CHAPTER 7

APPLICATION OF RESULTS ON A REGIONAL SCALE

7.1 Location of the study area

The study area is represented by the orthophoto: 2528 CC 23 Midrand (Halfway House) and covers an area of approximately 25×10^6 m^2. The area includes a major part of Midrand, currently one of the fastest developing nodes in South Africa, where office parks and light industrial complexes are taking advantage of the prime locations along the N1 highway.

In contrast, large portions of the study area comprise smallholdings located side-by-side with light industrial complexes. The smallholding community relies on groundwater for their irrigation and, in places, their domestic needs. Because of the high degree of development, groundwater is vulnerable to a number of potential groundwater-degrading activities. Contamination sources have not been identified since this falls outside the scope of this study. The study area is a unique example of human development dynamics in an urban environment and its impact on groundwater resources.

7.2 The Johannesburg granitoid dome

The Johannesburg Dome, shown in **Figure 7.1**, (also known as the Halfway House or Johannesburg-Pretoria dome) is a dome-like window of ancient granitoid, approximately 750 km^2 in area, situated between Johannesburg and Pretoria in South Africa. It is situated in the central part in the Gauteng Province.

7.2.1 Geology of the Johannesburg Dome

The Johannesburg Dome comprises mainly ancient granitoid. The lack of conformity between the foliations in the granitoids and the overlying rocks implies that the granitoid inlier is not a dome *sensu stricto* (Anhaeusser, 1973). Despite this, the term Johannesburg Dome has been retained in literature. The Johannesburg Dome consists of the following (Hilliard, 1994):

- An archean granitoid dome consisting of Tonalite-Trondjhemite gneisses, banded gneisses, a foliated granodiorite zone and granodiorites (Hilliard, 1994). Greenstone remnants are scattered throughout the basement inlier (Anhaeusser, 1973).

- Rocks of the Witwatersrand and Ventersdorp Supergroups are exposed along the south-eastern margin, and along the southern and south-western margin of the inlier respectively.

- The Black Reef Formation, which forms the base of the Transvaal Sequence, is exposed to the north-eastern, northern and north-western margin of the inlier and lies unconformably on the granitoids and greenstones as well as the rocks of the Witwatersrand and Ventersdorp Supergroups.

- The greenstone remnants that occur scattered throughout the basement inlier are the oldest rocks in the Johannesburg Dome area with an age of 3750-2870 Ma (Swazian Erathem, SACS, 1980). They includes mafic and ultramafic rocks (including the Muldersdrif and Roodekrans ultramafic complexes) altered to serpentinites, a variety of amphibolites, chlorite talc, talc carbonate and talc chlorite shists (Anhaeusser, 1973).

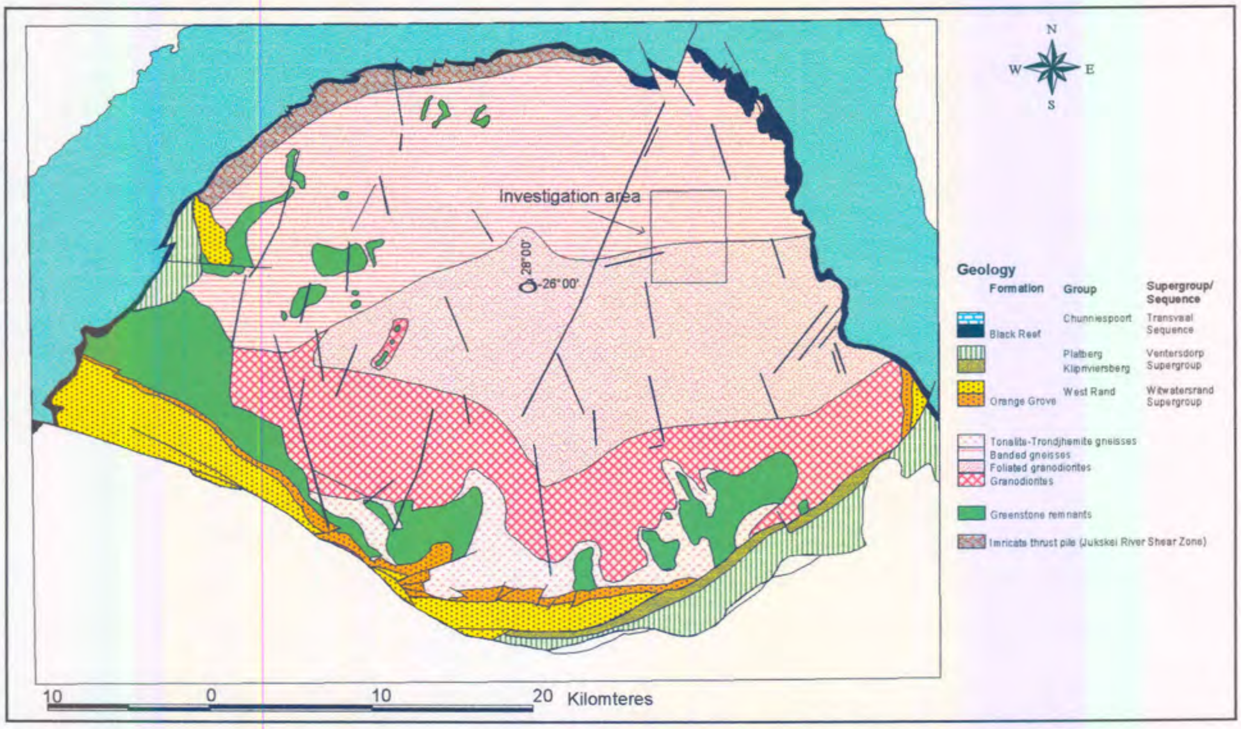

Figure 7.1: Geology of the Johannesburg Granitoid Dome (modified after Hilliard, 1994)

Hilliard (1994), based on the work of Anhaeusser (1973), identified four rock units within the granitoid inlier namely

- Tonalite-Trondjhemite gneisses
- Banded gneisses
- Foliated granodiorites
- Granodiorites

The tonalite-trondjhemite gneisses outcrop in the southern part of the inlier. They intrude the greenstone remnants and contain xenoliths of greenstone fragments (Hilliard, 1994). The gneissic foliation is parallel to the contacts of the greenstone remnants. This phenomenon suggests that the gneissic foliation formed during the intrusion of the tonalite-trondjhemite magma into the greenstone material (Anhaeusser, 1973).

The banded gneisses outcrop in the northern half of the granitoid inlier and consist of gneisses with a strong metamorphic banding defined by alternating quartz-feldspar and biotite rich layers (Hilliard, 1994).

The foliated granodiorites, according to Anhaeusser (1973), form a transitional zone between the granodiorites to the south and the banded gneisses to the north. Hilliard (1994) observed that the principal rock type of the foliated granodiorites is granodiorite with a weakly-developed gneissic foliation.

Ductile shear zones (previously known as crush zones) developed within all granitoids of the basement inlier. The shear zones are characterised by mylonitic foliation and extensive quartz veining (Hilliard, 1994). Two distinct strike orientations of the shear zones, NE and NNW, have been identified. The shear zones were reactivated as brittle faults after deposition of the Black Reef Formation. Quartz infiltrated the shear zone during the initial ductile deformation and subsequently caused extensive quartz veining during the brittle reactivation of the shear zones (Hilliard, 1994).

7.2.2 Weathering processes

A strong relationship exists between the geology of the granitoids and corestone as well as tor development on the Johannesburg Dome.

MacGregor (1952) observed that tors are largely confined to zones of homogeneous granite. Brink (1979) regards the occurrence of tors in the central part (foliated granodiorite) of the granitoid as a striking example of this hypothesis.

Anhaeusser (1973) arbitrarily delineates the boundaries of the Transitional Zone (foliated granodiorites) by identifying the area in which granitoids show tor development. Hilliard (1994), however, delineates the foliated granodiorite in accordance with the weak to moderate occurrences of gneissic foliations, implying that the foliated granodiorites are closely associated with tor development.

In the study area, this association is striking. The northern part of the study area consists of banded gneisses and no tor development has been observed. The southern part of the study area consists of foliated granodiorite and striking examples of tor development are evident. The best example is probably the Boulders Shopping Centre, which is located on top of huge granitoid boulders.

Because of a lack of correlation between mineralogical composition and topography, Brook (1970) states that the tors can not be explained by rock composition. However, Anhaeusser (1973) postulates that the reasons for tor formation are indeed connected to the geochemical variations between the different granitoids. Brink (1979) contends that the exceptionally high content of microcline feldspar is of paramount importance to the mode of weathering. The occurrence of more resistant microcline in the central part of the inlier causes the rocks to be more susceptible to corestone and tor formation than the granitoids, which contain more sodic feldspar, such as the tonalite gneisses in the southern part of the inlier.

