Blatt and Tracy 1997; Schaetzl and Anderson

2005). The definition is somewhat tweaked depending on applications, with engineering professions generally considering soil as uncemented to weakly cemented minerals, excavatable without blasting, or that disintegrates in water, or that can be manipulated for construction (e.g. Knappett and Craig 2012), roughly implying a uniaxial compressive strength of 1 MPa or less.

Soil profiles represent a characteristic, commonly occurring sequence of materials and are typically described in terms of soil horizons. The subdivision of a profile into horizons depends on the profiling approach employed. Soil scientists, for instance, will consider horizons to represent materials subjected to the same processes, whereas engineers and geologists subdivide the profile based on origin as this defines its mechanical and mineralogical properties.

Regolith is all the material between fresh rock and the surface of the earth, and is a useful term when confronted with an unclear separation of soil and saprolite, or transported and residual material.

Void space geometry

Void space geometry is often simplified to fit into empirical equations or simplifications of complex mathematical approaches. This commonly results in black box approaches where a single parameter is determined for the bulk volume under the assumption that the average value is accurate enough. The particle size representing the 10th percentile of the cumulative grain size distribution (d_{10}-value) does just this to infer hydraulic behaviour of soils using empirical approaches such as Hazen, Kozeny-Carman etc., and similarly the fracture aperture (e) overrides all fracture geometry and persistence issues, simplifying it to a set of smooth parallel plates, when applying the cubic law. Beyond this, we assume certain spatial extents, degrees of saturation, temperatures and barometric pressures, soluble salt contents, and other idealized conditions. Prior to employing such empirical simplifications, it remains important to understand the limitations and assumptions of the relevant methods.

Certain parameters are fixed requirements, as a lot can be inferred from accurate basic data instead of estimating complex parameters.

Particle size distribution

Soil grading, particle size distribution, or sometimes referred to as gradation, describes the percentage abundance of particle sizes. Grading and subsequently the sizes and shapes of the individual grains dictate the pore space present in a medium. The term well graded (or poorly sorted) is used to imply a wide range of particle sizes, where a sufficient fraction of fines is available to clog pores generated by the coarser fraction, typically resulting in reduced porosity. The converse is true for poorly graded (well sorted) material where a fairly uniform particle size limits the amount of clogging that can occur in pore spaces. The uniformity coefficient (C_U), as the d_{60}:d_{10} ratio, is commonly used as index parameter.

Porosity and void ratio

The porosity (η) is determined as the ratio of void volume to total volume (V_V:V_T) in an undisturbed sample, regardless of the fluid occupying the void space. This can also be estimated by relating the bulk dry density (ρ_D) to the density of the individual solid minerals weighted by abundance (ρ_S). To account for possible volume change under consolidation, the void ratio is often used, relating the volume of voids to the volume of solids (Equation 1).

$$\eta = \frac{V_V}{V_T} = 1 - \frac{\rho_D}{\rho_S}; e = \frac{V_V}{V_S} = \frac{\eta}{1-\eta} \qquad (1)$$

Porosity is governed by particle size distribution, packing, size, shape, and later influences as shown in Figure 1(a). Elaboration is shown in Figure 1(b) where the packing defines the ratio of void spaces to total volume with rhombohedral packing being less porous than cubic packing. Figure 1(c) shows how the porosity can remain unchanged, but, due to smaller pore space openings and connection throats, hydraulic conductivity can be substantially lower. These confirm that void connectivity and pore size and shape govern hydraulic conductivity as much as actual porosity, and that denser packing will result in lower porosities typically associated with lower hydraulic conductivities as well.

In order to accurately assess a given property (porosity in this instance), the volume under consideration needs to be representative (Figure 2). At some very small volume of investigation, porosity is either one (only voids) or zero (only mineral). Increasing this volume will result in including more of the other medium (solid or void), causing the porosity to fluctuate until it establishes a fixed value under a representative volume of investigation, known as the representative elementary volume (REV). Increasing the volume of observation yet further will cause the values to change again, either increasing or decreasing, due to macroscopic heterogeneity induced by, for instance, geological structures or contacts.

In the instance of rock, it becomes imperative to define the types of porosity:

- Primary, intergranular or interstitial porosity refers to those openings between individual mineral grains of sediment or crystallised or lithified in rock;
- Secondary or fracture porosity refers mainly to structural discontinuities or defects induced mostly in rock due to tectonism, such as joints, faults and shear zones, but also including bedding planes;
- Tertiary or karstic porosity refers mainly to weathering and total removal by means of dissolution, resulting in large void spaces or cavities.

For rock, primary porosity can occur with secondary porosity if rock is fractured, and tertiary porosity if the rock is soluble. Double porosity systems are common, and one type of porosity is typically responsible for water storage whereas the other improves transmissivity.