Major shear zones often form prominent linear topographical features. Hilliard (1994) postulates that the resistance in weathering is mainly caused by the extensive quartz veining associated with shear zones and to a lesser degree also by the resistant nature of mylonite.

McKnight (1997) postulates that deep weathering along major structural features may be explained by an advanced hydrolysis of silicate minerals, owing to the increased fracturing, and therefore the increased permeability in this zone. McKnight (1997) observed that deep troughs of highly weathered granitoids trend roughly parallel to bedrock structure. According to McKnight (1997), elongated ridges of shallow bedrock adjacent to deeply weathered troughs, particularly prevalent in the Randburg, Bryanston, and Rivonia areas, conform to the general macro-structural setting of the area. These preferential weathering zones are selectively being exploited by drainage features, with the result that landforms and the drainage pattern in the area are, to a large extent, defined by the underlying structural geological setting.

7.2.3 Geomorphic cycles

The present land surface in the Johannesburg Dome area was affected by the African and Post-African I and II geomorphic cycles.

The African cycle was initiated by a vertical upliftment of at least 1000 m during the Late Jurassic/early Cretaceous period (Brink, 1979). The cycle of erosion lasted more than 100 Ma and resulted in widespread planation. The African erosion event was polycyclic with periods of sedimentation followed by periods of erosion due to regional and global upliftment. However, Partridge & Maud (1987) state that this period should be regarded as a single unit. The long duration of this cycle caused widespread planation, with the surface at two levels, above and below the Great Escarpment. It caused the development of deep residual soil (up to 50 m deep) and extensive kaolinisation. It also caused widespread development of pedocretes. At the end of the cycle, the interior elevation was probably between 500 to 700 m a.m.s.l.

In the Johannesburg Dome area, the African erosion cycle is represented by hill crests higher than approximately 1 600 m a.m.s.l (**Figure 7.2**). These hill crests are manifested generally by five bevelled ridges, extending from the Witwatersrand quartzites in a northern direction towards the Rivonia/Midrand area (McKnight, 1997). One of these ridges is manifested in the investigation area, trending east-west in contrast to the general north-south trend of the ridges.

The ridges are characterised by undulating slightly concave crests and are often underlain by deep kaolinised, leached soils. The residual soil has in places been kaolinised to considerable depth. Feldspars have become thoroughly kaolinised thoroughly leached from the top layers, resulting in a spongy, micaceous, silty sand. The soil horizon is characterised by a very low bulk density and high void ratio and is known to have a collapsible grain structure. Few corestones are present in the profile, which have probably been completely weathered during the erosion cycle. This paleosol, possibly with a thick ferricrete cap, now removed by erosion processes, constitutes a deep weathering front below the African erosion land surface (Partridge & Maud, 1987).

The five ridges preserve a relict scarp structure and large corestones, tors and irregular pinnacles of bedrock have been exposed (McKnight, 1997). McKnight also observed deep kaolinised weathering troughs showing strong correlation with bedrock macrostructure. This zone corresponds to the base of the African Erosion Surface and foliated granodiorite bedrock.

The Post-African I cycle was initiated by an upliftment of 150 m to 300 m and was accompanied by a slight westward tilting. This event took place in the early Miocene period. Erosion carved into the older planar African erosion surface. The degree of weathering was not as intense as with the African erosion cycle but, nevertheless, considerably deep residual soils developed in the humid areas (Brink, 1979). The resulting landscape is not as smooth as that of the African erosion cycle.

In the Johannesburg Dome area, the Post-African I cycle is represented by areas approximately 1400 to 1600 m a.m.s.l. (**Figure 7.2**), generally corresponding with the partly undulating concave upper and middle slopes. Numerous gully heads occur within this zone and are characterised by irregular hardpan ferricrete up to 1.0 m in thickness (McKnight, 1997).

The Post African II cycle was initiated by a major asymmetrical upliftment of the subcontinent co-occurring with a major westward tilting of the land surfaces of the interior and monoclinal warping along the southern and eastern coastal margins. The event caused the formation of the Post African II erosion surface characterised by the incision of coastal gorges and the downcutting and formation of higher terraces along interior rivers.

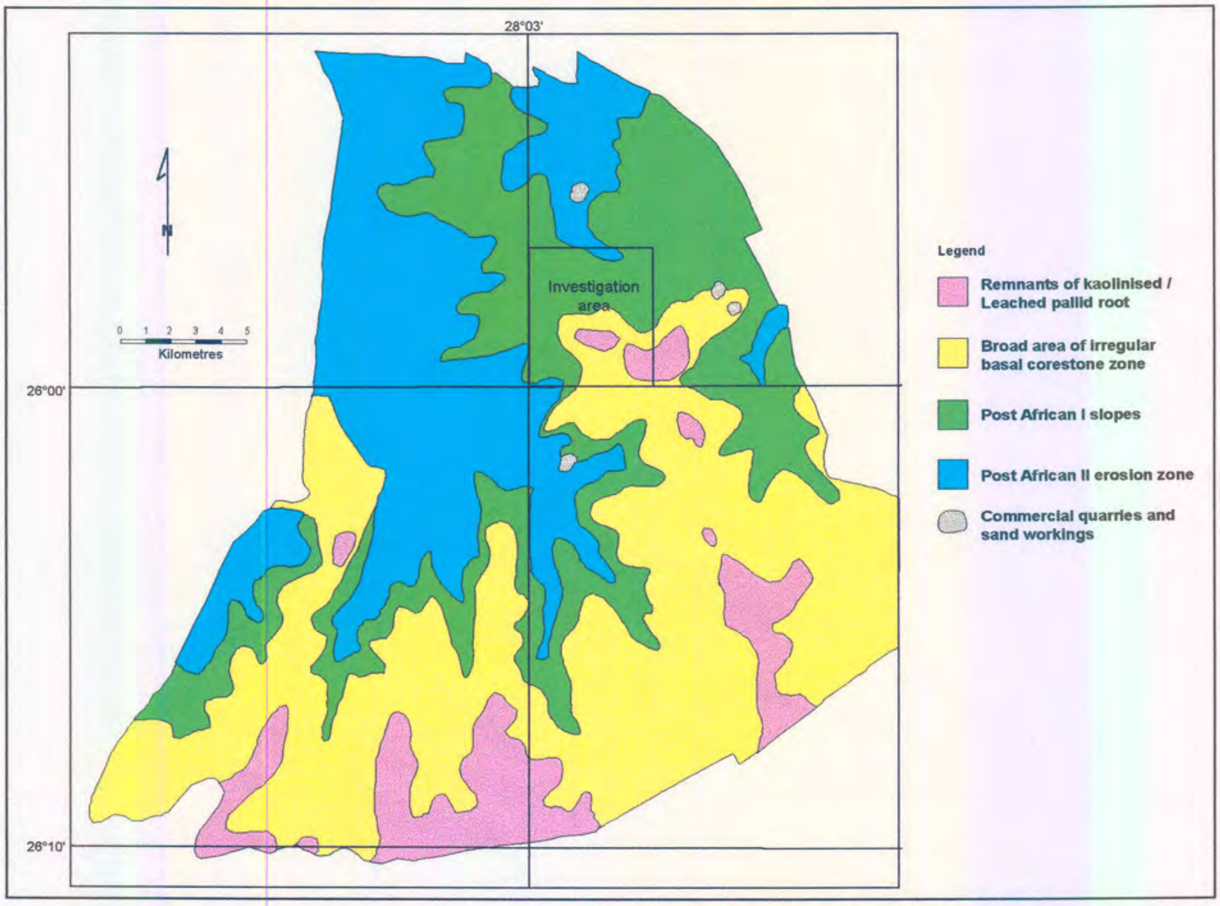

Figure 7.2: Erosion surfaces of the eastern Johannesburg Granitoid Dome (modified after McKnight, 1997)

The late Pliocene upliftment event and the concomitant Post African II erosion cycle caused incision along drainage channels within the undulating Post African I erosion surface of the Johannesburg Dome. The Post African II erosion surface is generally manifested in areas located below 1 500 m a.m.s.l. in particular along the middle and lower slopes along the Johannesburg Dome (McKnight, 1997). These areas are characterised by shallow, relict structured, frequently ferruginised, residual soil profiles. Numerous rock outcrops are present in the Jukskei, Riet, and Kaalfontein streams.