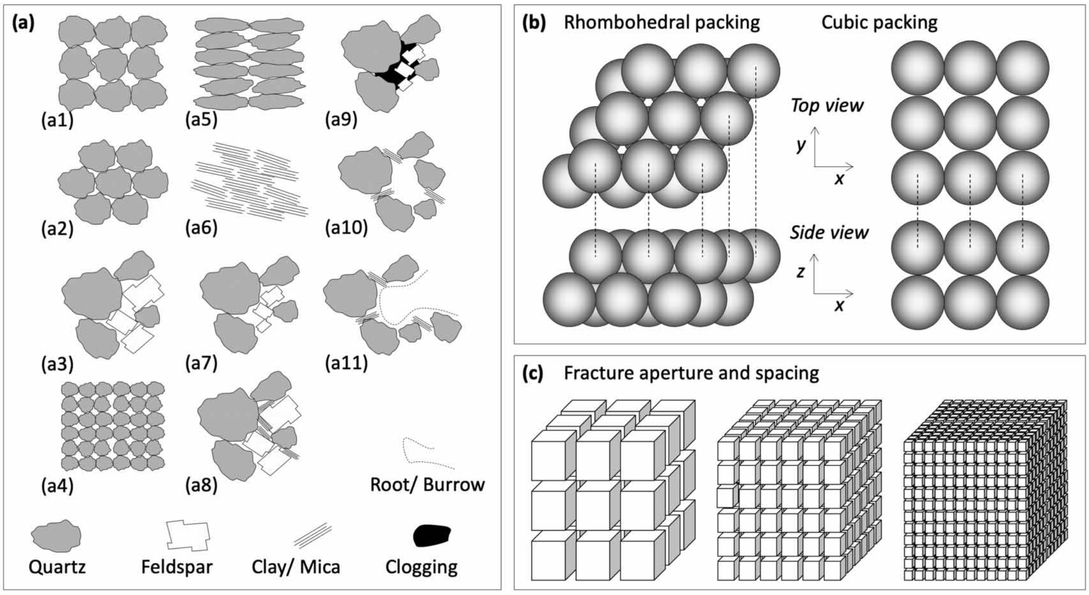

Figure 1. *Influences on primary (intergranular; interstitial) porosity:* ***(a)*** *(1) cubic packing of fairly uniform near-spherical grains, (2) tetrahedral or rhombohedral packing of fairly uniform near-spherical grains, (3) random packing of fairly uniform grains of variable shape, (4) cubic packing of fairly uniform near-spherical grains of finer texture, (5) elongated grains, (6) elongated clay platelets or micas, (7), coarse quartz and finer feldspar in a randomly packed mixed texture material, (8 varying grain size, grain shape and random densest packing, (9) clogging of pores by precipitates or fines, (10) open collapsible structure due to leaching of fines, (11) open structure due to animal burrows or plant roots. (Dippenaar 2012;2014; Dippenaar et al. 2014).*

Fractures

A fracture, often used synonymously with or used to imply defect, discontinuity or fissure, is described in the field by means of the descriptors depicted in Figure 3a. The mechanical aperture (e_m), as described in rock mechanics or structural geology, is affected by roughness infill to a smaller effective or hydraulic aperture (e_h) where the permeability of the fracture is reduced (Figure 3b).

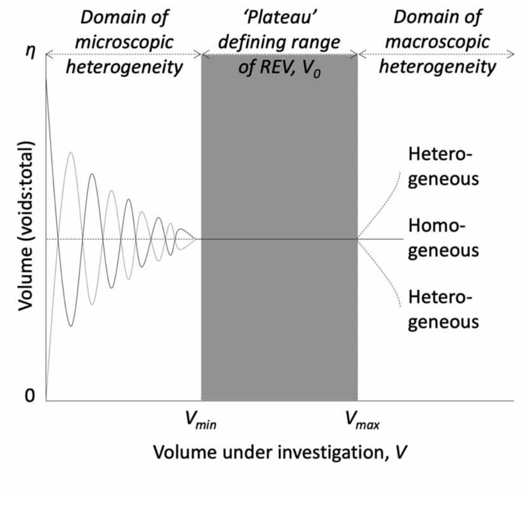

Figure 2. *The REV (representative elementary volume) concept (e.g. Bear 2007).*

The REV for fractured systems can vary. As shown in Figure 4, at some small scale, the matrix alone or the individual fracture governs the hydraulic properties, while at some large scale, a fracture network exists that again behaves like a porous medium. This is significant where different models need to be applied for different scenarios.

Water

Distribution and movement of water

The distribution of water and the associated hydrological connections are shown schematically in Figure 5. In this context, the following definitions apply (from Dippenaar et al. 2014 after Driscoll 1989; Fetter 1994; Fitts 2002; Todd and Mays 2005; Younger 2005):

- Subsurface water is divided into either water chemically bound to rocks and minerals, or interstitial water. The abundance of the latter determines the location of the vadose and phreatic zones. Interstitial water includes that found in dead-end pore spaces.
- The vadose zone (also the unsaturated zone or zone of aeration) occurs between the land surface and the phreatic surface and includes the soil zone and intermediate vadose zone. The intermediate vadose zone is commonly taken as below the zero flux plane, which is the point beyond which no upward movement of moisture occurs by means of evapotranspiration.
- The capillary fringe represents the boundary (a zone of

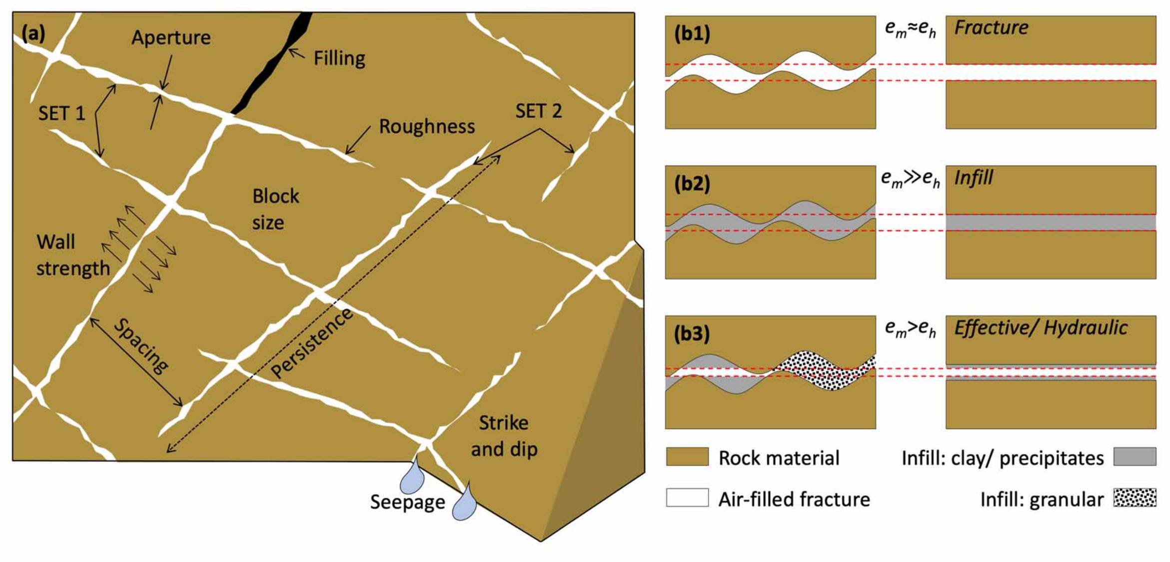

***Figure 3.** (**a**) Terms for the description of a fractured rock system (Gonzalez de Vallejo and Ferrer 2010), and (**b**) the influence of roughness and infill on mechanical (e_m) and hydraulic (e_h) aperture (Dippenaar and Van Rooy, 2016).*

transition) between the vadose and phreatic zones where the medium is saturated but at negative pore water pressures.

- The water table (or phreatic surface) is the boundary (a sharp line) between the phreatic and vadose zones where the pore water pressure equals atmospheric. It manifests as the water level in a well (indicated by the inverted triangle in cross-sections) and is an accurate marker of the transition from vadose to phreatic zones.
- The phreatic zone is also referred to as the saturated zone where pore water pressures are positive, and pores are water-saturated.