7.2.4 Climate and vegetation

The region is characterised by warm to hot summers and mild winters. Rainfall occurs predominantly in summer and little rainfall is recorded in winter months. The average yearly rainfall is 709 mm. Rainfall occurs mainly in the form of thundershowers. Wind direction is predominantly north-west and the wind velocity is mostly light to intermediate. This climate is typical of the Highveld region.

The indigenous vegetation consists of typical Highveld grass that include *Themeda triandra*, *Trystachya leucothrix*, *Trachypon spicatus* and *Elionurus meticus* (Accocks, 1988). Some exotic trees, mainly *Eucalyptus* and *Acasia Mearinsii* (Black Wattle) also occur in the area.

7.2.5 Surface drainage

Drainage patterns within the Johannesburg Dome area are predominantly controlled by the underlying structural geology. Drainage features, consisting of a number of small streams, flow mainly northwards in the northern portion of the study area and south westwards in the southern portion. These flow directions are consistent with the local structural trends in the area.

The prominent east-west trending ridge forms a watershed, with the northern streams draining into the Rietspruit River and the southern streams flowing along a number of small streams before they eventually flow into the Jukskei River.

Surface water shows a close interrelationship with the groundwater occurrences, especially groundwater from the shallow weathered aquifer. In turn, the shallow weathered aquifer shows close correlation with seasonal effects. This interrelationship between groundwater and surface water resources is in line with the concepts and philosophy of integrated surface and groundwater systems, supported and currently being implemented as part of the Integrated Catchment Management policies in South Africa.

7.2.6 Groundwater occurrence and potential

The Johannesburg Dome represents a typical hard rock environment. Three aquifer systems can be identified, namely a shallow primary weathered aquifer system and a deep secondary aquifer system occurring in unweathered granitoids and associated with fractures, joints, and other discontinuities within the rock mass. In addition, perched aquifers may occur on hardpan ferricrete and shallow bedrock units.

Although little is known about the groundwater conditions within the Johannesburg Dome, experience in other hard rock environments suggests that groundwater in the deep aquifer will mainly occur along deeply weathered structural features. These zones are fractured and highly permeable, resulting in good borehole yields. However, the surrounding granitoid is virtually impermeable with a very low primary porosity value. The deep secondary aquifer will therefore be recharged mainly from the overlying shallow aquifer systems.

In contrast to the deep aquifer, groundwater in the unconfined shallow aquifer generally occurs within unconsolidated completely weathered and residual granite. Weathering of the granitoid bedrock generally results in an increase in porosity and permeability in relation to unweathered rocks. The increase in size and frequency of pore spaces is mainly caused by mineral dissolution during weathering processes. Porosity in the residual granite is high, typically between 30 and 40 per cent, and permeabilities are medium to low, because of high silt and clay contents. Medium to low borehole yields are expected for boreholes located within the weathered aquifer.

Depending on the weathering mode, transition between residual soil and unweathered bedrock may be either abrupt or gradual. In the case of a gradual transition, the soil profile may possibly include closely jointed, medium to highly weathered, highly permeable granite, situated between the overlying medium to low-permeability residual soil and the underlying impermeable granitoid bedrock. Groundwater preferably flows along these zones and discharges into low-lying drainage channels. In the case of an abrupt transition, medium- to low-permeability residual soil directly overlies impermeable granitoid bedrock, with groundwater perching on top of the bedrock.

In addition to shallow bedrock conditions, groundwater is sometimes perched on low-permeability hardpan ferricrete and clay layers (such as low-permeability clayey residual ultra-mafic rock; greenstone remnants).

As mentioned before, deeply weathered troughs trend roughly parallel to bedrock structure. These preferential weathering zones are being selectively exploited by drainage features, with the result that landforms and the drainage pattern in the area are, to a large extent, defined by the underlying structural geological setting. Areas with high groundwater potential will therefore be located mainly along drainage channels exploiting preferential deeply weathered zones.

The weathered aquifer acts as a storage reservoir, releasing groundwater into fractured zones. The shallow aquifer also discharges into the overlying drainage channels. Perched groundwater along hardpan ferricrete layers also discharges into drainage channels.

7.3 Acquisition and analyses of geotechnical data

The investigation area was extensively investigated by a number of institutions. Both the Council for Geoscience and the CSIR conducted regional engineering geology investigations in the area. Information obtained during these investigations includes a regional engineering geology report (Council for Geoscience, 1998) dealing with engineering geology aspects of large parts of the Johannesburg Dome (including the study area) and the adjacent dolomitic areas and included a large number of soil profile descriptions and geotechnical laboratory results.

The CSIR provided soil profile descriptions and geotechnical laboratory results from their geotechnical database as well as a land facet map of the investigation area. The land facet map was compiled by means of API and captured in a GIS database.

Some private consultants provided geotechnical data, mostly in the form of soil profile descriptions. The geotechnical data accumulated during **Experiments 3** and **4** were also applied to the regional study.

In addition to geotechnical data, borehole data were obtained from the National Groundwater Database of DWAF. A regional borehole census was conducted to supplement groundwater data. Prominent features, such as bedrock outcrop, ferricrete outcrop and seepage zones, were mapped.

7.3.1 Land system classification

The Johannesburg Dome area was one of the first areas in South Africa classified by the land system approach. Several publications on applying the land system approach for engineering geology purposes are based on investigations of the Johannesburg Dome region (Brink & Williams, 1964; Brink & Partridge, 1967; Brink, Partridge, Webster & Williams, 1968; Partridge, 1969, Stiff, 1994, Stiff, 1997). The CSIR published a series of GIS based maps, indicating land facets for the Johannesburg Dome and surrounding areas.

The major part of the Johannesburg Dome is represented by the Kyalami Land System. The Kyalami Land System follows the boundaries of the Johannesburg Dome and is characterised by an undulating landscape with mainly north-southern trending ridges and convex slopes, seldom exceeding 12° (Brink & Partridge, 1967). The land system occurs at an elevation of between 1 400 m to 1 700 m a.m.s.l. In addition, the Boskop and the Muldersdrift Land Systems have also been identified. The Boskop Land System is associated with shear zones (crush zones) within the granitoid rock comprising mylonite. Mylonite is more resistant to weathering than the surrounding rocks, resulting in razorback ridges with a general north-eastern/ south-western trend. The Muldersdrift Land System represents areas underlain by major patches of greenstone remnants scattered throughout the Johannesburg Dome. However, because certain minor patches of greenstone remnants do not display significantly different surfaces than the Kyalami Land System, these areas are included in the Kyalami Land System.

Brink and Partridge (1967) identified a number of land facets and variants comprising the Kyalami Land System. The basic land facets consist of:

- Hill crests that can be recognised between high-lying areas with slopes of less than 2°
- Convex side slopes that can be recognised areas between low and high-lying areas with slopes of less than 12°

- Gully slopes that can be recognised by their location at stream heads and a change in slope relative to the side slope, generally hosting these facets

- Alluvial floodplains and drainage lines occur along non-perennial streams that generally exhibit a sub-parallel drainage pattern

Brink and Partridge (1967) identified a number of variants for each land facet, mostly to differentiate between underlying residual granite and residual basic metamorphic rocks, representing the greenstone remnants scattered throughout the Johannesburg Dome.

In addition, land facets occurring less frequently, such as tors, whalebacks and alluvial terraces occur throughout the Johannesburg Dome. Non-connate facets including pan floors and pan sides remnant of the African Erosion Cycle, dyke ridges and pediment occur within the area.

Brink and Partridge (1967) found close correlation between the land facets and the underlying soils and rocks. Hill crests representing the base of the African Erosion Cycle typically comprise deeply weathered, sometimes kaolinised, leached silty sand. Hill crests representing Post-African Erosion Cycles comprise generally of shallow silty sand residual granite. Hardpan ferricrete is generally associated with gully heads and may also occur in low-lying side slopes.

Land facet classification

Land facets were identified by means of stereoscopic aerial photo interpretation (API). API proved to be a fast and cost effective method of accurately identifying areas with similar physical attributes. The land facet map, as derived from API, is shown in **Figure 7.3**.

The study area is dominated by a major east-west trending ridge that represents remnants of the African Erosion Surface. It forms part of a major north-south trending ridge extending from Venterdorp lavas in the region of Isando to Midrand. Several north-south trending, undulating, slightly convex ridges are clearly visible in the area and correspond to the general macro-structural model.

The structural geology is an important controlling factor in preferential weathering and secondary aquifer development. Drainage features often follow these preferential weathering zones, resulting in linear topographic features as are evident in the study area. Identification of these zones, generally associated with high groundwater potential, is essential since these areas are vulnerable to groundwater contamination. Geological structures were identified by means of API. Geological structural features can generally be readily identified by their linear appearance.