Water moves between the land surface and the subsurface through a series of processes (from Dippenaar et al. 2014 after Driscoll 1989; Fetter 1994; Fitts 2002; Todd and Mays 2005; Younger 2005). Infiltration is that first entry of water into the subsurface from the surface. The porosity of the surficial soil creates openings for water entry, but evaporation and transpiration can still affect water in this shallow zone. From here, water generally moves sub-vertically downwards under the influences of gravity or disperses three-dimensionally under the influence of capillary action. Infiltration becomes percolation (or potential recharge) where water migrates sub-vertically downwards within the unsaturated zone in near-saturated conditions under the influence of gravity. Seepage or flow is significantly less influenced by evapotranspiration processes and capillary processes. Interflow refers to water migrating laterally and to either discharge as a seep or to begin percolating at another point further down. 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. Various reasons exist for the development of interflow systems, including perching and basal confinement. Recharge refers specifically to water eventually breaching the water table and entering the phreatic zone.

Aquifer properties

Subsurface hydraulics is based on Bernoulli's equation (as derived by Euler based on Bernoulli's principle relating pressure and flow velocities) and Darcy's Law (the latter simplified from the Navier-Stokes equation and analogous to most other first order rate laws such as Fick's Law for diffusion or Newton's Law of viscosity). Equation 2 shows Darcy's Law, calculable from the hydraulic conductivity (K, discussed later), hydraulic gradient (dh/dl) and cross-sectional throughflow area (A). With the required simplifications, water levels are measured and converted to heads, which in the end become very important to determine hydraulic gradients, pressure heads, and confinement of aquifers (Figure 6).

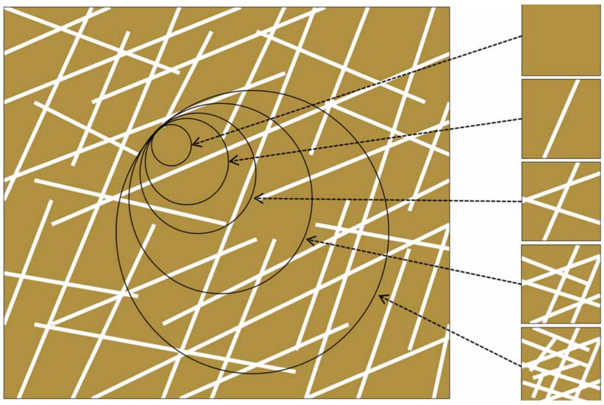

***Figure 4.** Influence of scale of consideration on the influence of the fractures on the system.*

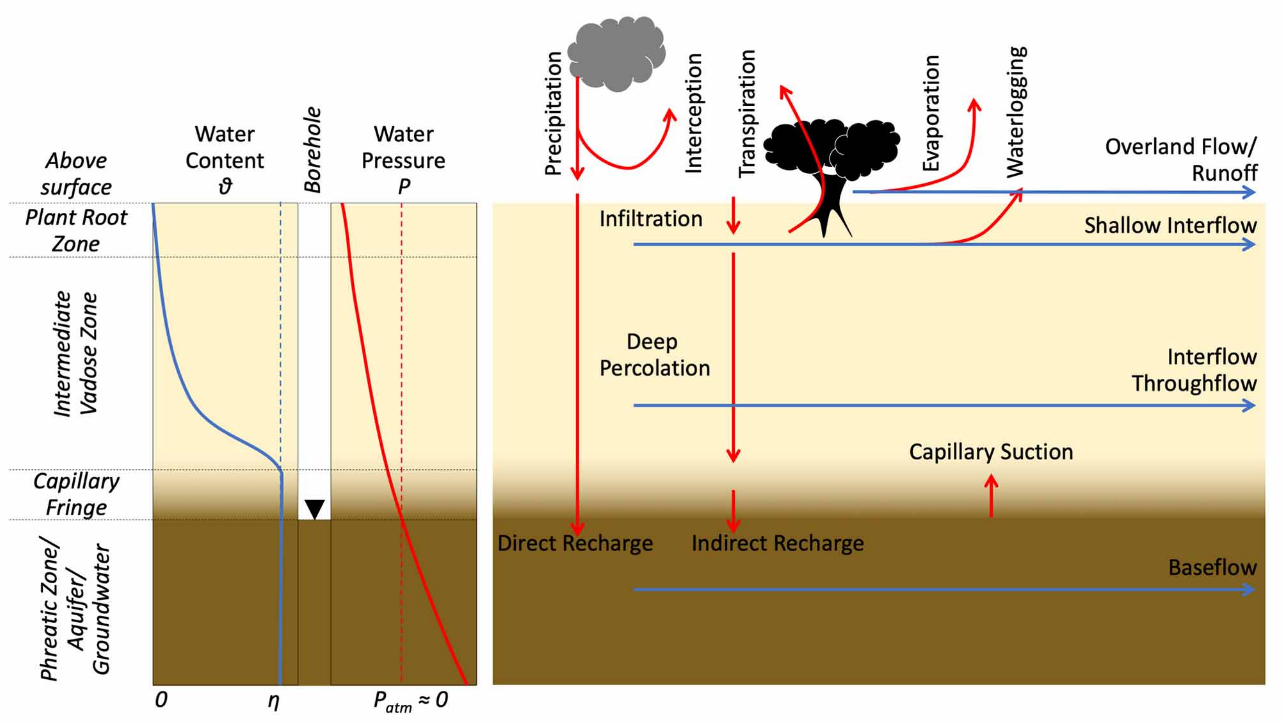

Figure 5. *The hydrological cycle and the distribution of water in the Earth's crust (adapted from Dippenaar et al. 2014;2019, after Driscoll 1989; Fetter 1994; Fitts 2002; Todd and Mays 2005; Younger 2005).*

$$Q = K\frac{dh}{dl}A \qquad (2)$$

The static water level (SWL) is measured from land surface downward to the water level during conditions in which recent changes (pumping, sudden recharge) have not taken place.

The hydraulic head (h) represents the total mechanical energy per unit weight of water as per Bernoulli's equation. With the units of length (e.g. metres), it is measured vertically upward from some datum level to the water level. The hydraulic heads of different monitoring points, such as boreholes, are required to determine the hydraulic gradient. The hydraulic gradient is the degree and direction of slope of the hydraulic head and determines the rate (along with permeability) and direction of groundwater flow.

Unconfined aquifers are open to the atmosphere and have a distinct water table where pore water pressure equals atmospheric pressure. Water levels as measured in boreholes closely resemble actual water tables in the aquifer. Being in direct contact with the atmosphere, contaminants can enter the phreatic zone fairly easy given the absence of confining layers. Confined aquifers, on the other hand, have a low permeability aquiclude above the aquifer. Water is therefore often at significantly higher pressures, and water levels measured in boreholes resemble the potentiometric surface and are higher than the top of the saturated zone. Occasionally, as indicated, boreholes may become free-flowing at the ground surface, known as artesian. The confining layers here protect the aquifer from the entry of contaminants. A perched aquifer is one that exists above a zone of unsaturated material. This is made possible by a layer of low permeability forcing local ponding and saturation. The evidence for perching is the existence of two water tables in one location: the upper, perched one, and the lower, regional water table.

Hydrogeologists are involved in acquiring sustainable sources of groundwater for certain purposes. From a hydrostratigraphic point-of-view, the search for an aquifer includes aspects such as a suitable vadose zone to allow for recharge while also protecting the groundwater quality, and appropriate confining layers to allow for the storage and underground damming of water. The properties of the aquifer itself may be enhanced by secondary (tectonic and neotectonic) to tertiary (weathering and geomorphological) processes.

An aquifer is classically defined as:

- "… a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells. The intrinsic permeability of aquifers would range from about 10^{-2} darcy (1 darcy ≅ 1 cm^3/s) upward" (Fetter, 1994);
- "… a permeable region or layer in the saturated zone" (Fitts, 2002);
- "… a saturated permeable geologic unit that can carry water under ordinary hydraulic gradients" (Freeze and Cherry, 1979);
- "… beds of rock with high porosity that are capable of holding large quantities of water" (Shaw, 1994).

The porosity, void size and connectivity of porosity dictate the ability of a medium to transmit fluids. Certain media may be more prone to storing rather than transmitting water (e.g. clays with large porosities but low hydraulic conductivities), whereas others may have both high storage and transmissivity (e.g. unconsolidated sands or highly fractured rock). Probably the most fundamental hydraulic parameters relate to the ability of fluids to move through geological media. These are termed the hydraulic conductivity (K), intrinsic permeability (k) and transmissivity (T), calculated as a function of water's density (ρ_W), dynamic viscosity (μ_W), gravitational acceleration (g) and saturated aquifer thickness (b) as shown in Equation 3.

$$K = \frac{k\rho_W g}{\mu_W} = \frac{T}{b} \tag{3}$$

Aquifers transfer water through having high transmissivity (related to permeability) and high storage (related to porosity), whereas aquitards retard the movement of water even though often storing large volumes of water. Aquicludes very nearly exclude or prevent the movement of water through having low transmissivity and storage. Aquitards and aquicludes generally basally confine aquifers to allow the build-up of saturation and to get pore water pressures to fall within the definition of the phreatic zone. There is therefore interaction between different lithostratigraphic units which defines the hydrostratigraphical system.

Hydraulic behaviour

The hydraulic behavior of earth materials is typically described in terms of:

- Lithology (rock type; bedrock, saprolite, sediment or soil; dip, strike, faulting; jointing);
- Porosity (primary, secondary, tertiary);
- Hydrogeological function (aquifer, aquitard, aquiclude);
- Confinement (unconfined, semi-confined, confined);
- Saturation (seasonal or episodic waterlogging; phreatic; vadose; dry).

In this context, not all media are aquifers, even if wet, and some media with very high transmissivity and storage may be dry.

As soil profiles develop, some horizons are leached while other serve as zones of concentration. The residuum (residual horizon) is one of the horizons prone to densification as the abundance of secondary clay minerals increases (due to weathering of the original minerals), and collapses into a denser packing under hydrodynamic consolidation (water flow causing rearrangement of particles) or overburden stresses (e.g. Hencher 2012). This causes the primary permeability and porosity to both be lower in this horizon (Figure 7). The behaviour of a given material may also be influenced by materials nearby. A certain medium may be saturated or unsaturated simply based on how other materials confine, cause ponding or supply water to that medium.

Different flow scenarios occur in the subsurface, any or all of which may contribute to flow in a given setting. Some of the more common scenarios include (Figure 8; Dippenaar and Van Rooy 2019):

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

Understanding the complexity of ground conditions under variable moisture and flow conditions is imperative in understanding the hydrological behaviour of a hydrostratigraphic unit.

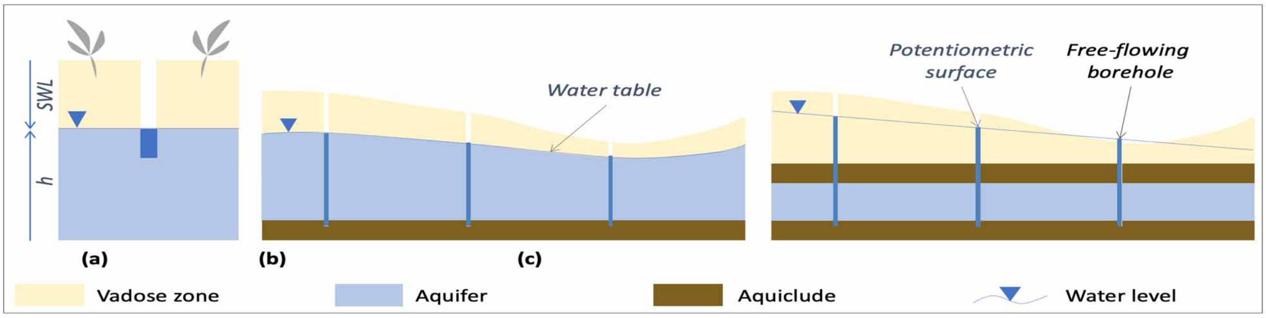

Figure 6. *(**a**) Hydraulic heads (h) as a function of static water level (SWL), and (**b**) the water table in unconfined aquifers compared to (**c**) the piezometric surface in confined aquifers.*