A total of five sets of structural features were identified in the area. The most prominent are the north-south, northeast-southwest and, to a lesser degree, north-northwest south-southeast trending features. These features correspond to the general macro structural model of the Johannesburg Dome (Hilliard, 1994; Anhaeusser, 1973; McKnight, 1997).

The prominent Glen Austin Fracture Zone, identified by McKnight (1997) as a possible major controlling structural feature of the Johannesburg Dome, is not clearly visible in representations of the study area. The sharp contrasts between the weathering and soil characteristics of the areas to the north and those to the south of the study area, observed in numerous engineering geology investigations of the Johannesburg Dome, are manifested in the study area. McKnight (1997) attributes this to the Glen Austin Fracture Zone forming a possible half-graben structure with a downthrow to the south. However, these contrasts do not show direct correlation with the fracture zone.

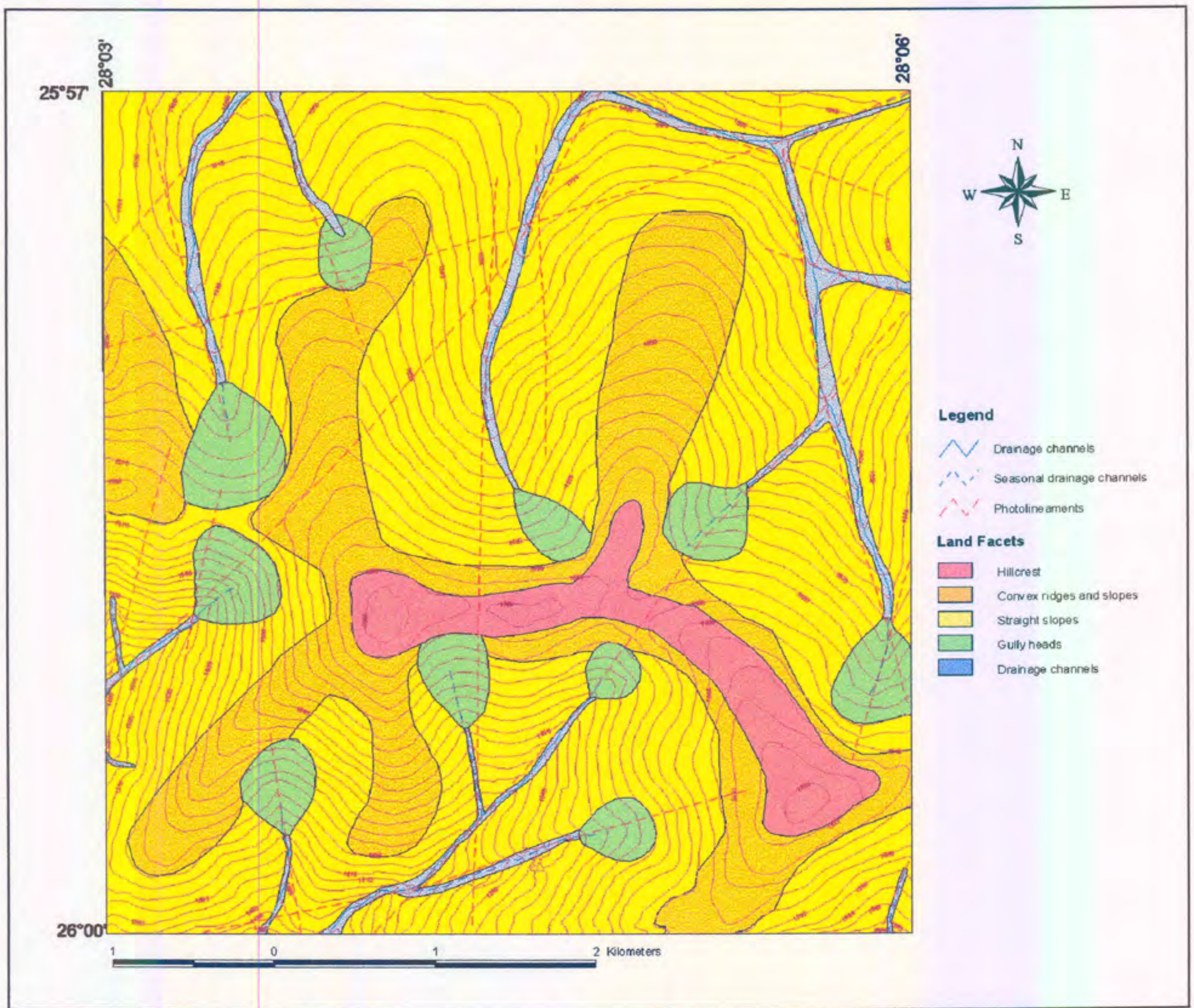

Figure 7.3: Land facet map of the study area as derived by API

The northern portion is generally characterised by undulating terrain with generally shallow residual soils and scattered granitoid outcrops occurring along low-lying drainage channels, such as the Rietspruit River. In contrast, the southern portion is characterised by incised Post African II valleys, as is evident in the Vorna Valley, Carlswald and President Park areas. The area is characterised by deeper weathered soils and a well-defined corestone zone. These differences can be explained by differences in geology and different geomorphic events affecting the weathering patterns in the different areas.

7.3.2 Description of materials

The description of geotechnical material occurring throughout the study area has mainly been based on geotechnical investigations conducted by the Council of Geoscience (1998). A significant geotechnical database was produced, which included large amounts of soil profile descriptions, obtained from the Council for Geoscience, the CSIR and the private sector.

Transported material

Fine colluvium typically comprises the top one metre of a soil profile and occurs along most of the investigation area. It comprises silty to clayey sand with scattered sub-rounded quartz and granite gravel. The soil is often voided and leached.

Hillwash frequently occurs along gully heads and on the lower side slopes adjacent to drainage channels. The hillwash typically comprises a thin layer of silty to clayey sand and is frequently underlain by hardpan ferricrete.

Alluvium occurring along drainage channels typically comprises dark grey, sandy to silty clay, sometimes intercalated with light grey coarse sand. The grey colour indicates saturated reducing conditions.

The gravel pebble marker indicates the transition between residual and transported soils. It may be up to 0.40 m thick and typically comprises a tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of frequently ferruginised, silty fine, medium and coarse sand. The overall consistency of the layer is generally medium dense to dense.

Residual granite

The geotechnical characteristics of residual granite are mainly a function of its position within the Kyalami Land System landscape.

A distinction is made between hill crests occurring on the African Erosion Cycle and those on the Post African Erosion Cycles. Hill crests occurring on the former cycle are characterised by deep, kaolinised, highly leached soils. The top pallid highly leached horizon often exhibits a collapsible grain structure.

Hill crests occurring on Post-African Erosion Surfaces comprise a red-brown, stained dark brown and orange-brown, loose to medium dense, voided, silty to clayey sand with fine sub-angular quartz gravel and, sometimes, fine ferricrete concretions. Corestones occur sporadically in the southern portion, while shallow bedrock occurs in the northern portion of the study area.

Convex and straight side slopes comprise red-brown, yellow-brown or grey-brown, loose to medium dense, voided, clayey to silty sand with or without loose to tightly packed coarse, medium and fine ferricrete concretions. Relict rock structures may occur in the soil profile and generally consist of zones of light-grey, loose, clayey sand.

Concave side slopes are not generally defined on the Kayalami Land System (Brink & Partridge, 1967; Stiff, 1994). However, soil profiles on lower-lying areas of the slopes indicate significant differences from soil profiles on upper-slopes. Accordingly, Aucamp (Council for Geoscience, 1998) defines a slightly concave side slope facet occurring on the lower-lying areas on side slopes, close to drainage channels.

The residual material comprises red-brown, stained red, yellow and orange, medium dense to dense, highly ferruginised, silty sand. Hardpan ferricrete frequently occurs at shallow depth. The downward flow of water is impeded by low-permeability material. In addition, gully head areas are characterised by upward hydraulic gradients and groundwater discharge resulting in the development of seepage zones. This groundwater flows mainly in a horizontal direction along the E-horizon, which overlies the ferruginised horizon. The E-horizon comprises shallow, pallid and leached, loose, slightly silty sand.

Apart from concave side-slopes and gully heads, hardpan ferricrete may develop sporadically along convex and straight side slopes and hill crests occurring on Post African erosion surfaces. Hardpan ferricrete may develop either in colluvium or residual granite.

Residual greenstones

Residual greenstones occur sporadically within the Johannesburg dome. The greenstones are generally altered to serpentine shists. The residual material generally comprises orange-brown to olive-green, speckled dark grey, light grey and light red, stiff, occasionally slickensided clay.