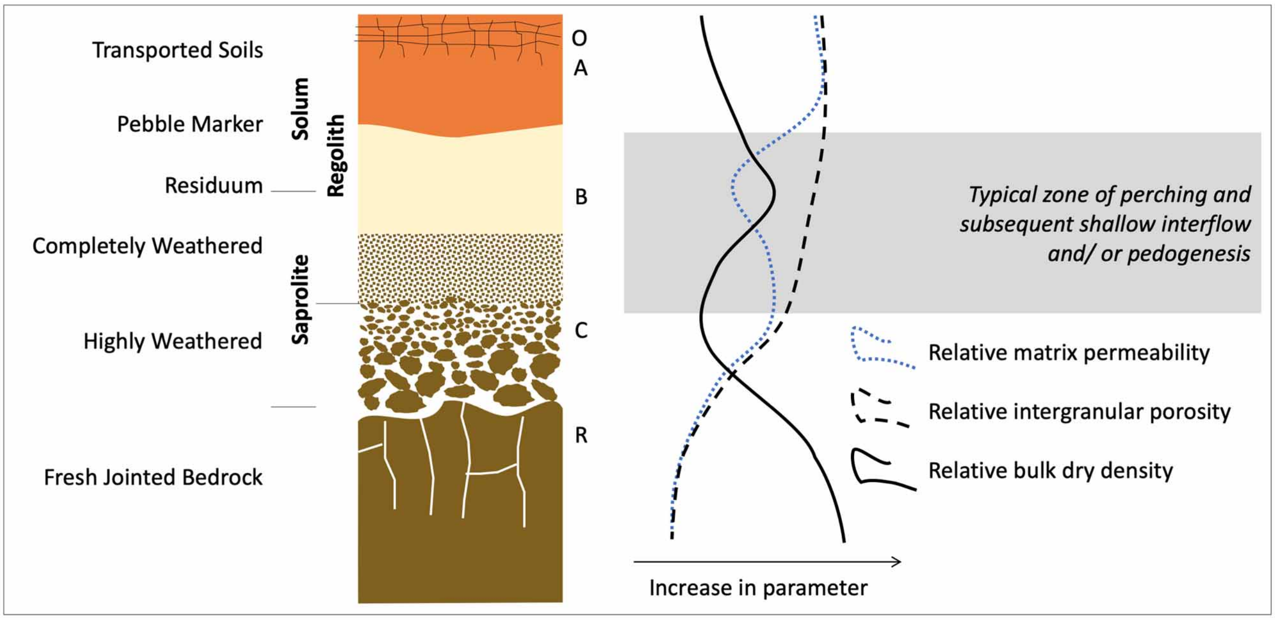

Figure 7. *Typical permeability, porosity and dry density of different soil horizons (adapted after Dippenaar and Van Rooy 2014; Foster 1984, 201; Hillel 2003; Koita et al. 2013; Hencher 2012).*

South African hydrostratigraphy

South African examples

Hydrogeological studies around South Africa include a wide variety of topics and approaches. Some studies are more theoretical, relying on basic geological, climatic and land use information to make predictions about aquifer use potential or vulnerability (Gomo and Vermeulen, 2017). Others use widespread basic data, such as rainfall and water levels, in a more numerical fashion to quantify a single parameter, such as recharge response to rainfall (Ndlovu and Demlie, 2018). Another regional study, using government monitoring datasets, attempted to apportion hydrochemical characteristics to natural or anthropogenic sources (Masindi and Abiye, 2018).

These broad, regional studies are contrasted with those that focus on smaller geographical areas and can therefore afford to incorporate more accurate and complex hydrostratigraphic information into the interpretation (Cobbing, 2017; Parsons, 2009). Additionally, these smaller studies often make use of freshly acquired data (Miller et al, 2017), rather than existing or generic data. Some of these more focused studies still limit the data to one or a few parameters, such as groundwater quality (Odiyo and Makungo, 2012). Others do attempt to integrate several aspects of hydrogeology and hydrology for a broader audience (e.g. Dippenaar and Van Rooy 2014; Dippenaar et al. 2019).

For example, Lin and Lin (2019) applied a numerical model to a small volume of the Table Mountain Group, a fractured quartzite aquifer system, in the Rawsonville area, Western Cape, to model drawdowns and attempt to generate a sustainable yield from the system. Generation of the conceptual model required input on surface water-groundwater interaction, aquifer geometry and hydraulic parameters, calculated from pumping tests. Work at this location has been ongoing for many years, in order to create an adequate understanding of the hydrogeology. A very different approach to also producing a sustainable yield estimate was undertaken by Cobbing (2017), who used water levels, rainfall and the geological setting at the Grootfontein aquifer in the dolomites near Mahikeng, North West Province. In spite of attempting to determine the same parameter, these

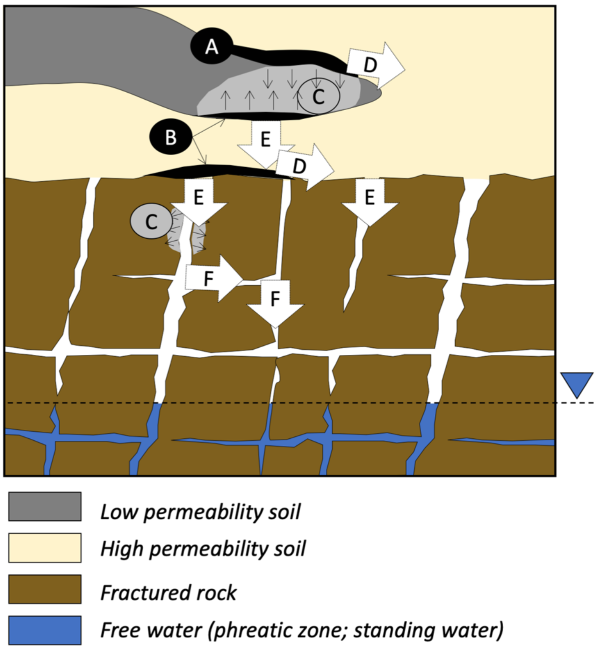

Figure 8. *Proposed partially saturated flow scenarios across a soil-rock interface and the implications of anthropogenic disruption on apportioning the source of the seepage (Dippenaar and Van Rooy 2019.*

two studies used very different methods, in part because the availability of data was very different, but also because the hydrogeological settings were different.

Scaling issues

Water and solute budgets are an important part of any hydrogeological investigation and depends on a detailed understanding of groundwater fluxes across interfaces along a continuum of temporal and spatial scales (National Research Council, 2004). In heterogeneous and anisotropic systems, like most fractured aquifers, there will be a variability of flux values across scales and hydrostratigraphic interfaces owing to the difference in hydraulic parameters and the hydrodynamic processes dominant within the area of influence. Understanding the behaviour of these systems at different scales are important for judicious management of the systems, and it is therefore also important to understand the interplay between different hydrostratigraphic units at a variety of scales.

Scaling can often refer to scale invariance where processes behave similarly at small and large scales, and when upscaling or downscaling data (Blöschl, 2001). The use of statistical approximations such as REVs are at best trying to simplify complex systems and non-linearities. This might hold for catchment-wide management but poorly represent localised wellfield conditions. Similarly, point measurements are poor approximations for larger scale parameterisation. A lack of data at the appropriate scales results in adaptation and adoption of observations at other scales (Gentine, 2012).