Weathering troughs

Not much has been published on the highly weathered material occurring in deep weathering troughs, formed by preferential weathering along geological structures. The material comprises highly weathered, kaolinised and highly permeable granite rock (saprolite) and overlies a medium to slightly weathered, highly fractured granitoid rock.

7.3.3 Statistical analysis

Geotechnical data of the study area as obtained from the Council for Geoscience, the CSIR and the private sector were statistically analysed in order to determine the geotechnical characteristics of the different soil horizons in each land facet type. The geotechnical data were analysed to determine the central tendency of a particular geotechnical property. In addition, the measure of variability was determined. Typical geotechnical properties for the different soil horizons are summarised in **Table 7.1**.

Table 7.1: Typical gravel/sand, silt and clay contents for the different soil horizons

Material		Sand & gravel (%)	Silt (%)	Clay (%)
Hillwash	Average	74	21	4
	Median	76	22	3
	Coefficient of Variability (%)	11.75	31.41	100.80
	Maximum	87	39	20
	Minimum	53	11	1
	Number of samples	16	16	16
Residual granite	Average	72	21	6
	Median	71	22	5
	Coefficient of Variability (%)	18.07	55.87	69.71
	Maximum	92	54	18
	Minimum	40	5	0
	Number of samples	42	42	42
Ferruginous horizon	Average	80	14	6
	Median	81	15	4
	Coefficient of Variability (%)	17.58	59.05	91.52
	Maximum	98	26	15
	Minimum	59	2	0
	Number of samples	5	5	5
Alluvium	Average	42	39	19
	Median	38	43	16
	Coefficient of Variability (%)	58.89	44.90	78.49
	Maximum	81	64	43
	Minimum	16	16	3
	Number of samples	6	6	6

Table 7.1 indicates that, with the exception of alluvium, all materials exhibit similar characteristics concerning sand/gravel, silt and clay contents. Similar trends were observed for grain-size distributions. The materials, with the exception of alluvium, had almost exactly similar average sand/gravel, silt and clay contents.

Variations in soil fraction contents between different testpits were high, especially the clay contents, but similar variations were recorded for all materials. No significant differences in soil fraction contents between soils from different land facets were observed.

It is argued that (with the exception of alluvium, materials originating from intrusive dykes and greenstone remnants) materials within the study area are similar in composition, irrespective of their origin and location within particular land facets. The large variability encountered can be attributed to the fact that samples are not representative of the particular soil horizon and, in the case of clay content, that the general low clay percentage is sensitive to variation analysis. The similarity in soil composition is caused by similar bedrock materials that are subjected to similar weathering processes. However, significant geotechnical differences may exist between the different soil horizons largely caused by leaching and ferricrete development within the different soil horizons.

7.4 Hydrogeological characteristics

Although field evidence is limited, the groundwater characteristics of the area are similar to hard rock environments, namely shallow weathered, low-yielding aquifers and secondary fractured aquifers with a higher yield.

7.4.1 Shallow groundwater

A total of 109 selected soil profile descriptions throughout the study area were analysed in terms of seepage and groundwater levels recorded in the testpits. The following observations were made:

- Of all the soil profile descriptions recorded during the period of May to October, none made any reference to seepage or shallow groundwater conditions encountered during testpit inspection. In contrast, 38 per cent of the soil profile descriptions recorded during the period of November to April recorded seepage or shallow groundwater conditions.
- In three cases, engineering geologists observed that seepage took place after a rainstorm.
- Many residents complained about surface seepage occurring after rainstorms. During field investigations, surface seepage was observed at several places. In all of these cases, hardpan ferricrete or shallow rock outcrop was observed close to the seepage area. Seepage was particularly severe during and just after the 1995/1996 rain season, characterised by above average precipitation.
- In 61 per cent of cases where seepage was observed in testpits, it was observed less than 1.5 metres below surface and before refusal on granite rock or very dense material and in 31 per cent of the cases, seepage was detected at or near refusal depth. The depth of the testpits varied between 1.6 to 6.9 metres.
- In 9 per cent of the cases, water seepage was observed occurring from a ferruginous layer.

The above observations imply a seasonal perched aquifer occurring throughout the study area. The perched aquifer forms during the rainy season and discharges along gully slopes and lower side slopes. Water infiltrates the ground and accumulates either on shallow bedrock or hardpan ferricrete layers. Accumulation of groundwater occurs after rain events and then flows laterally along the low-permeability underlying layer from where it discharges along the ground surface where the low-permeability layers outcrop, generally along gully slopes. A portion of the groundwater evaporates while another portion flows into deeper fractured aquifer systems.

The perched aquifer dries up during the dry season. The little rainfall that infiltrates the perched aquifer is stored in the aquifer before it evaporates. Little surface seepage occurs during the dry months. However, surface seepage may occur well into the dry season in the case of very wet season in which large amounts of water occur in the perched aquifer systems.

7.4.2 Groundwater recharge and discharge areas

The drainage channels in the study area are hydraulically connected to perched and shallow aquifer systems. All the drainage channels in the area are classified as effluent streams, implying that perched and shallow aquifers discharge into drainage channels. However, in the case of drought, groundwater levels may drop to below the stream level and this may result in the shallow and perched aquifer systems being recharged by the streams.

Gully heads usually represent groundwater discharge areas. Perched groundwater, flowing horizontally along low-permeability ferruginised zones, intersects the side-slopes and results in groundwater being discharged into stream heads. Similar situations may occur in the case of shallow bedrock.

The interrelationship between surface water, shallow and perched aquifer systems and deep aquifer systems in the Johannesburg Dome region has already been discussed. Because of this interrelationship it follows that any interference with either of these systems may result in the other water resources being affected. High groundwater extraction rates from secondary aquifer systems may cause the groundwater level of the shallow aquifer to drop below stream level. This may result in groundwater being recharged by the stream.

To summarise, groundwater discharge areas are mainly associated with drainage channels, flood plains, gully heads and, to a lesser extent, the lower portions of side-slopes. The remainder of the area can be classified as recharge zones. The recharge rate relates closely to the hydrogeological properties of the individual land facet zones

7.4.3 Preferential flow

A number of possible situations with respect to preferential flow were identified.

- Macropore channelling occurring in the top transported soil along biopores, in particular plant root channels and termite holes
- Macropore channelling associated with relict rock structures occurring in residual granite
- Fingering flow occurring within silty sand overlain by a low-permeability ferruginised soil horizon
- Funnelling flow occurring along the interface between low-permeability ferruginised layers and residual material

Not much research was conducted on the mode and extent of preferential flow within the vadose zone. Results from **Experiments 3** and **4** reveal that macropore channelling, in particular macropore channelling along biopores, may occur within the vadose zone. The extent of this type of preferential flow is probably negligible. However, it is possible that significant macropore channelling may occur in certain situations, e.g. where extensive termite activity occurs.

Little is known about the occurrence and extent of fingering and funnelling in the study area. Because of the extensive ferruginous development in the area, it is suspected that funnelled flow along less permeable ferruginous layers may significantly affect the groundwater situation. It is very difficult to determine the extent of these layers. In addition, very little is known about the continuity of ferruginous layers, adding to the uncertainty with regard to this mode of flow.

7.4.4 Borehole census

A borehole census was conducted in the study area in order to obtain a better understanding of the groundwater situation. In spite of the large number of groundwater users present in the area, the borehole census showed a poor response from the smallholding community, which could be ascribed to the fact that many owners could not be reached. It was decided to focus on a few quality responses rather than following a quantitative approach that could be flawed by many errors.

Borehole data were gathered mainly from Glen Austin, Erand, Blue Hills and Carlswald agricultural holdings. Many smallholding residents were connected to municipal services for their water needs. Although many of these residents still used borehole water for gardening and irrigation purposes, some boreholes were not maintained and were subsequently destroyed.

In all cases except one, the quality of the water was described as very good. The poor quality of water encountered in one borehole could be ascribed to rotting vegetation affecting the water quality of the perched aquifer. Although a few residents had the groundwater tested, no water quality results were available. Some residents observed a high lime content in the groundwater.

Depth to groundwater levels varied from ground surface to 25 m. Two distinct groundwater levels could be identified, namely a shallow groundwater level that varied from ground surface to 10 m and a deep groundwater level of more than 10 m. Shallow groundwater conditions were recorded for most of the northern portion corresponding to shallow weathering profiles characteristic of the Post-African erosion surfaces. In contrast, deeper groundwater levels were observed in the more deeply weathered materials in the New Road onramp area, corresponding to the African erosion surface. In many cases, the depth to groundwater surface could not be obtained because many boreholes were equipped with pumps.