New scaling laws should be developed to improve models and decision-making. There is a distinct lack of scaling in groundwater hydrology and most literature works from a conceptual framework that rarely applies at the very local level.

Hydrostratigraphic knowledge framework

Hydrogeological studies should be conducted in such a way that whatever their data input and methods, the conclusions should be able to feed into a unified understanding of hydrogeology, thereby allowing hydrostratigraphic classification of the aquifers or region concerned, and comparison with other studies and areas. It is not expected that any study will ever incorporate all forms of data and information to create a perfect and final hydrostratigraphic outcome, but rather, all studies should be aware of how they fit into the overall scheme of hydrostratigraphic knowledge.

Figure 9 is a proposed hydrostratigraphic knowledge framework, showing some of the major knowledge areas needed to understand the hydrogeology of an area. The lower three segments are relatively unchanging over human timescales and can be thought of as the conceptual earth system. The upper two segments are temporally variable and include natural and anthropogenic factors that are subject to change. The most basic or fundamental information resides on the outside of the pentagon and influences that closer to the middle. Solid arrows

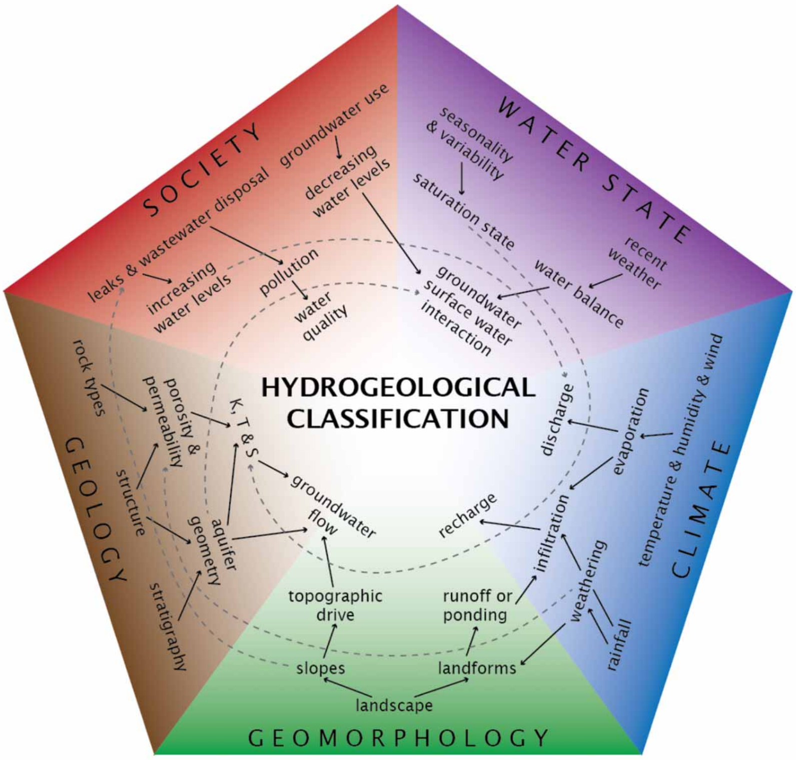

Figure 9. *Proposed hydrostratigraphic knowledge framework, showing the progression from fundamental properties around the periphery, towards more specific parameters, steadily allowing better hydrostratigraphic classification. The three lower segments are the conceptual earth system, being relatively unchanging on a human timescale, whereas the upper two segments are the temporally variable factors, both natural and anthropogenic.*

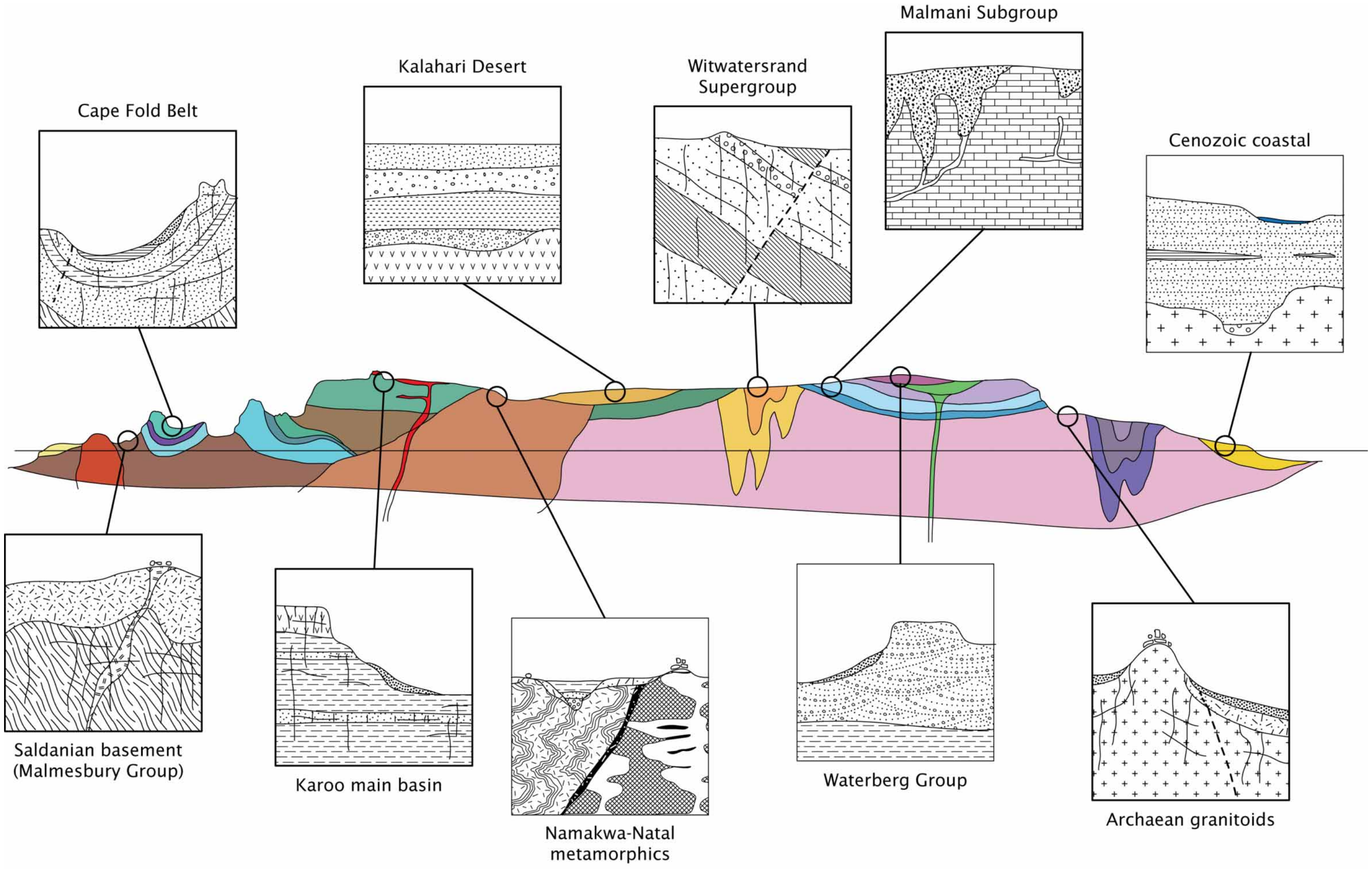

Figure 10. Hydrogeological properties of significant South African lithostratigraphic sequences.