Groundwater yield varied from 0.01 to 8.3 l/s. Two boreholes (BH006 and BH008) showed a yield of more than 5 l/s. Both these boreholes could be associated with geological structures as interpreted from aerial photo interpretation. These boreholes possibly represent deeply weathered, high-permeability secondary aquifers.

Based on these observations, it was concluded that there are probably at least three aquifer systems in the study area:

- A shallow seasonal perched aquifer associated with shallow bedrock and highly ferruginised to hardpan ferricrete
- A shallow weathered aquifer associated mainly with deeply weathered silty sand of the African erosion cycle
- A deeply weathered, highly permeable and often high-yielding secondary aquifer associated with geological structures

These aquifer systems showed remarkably good correlation to geomorphic erosion surfaces and land facets within the study area.

7.5 Pedo-transformations

7.5.1 Estimation of saturated hydraulic conductivity

A total of 66 soil samples were collected in the study area from testpits. The soil samples were collected as part of the regional engineering geological mapping of the Midrand/Centurion area conducted by the Council for Geoscience (1998). Foundation indicator tests were conducted and the particle size distributions were determined.

Saturated hydraulic conductivity was estimated applying the empirical equations of Campbell (1985), Campbell and Shiozawa (1992) and Rawls *et al* (1982). These methods were discussed in **Chapter 4**. A correction factor, determined for **Experiment 4**, was included in the equations in order to compensate for factors such as grain shape and packing that vary with each soil type. The results are summarised in **Table 7.2**.

Table 7.2: Estimated saturated hydraulic conductivities as derived from soil fractions

	Campbell	Campbell and Shiozawa	Rawls *et al*
Average estimated K_s (m/s)	5.93×10^{-7}	1.22×10^{-6}	2.96×10^{-7}
Median estimated K_s(m/s)	5.53×10^{-7}	6.69×10^{-7}	2.56×10^{-7}
Coefficient of variation (%)	51.81	116.01	60.16
Maximum estimated K_s(m/s)	1.56×10^{-6}	7.45×10^{-6}	8.44×10^{-7}
Minimum estimated K_s(m/s)	1.04×10^{-7}	1.01×10^{-7}	2.61×10^{-8}
Number of samples	66	66	66
Measured K_s(m/s)	5.90×10^{-7}	5.90×10^{-7}	5.90×10^{-7}
Percentage error	6.35%	-11.86%	56.55%

Table 7.2 shows remarkably good correlation between measured hydraulic conductivity as derived from **Experiment 4** and estimated median hydraulic conductivity as derived from all three empirical equations. However, large variations in estimated hydraulic conductivity were recorded in response to the high variability in the soil compositions of the soil samples. The good correlation between measured and estimated hydraulic conductivity confirms the similarity of soil materials.

In addition to soil fractions, saturated hydraulic conductivity was estimated from grain-size distributions by means of ten popular empirical equations. The application of these empirical equations was discussed in **Chapter 6**. As in the case of the soil fraction equations, a correction factor was included in the empirical equation to compensate for factors such as grain shape and packing. The results are indicated in **Table 7.3**.

Table 7.3: Estimated saturated hydraulic conductivity derived from grain size distribution curves

	Average estimated K_s (m/s)	Median estimated K_s (m/s)	Coefficient of variation	Maximum estimated K_s (m/s)	Minimum estimated K_s (m/s)	Per cent error
Hazen (1930)	2.84×10^{-6}	1.24×10^{-7}	514.53%	9.54×10^{-5}	6.10×10^{-9}	79.05%
Amer & Awad (1974)	4.01×10^{-6}	3.21×10^{-7}	455.79%	1.19×10^{-4}	8.63×10^{-9}	45.62%
Shahabi *et al.* (1984)	9.02×10^{-6}	2.92×10^{-6}	271.44%	1.54×10^{-4}	1.29×10^{-7}	-79.78%
Kenney *et al.* (1984)	1.19×10^{-6}	3.48×10^{-8}	629.61%	4.90×10^{-5}	8.71×10^{-9}	94.10%
Slichter (Vukovic & Soro, 1992)	3.76×10^{-6}	1.64×10^{-7}	514.53%	1.27×10^{-4}	8.10×10^{-9}	72.21%
Tarzaghi (Vukovic & Soro, 1992)	3.82×10^{-6}	1.67×10^{-7}	514.53%	1.29×10^{-4}	8.23×10^{-9}	71.76%
Beyer (Vukovic & Soro, 1992)	2.49×10^{-6}	4.73×10^{-8}	547.58%	8.93×10^{-5}	3.93×10^{-10}	91.99%
Sauerbrei (Vukovic & Soro, 1992)	8.47×10^{-6}	1.32×10^{-6}	355.21%	1.91×10^{-4}	8.47×10^{-9}	-55.42%
Pavchich (Pravednyi, 1966)	1.43×10^{-5}	3.38×10^{-6}	237.69%	2.02×10^{-4}	2.27×10^{-8}	-82.57%
USBR (Vukovic & Soro, 1992)	5.59×10^{-6}	7.20×10^{-7}	287.84%	9.80×10^{-5}	3.20×10^{-9}	-18.06%

n = 43, measured $K_s = 5.90 \times 10^{-7}$ m/s

Table 7.3 indicates a large variability of estimated saturated hydraulic conductivity for all ten empirical equations applied. Many equations show differences of up to five orders of magnitude between the minimum and maximum predicted saturated hydraulic conductivity for the soil samples. Variations in predicted saturated hydraulic conductivity of more than 500 per cent were calculated for the soil samples tested.

7.5.2 Estimation of soil-water retention characteristics

Soil-water retention characteristics were estimated from soil fractions, applying the Gupta and Larson (1979) empirical equation. This method was applied to soils of Experiment 4 and is described in **Chapter 6**. Estimated volumetric water contents at several soil suction values for 43 soil samples obtained from the study area are presented in **Table 7.4**. These estimated values were compared to measured values derived during Experiment 4.

Table 7.4: Estimated volumetric water contents at various suction values

	Estimated volumetric water content at soil suction (kPa)					
	4	**10**	**33**	**60**	**100**	**1000**
Average volumetric water content	0.260	0.199	0.159	0.146	0.137	0.102
Median volumetric water content	0.258	0.196	0.155	0.143	0.134	0.098
Maximum value	0.370	0.326	0.276	0.255	0.239	0.190
Minimum value	0.146	0.098	0.078	0.071	0.066	0.045
Coefficient of variation (%)	17.53%	24.65%	27.42%	27.60%	27.74%	30.99%
Measured value (Experiment 4)	0.206	0.181	0.157	0.145	0.136	0.095
Percentage error	-20.20%	-7.35%	1.11%	1.33%	1.47%	-2.44%
Number of samples	66	66	66	66	66	66

Table 7.4 indicates significantly less variation in estimated volumetric water contents compared to estimated saturated hydraulic conductivity values. These variations correspond to variations in soil fraction composition. This indicates that soil retention characteristics are closely related to grain-size distribution. This trend is further confirmed by the normal distribution curve of the estimated values, as indicated by the similar average and median values. The results confirm that water-retention characteristics are mainly a function of the specific surface of the grains, implying that they are also a function of grain-size distribution, especially for high soil suction values.

With the exception of water contents at a soil suction value of 4 kPa and, to a lesser extent, 10 kPa, estimated volumetric water contents are remarkably similar to the values measured during Experiment 4. This indicates that, although variations occur for different soil samples, water retention characteristics are similar to soils occurring in the study area. The deviations at lower soil suctions occur because of the importance role pore-connectivity and pore-size distribution plays at near saturated conditions, which is not considered by the Gupta & Larson (1979) equation.

7.5.3 Estimation of unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity is mainly a function of both saturated hydraulic conductivity and the soil-water characteristic curve. It has earlier been established that the soil-water retention characteristics and saturated hydraulic conductivity correspond to the results of Experiment 4. It is therefore expected that the unsaturated hydraulic conductivity of residual soils in the study area will be similar to those determined during Experiment 4. The expected variability for unsaturated hydraulic conductivity values in the residual soils is functions of:

- The variability of saturated hydraulic conductivity
- The variability of soil-water retention characteristics
- Variability as a result of errors in describing the soil-water characteristic curve
- Inaccuracies regarding predicted hydraulic conductivity from the soil-water characteristic curve

It has been shown that equations developed by Van Genuchten (1980) and Fredlund and Xing (1994) accurately describe the soil-water characteristic curve. It has also been shown that predicted unsaturated hydraulic conductivity can be accurately predicted from soil-water characteristic curves, provided that the saturated hydraulic conductivity is known. Since it has been shown that major variations occur for estimated hydraulic conductivity, it can be concluded that the variability of unsaturated hydraulic conductivity will be similar to that of saturated hydraulic conductivity. Unsaturated hydraulic conductivity as derived from Experiment 4 is shown in **Table 7.5**

Table 7.5: Unsaturated hydraulic conductivity at various soil suction values for residual soils in the study area.