indicate the stronger of these dependencies, but are not to be taken as the only connections. For the sake of clarity and aesthetic in the diagram, the number of arrows was limited. The dashed arrows show some examples of more distal dependencies; ones that can cross boundaries. These were also limited for the sake of visual clarity. The exact terms and arrows should all be seen as somewhat indicative and suggestive rather than absolute, although a serious attempt was made to create a thorough and logical depiction.

The diversity of hydrogeological settings in South Africa creates a demanding environment to implement a single hydrostratigraphic classification. Even within one major aquifer system, the range of studies and information possible is tremendous, as amply illustrated by the 35 articles, by a variety of authors, in a single volume on the Table Mountain Group (Pietersen and Parsons, 2002). Such abundant work, however, has created a platform where realistic hydrostratigraphic classification is possible, as seen in Blake et al (2010). Countrywide integration and comparison, however, remains a more distant goal. To accelerate this and provide some sense of the challenge and opportunity, a schematic of the major aquifer types and settings has been made (Figure 10). In this simplified, schematic cross-section for the country are inserted ten hydrogeological settings that typify some of the major stratigraphic units. Each of these ten settings is described in Table 1, in a very general way, using some of the more important parameters from the hydrogeological knowledge framework in Figure 9. Figure 11 provides a legend for the stratigraphy seen in the cross-section, and Figure 12 supplied photographic examples of some typical settings covered in this paper.

Conclusions and recommendations

Hydrostratigraphy is not a well-developed branch of hydrogeology, perhaps because of the complexity inherent in the science of groundwater and the tendency to oversimplify the role of the vadose zone. Studies worldwide (including those in South Africa) mostly focus on small geographic areas or a small set of variables over larger geographic areas. Even then, developing a hydrostratigraphic nomenclature requires effort usually well beyond that of single studies, small groups of authors or a limited set of techniques.

Correct and consistent use of terminology is essential to allow comparison between studies, which is a prerequisite for integration of results and ultimately development of a hydrostratigraphic classification. Use of fundamental parameters to estimate or calculate hydrogeological terms is often necessary, creating uncertainty in the accuracy of the results. Furthermore, context is critical, being the appreciation that data may not be representative or may be outdated. This is particularly relevant when using point source information (borehole data), old national datasets, or aggregated values.

A hydrostratigraphic knowledge framework has been proposed to allow authors to see how their work slots in, and to encourage more consistent description of hydrogeological results. It will also be useful to determine the areas of knowledge that a study did not cover and so direct future work

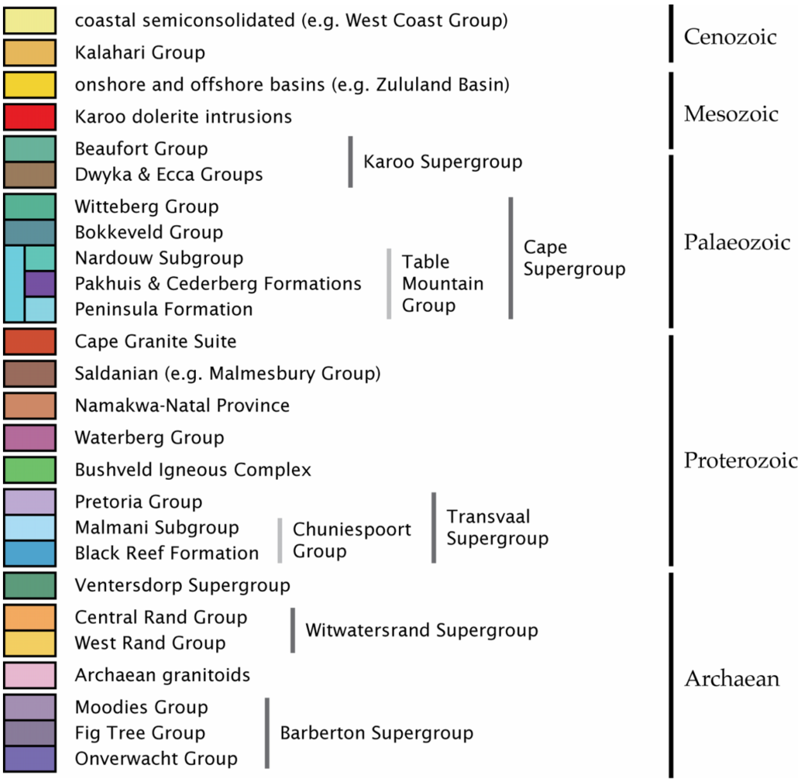

Figure 11. *Legend for Figure 11, also being a simplified and incomplete stratigraphy of South Africa.*

Table 1. Hydrogeological properties of significant South African lithostratigraphic sequences.