Soil suction (kPa)	Experiment 4	
	K (Van Genuchten)	K (Fredlund & Xing)
1.00	1.4×10^{-8}	5.0×10^{-7}
5.00	1.4×10^{-10}	5.4×10^{-10}
10.00	1.4×10^{-11}	1.0×10^{-10}
20.00	1.4×10^{-12}	2.3×10^{-11}
50.00	6.7×10^{-14}	3.4×10^{-12}
100.0	6.5×10^{-15}	7.8×10^{-13}
1000	2.9×10^{-18}	5.9×10^{-15}

7.6 Delineation and characterisation of hydrogeological units

Since the residual soils occurring in the study area were of similar composition and characteristics, the delineation of hydrogeological units had to be based on other physical attributes. The physical attributes identified as having a significant impact on the vadose zone situation include:

- Depth to impermeable bedrock material
- Presence of weathering troughs associated with geological structures
- Depth to shallow groundwater surface
- Presence of a low-permeability ferruginous layer
- Presence of hardpan ferricrete
- Presence of a perched groundwater level associated with low-permeability ferruginous layers or hardpan ferricrete
- Presence of corestones in the soil profile
- Presence of dykes or remnant greenstones

These physical attributes are present in the soil profile and differ from other hydrogeological units mainly because of differences in underlying geology and the geomorphic events to which the soils have been subjected.

The unique hydrogeological units were delineated by means of the land systems approach. The results were incorporated in a GIS system. In addition to the land facet map, the following information was incorporated in the GIS system:

- The bedrock geology, as derived from the geology map compiled by Hilliard (1994)
- The structural geological setting as interpreted by means of aerial photo interpretation
- Outcrop conditions as mapped and compiled by the Council of Geoscience (1998)

- A map indicating areas subjected to different geomorphic events. This map is largely based on work by McKnight (1997)

By incorporating these sources of information in a GIS system, zones exhibiting similar hydrogeological characteristics could be identified. The hydrogeological zones were delineated by overlapping bedrock geology, the land facet, geomorphologic and geotechnical maps. The GIS compiled map was then simplified based on soil profile descriptions. Four major geohydrological zones were identified which closely resemble land facets for the area, namely:

Zone A: Areas representing high-lying topographical features such as hill crests and convex ridges.

Zone B: Areas representing side slopes (upper and lower side slopes) characterised by soil profiles generally deeper than 2m.

Zone C: Areas representing stream heads, gully slopes and side slopes characterised by shallow soil profiles less than 1m deep.

Zone D Drainage channels in which alluvial material has accumulated or where bedrock has been exposed.

The major geohydrological zones were then subdivided into zones corresponding to bedrock geology, geomorphology and geotechnical mapping. Areas depicting zones of similar hydrogeological characteristics are shown in **Drawing 1.**

7.6.1 Description of the hydrogeological zones and assessment of groundwater recharge and vulnerability

The hydrogeological zones identified and delineated are depicted in **Drawing 1**. Typical cross-sections and the interpreted hydrogeological assessment are described below.

A total of 116 soil profiles, obtained from the study area were classified according to their position relevant to the delineated zones as depicted in **Drawing 1**. Typical soil profiles and conceptual unsaturated flow models were established for each of the hydrogeological zones, based on the soil profiles and previous research by, in particular Brink & Partridge (1967), Stiff (1994) and McKnight (1997).

The South African nomenclature defines five weathering stages, as opposed to the traditional six weathering stages defined internationally. Completely weathered rock is described as residual soil in the South African nomenclature while residual soil is often referred to as reworked residual soils. Although the South African nomenclature is probably more descriptive of the material (completely weathered rock is defined as a soil by engineering standards) it is recommended that the international terminology be used to prevent confusion. In this thesis, the international recognised terminology is used with the South African term in brackets, i.e. – completely weathered granite (S.Afr: residual granite).

Zone A1

Zone A1 represents hill crests occurring on the lowered African erosion cycle. The zone corresponds to KYAL0101 (Residual sandy clay with collapsible grain structure on granite) as proposed by Brink & Partridge (1969) and modified by Stiff (1994). It also corresponds to the Interfluve Crest (Remnant of deep kaolinised leached zone) as proposed by McKnight (1997)

A total of 29 soil profiles, representative of Zone A1, had been obtained in the study area. Most of these soil profiles formed part of geotechnical investigations for the construction of medium to large structures, which involved *inter alia* piling. Consequently, many soil profiles were described up to 12m in depth.

Zone A1 soils are characterised by a deep, often kaolinised, highly leached profile. The top pallid, highly leached horizon often exhibits collapsible grain structure.

The hillwash consist of 0.5 to 1.2m of reddish brown to pale brown, loose, intact silty sand with scattered sub-rounded quartz and granite gravel and roots. The soils are often friable, voided and leached. The hillwash is underlain by an often poorly developed pebblemarker. It is typically between 0.1 and 0.3m in thickness and is sometimes absent in the soil profile. It consists typically of a tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of frequently ferruginised, silty fine, medium and coarse sand. The overall consistency of the layer is medium dense to dense.

The residual granite underlying the pebble marker consists of orange-brown to red-brown, loose to medium dense, voided, silty to clayey sand with fine sub-angular quartz gravel and, sometimes, fine ferricrete concretions. The consistency of the soils generally increases with depth, becoming medium dense to dense, with medium dense soil comprising the top approximately 1.0 m of residual granite. The collapsible grain structure of this pallid root zone, and its associated geotechnical problems, has been well documented. According to Partridge and Maud (1987), extensive weathering during the African erosion cycle resulted in the development of highly leached soils, probably with a thick ferricrete cap. The soils therefore represent the base of a thick ferricrete layer, which has since been eroded away.

The orange-brown to red brown leached soil layer is often underlain by extensive pale brown, to yellow, soft sandy clay with occasional fine quartz gravel. This completely weathered (S.Afr: residual) kaolinised zone represents extensive *in situ* chemical weathering of the granitioid rock. Nearly all minerals, with the exception of quartz, have been weathered to kaolinite (with some minerals first weathered to montmorillonite and then to kaolinite) under humid climatic conditions, typical of the paleo-climate during the early Miocene age. Fingers of leached, reddish brown, residual granite were observed, extending into the kaolinised zone along preferential weathering zones.

The orange brown, leached layer is generally underlain by pale grey to pale brown, veined and pegmatitic in places, highly weathered, often jointed, very soft granitoid rock. These zones correspond to the kaolinised zones, but have not been weathered to a similar extent. Occasional moderately weathered corestones occur within the soil profile. The thickness of the highly weathered zone varies significantly (0 to 4m).

The weathering profile is approximately 10m in thickness. The weathering profile is noticeably consistent in its thickness, given the typical heterogeneous nature of these profiles. Groundwater occurs approximately 8m below ground surface and is perched on the impermeable bedrock material.

Flow through the vadose zone is complex. The preferential weathering zones are important aspects in flow through these zones. The conceptual unsaturated groundwater flow model is represented in **Figure 7.4**. The medium to high permeability of the soils implies that recharge events will be related closely to rainfall events. During infiltration, water will move predominantly along the more permeable preferential weathering zones as indicated by **Figure 7.4**. In periods between rainfall events, groundwater will mainly be recharged (though on a limited scale) along the less permeable (though characterised by higher water-retaining properties) sandy clay. The jointed, highly to medium weathered rocks, although possibly highly permeable, will have little effect on the recharge rate, because flow through joints will depend on the flow rate through overlying soils. High flow velocities will occur along these joints, resulting in lower travel times and hence higher vulnerability. This effect will be overshadowed by the predominant flow along preferential weathering zones.

However, it is expected that the main pathway of water within the phreatic zone will be along highly permeable, medium to highly weathered, jointed, soft rock zones. Flow along these zones will be mainly horizontal. This zone could:

i Provide base flow to streams,

ii Result in seepage along lower slopes characterised by a shallow bedrock or ferricrete layers or

iii Recharge deeper fractured aquifer systems.

The fact that seepage has occurred in several places within the study zone for several months after the particularly wet 1995/1996 rain season indicates that the weathered zones act as a storage zone.