Hydrostrat Area	***Rock types***	***Climate***	***Landscapes***	***Porosity***	***Aquifers***	***Recharge***	***Borehole yield***	***System yield***	***Sustainability issues***	***Water quality***
Coastal	unconsolidated sediments and calcarenite	perennial rain	hilly to flat	primary	sand, gravel	regular	high	mod.	groundwater surface water interaction	rural and agricultural impacts
Kalahari	unconsolidated sediments, sandy at surface	semi-arid, summer rain	very flat with sand dunes	primary	sand, gravel	episodic	high	low	groundwater dependant towns and farms, low recharge	natural salinity and NO_3
Karoo	sandstone, siltstone, mudstone, dolerite	semi-arid, summer rain	steep rocky hills and plains	secondary	fractured sandstone	episodic	mod.	low	groundwater dependent towns and farms, low recharge	agricultural, high U
Cape Fold Belt	quartzite with minor siltstone, conglomerate, tillite	Mediterranean, winter rain	steeply mountainous	secondary	fractured quartzite	annual	high	high	baseflow to springs and rivers from TMG	low TDS, naturally acidic
Saldanian Basement	metasediments: shale, phyllite, hornfels; Metavolcanics	Mediterranean to semi-arid, winter rain	hilly	mixed	saprolite, fractures, veins	irregular	mod.	low	groundwater dependent wetlands, low recharge	minor salinity, agricultural
Namaqua Metamorphics	high grade meta-morphics: gneiss, schist; shears, veins, pegmatites	semi-arid	very flat with small rocky hills	mixed	saprolite, fractures, veins	episodic	low	low	low recharge	salinity, high U
Waterberg	sandstone, Conglomerate	subtropical, summer rain	gently mountainous	minimal	scree	annual	mod.	low	small aquifers	good, shallow aquifers
Malmani Dolomite	dolomite, chert, wad	subtropical, summer rain	flat to undulating	tertiary and primary (wad)	karst and saprolite (wad)	annual, fast	high	high	fast ingress of pollutants, some urban issues (sinkholes)	good, possible pollution in developed areas
Witwatersrand	quartzite, slate	subtropical, summer rain	flat with minor hills	secondary	fractured quartzite, faults	annual	mod.	mod.	mine voids, urban and industrial issues	AMD, urban and other development, high TDS, U
Archaean Granitoids	granite, grus	subtropical, summer rain	hilly	mixed	saprolite, fractures	irregular to annual	mod.	low	small aquifers, flow complex in fractures and saprolite	town, mining and agricultural impacts

AMD = acid mine drainage, TDS = total dissolved solids, TMG = Table Mountain Group, U = uranium

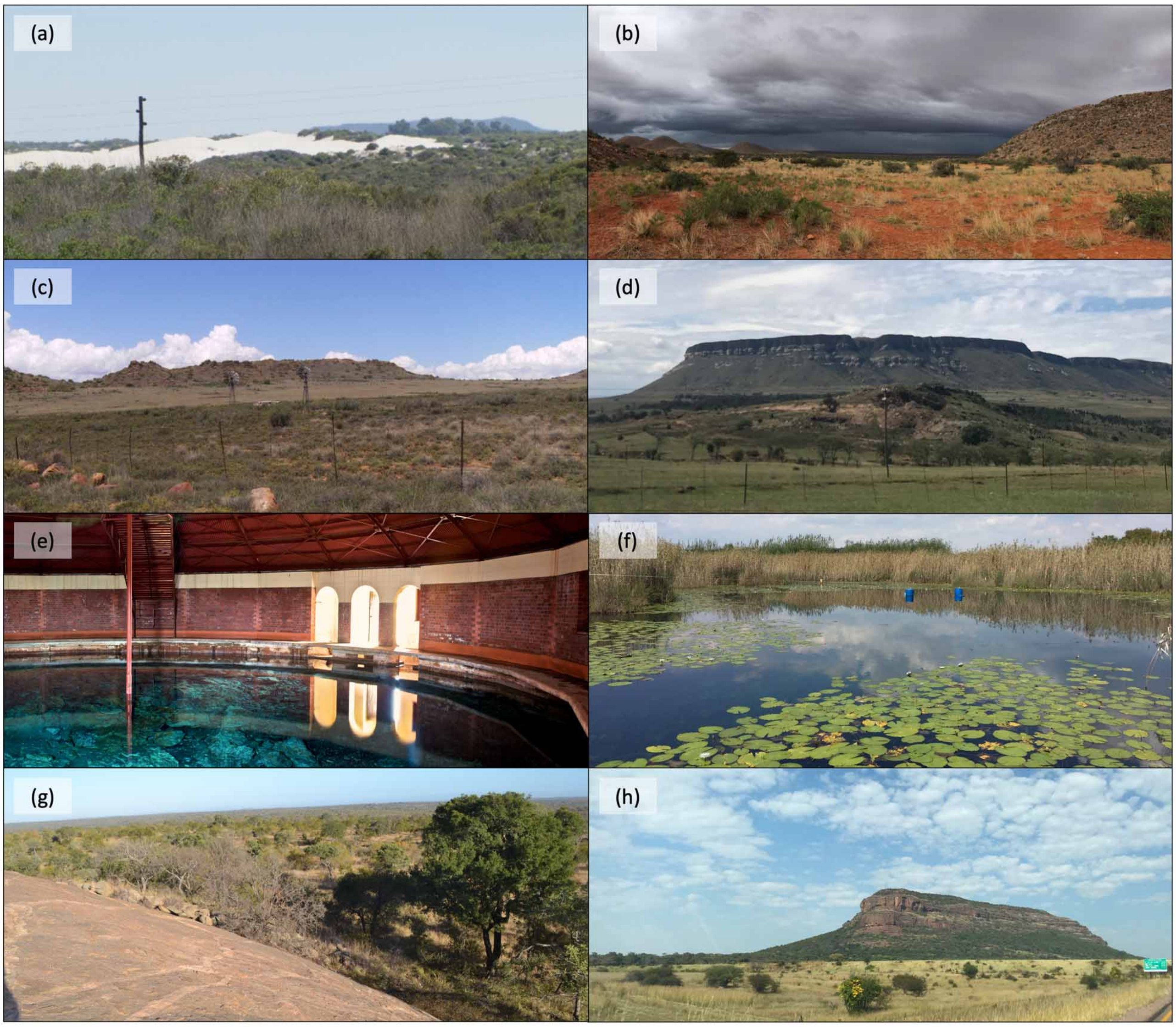

Figure 12. *Examples of different South African hydrostratigraphic settings:* ***(a)*** *coastal sands at Atlantis (Western Cape, 2012);* ***(b)*** *Ghaap Group covered by Kalahari sands (Northern Cape; 2019);* ***(c)*** *Jurassic dolerite dyke in Karoo Supergroup sedimentary rocks (near Beaufort-West; 2007);* ***(d)*** *Karoo Supergroup sedimentary rocks capped by basalt (Harrismith; 2019);* ***(e)*** *Grootfontein spring in Malmani Subgroup dolomite (Pretoria; 2014);* ***(f)*** *Marico spring in Malmani Subgroup dolomite (Groot Marico; 2018);* ***(g)*** *View from granite inselberg to plain on Nelspruit Suite Granite (Skukuza; 2015);* ***(h)*** *Kranskop of the Waterberg Group (Modimolle; 2019); all images © MA Dippenaar.*

towards filling those information gaps. It is hoped that ultimately hydrogeological studies will be more easily comparable and hydrostratigraphic classification can be done in a more uniform manner countrywide.

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