Areas underlain by Zone A1 are recharge areas almost without exception. In general, it can be concluded that the shallow aquifer systems are vulnerable to pollution due to the low travelling times. Since fractured aquifer systems are generally associated with linear drainage features in the study area, it can be concluded that the potential for groundwater will be low. However, the zones are important since these zones act as water storage and are recharging deeper aquifer systems.

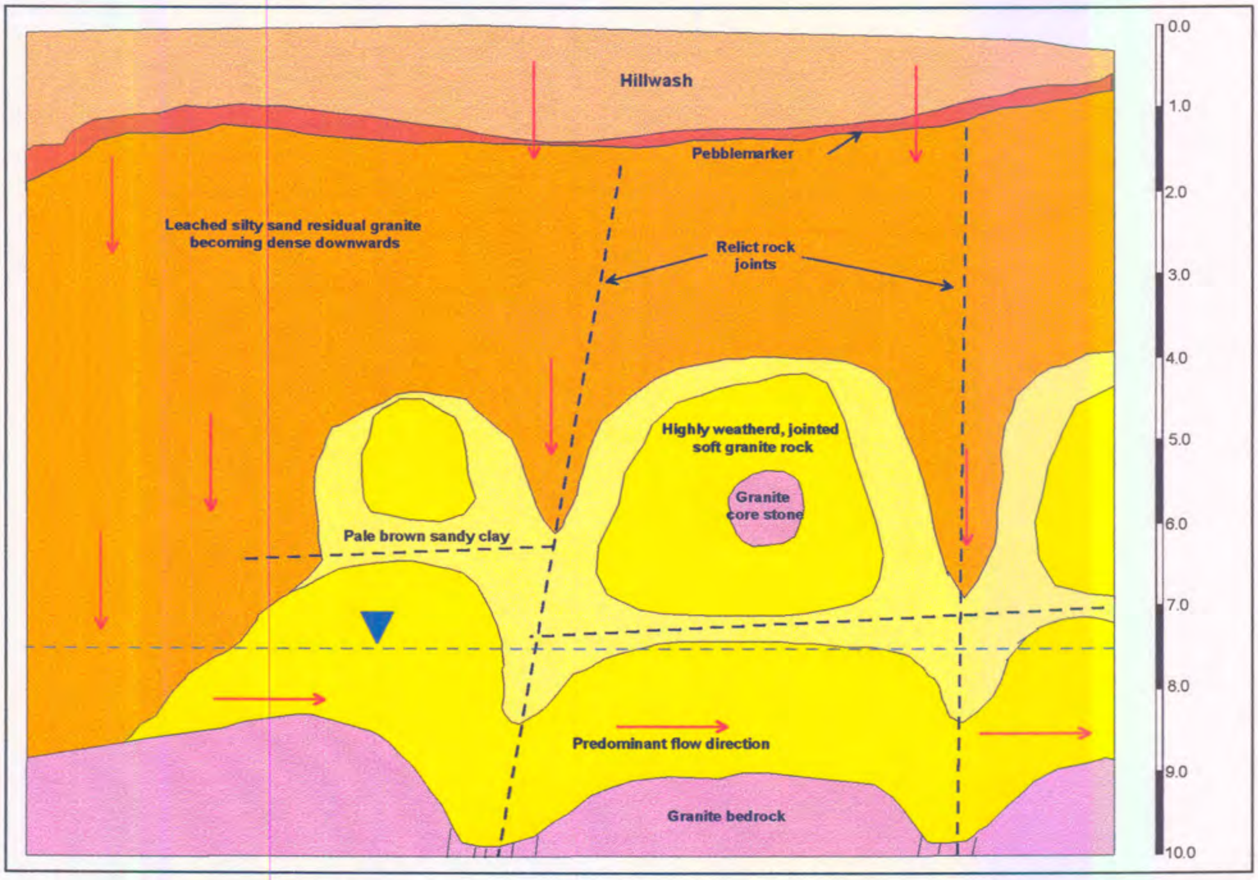

Figure 7.4: Typical soil profile and conceptual unsaturated groundwater model for Zone A1

Zone A2

Zone A2 represents concave ridges within the study area. These areas generally occur along topographic highs with the ridges sloping mainly northwards or southwards towards low-lying drainage channels. The zone corresponds to KYAL0101 (Residual sandy clay with collapsible grain structure on granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also corresponds partly to the Interfluve Crest (Remnant of deep kaolinised leached zone) and partly to the Scarp and Shelf (basal corestones zone) as proposed by McKnight (1997). A total of 18 soil profiles, representative of Zone A2, were obtained in the study area.

As in Zone A1, Zone A2 soils are characterised by a deep highly leached profile. The top pallid, highly leached horizon often exhibits collapsible grain structure. Zone A2 also represents the transitional zone between Zones A1 and B1/B2 and between Zones A1 and C1. Consequently, soil profiles are highly variable, with soil depths ranging from 0.2m to deeper than 2.5m and refusal on either hardpan ferricrete or soft rock granite. The central parts of Zone A2 are generally more representative of Zone A1, while the edges of the zone are more representative to Zones B1, B2 and C1.

The hillwash consists of 0.2 to 0.7m of reddish brown to pale brown, loose, intact silty sand with scattered sub-rounded quartz and granite gravel and roots. The soils are often friable, voided and leached. The hillwash is underlain by a pebblemarker, sometimes absent or poorly developed and sometimes well developed, with a thickness between 0.1 and 0.4m. It typically consists of a tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of frequently ferruginised, silty fine, medium and coarse sand. The overall consistency of the layer is medium dense to dense.

A total of 17 per cent of soil profiles recorded refusal on hardpan ferricrete. These profiles were recorded close to the contact with Zone C1 (gully slope). Refusal occurred between 0.4m and 1.1m from ground surface. The hardpan ferricrete comprises orange-brown, mottled black and dark yellow, medium hard ferricrete. The hillwash and residual granite overlying the hardpan ferricrete are grey-brown, very loose to loose, voided, silty sand with sporadic quartz gravel.

A total of 44 per cent of soil profiles recorded refused on very soft rock granite. These profiles were recorded close to the contact with Zone B1 (straight slope). A typical soil profile comprises hillwash and pebble marker overlying a pale orange-brown to pale grey, sometimes weakly cemented ferruginous, loose to dense, silty sand, residual granite (S.Afr: reworked residual granite). This layer is generally underlain by pale orange brown, dense to very dense, relict jointed, silty sand completely weathered granite (S.Afr: residual granite)

A total of 39 per cent of soil profiles recorded no refusal to approximately 2.0m depth. These profiles were mainly recorded along the central parts of Zone A2. A typical soil profile comprises hillwash and pebble marker overlying reddish brown, voided, sometimes weakly cemented ferruginous, loose to dense, silty sand, completely weathered granite (S.Afr: residual granite).

Seepage was recorded in only on test pit. It is possible that the groundwater level occurs at depths greater than 2m.

Flow through the vadose zone is expected to be complex and flow characteristics depends on the underlying soil profile. In general, it is expected that flow in the central parts of convex ridges will be similar to Zone A1, i.e., water infiltrates predominantly along the more permeable preferential weathering zones. As in Zone A1, water will be perched on top of impermeable granite rock and will then flow down-slope along the more permeable jointed highly weathered granite.

Along the edges of Zone A1, representing transition to Zones B1 and C1, highly weathered granite is absent from the profile and the shallow bedrock occurs at approximately 2m depth. The fact that no water has been encountered during recording of the soil profile indicates that limited water is stored within these layers. Water either flows down-slope to drainage areas or is removed by evapotranspiration processes. Flow within soils characterised by hardpan ferricrete layers will be similar to that of Zone C1 and will be described in the relevant section.

The conceptual unsaturated groundwater model for Zone A2 is shown in **Figure 7.5**. The medium to high permeability of the soils implies that recharge events will be closely related to rainfall events. The high permeability of soils also implies high evapotranspiration rates. However, in the case of very high evapotranspiration rates, the top soil layers will dry out rapidly. This will result in a significant decrease in hydraulic conductivity and consequently, the upward movement of water from deeper more saturated zones will be impeded. In the case that water is perched on shallow bedrock or hardpan ferricrete, evapotranspiration processes will remove the perched water.

Areas underlain by Zone A2 are almost without exception recharge areas, the exceptions being very shallow soils where seepage may occur, thereby acting as a discharge point. In general, it can be concluded that the shallow aquifer systems are vulnerable to pollution due to the low travelling times. Since fractured aquifer systems are generally associated with linear drainage features in the study area, it can be concluded that the potential for groundwater will be low. However, linear features, that could represent fractured zones with a high potential for groundwater, occasionally cross Zone A2 areas at several topographic saddles.

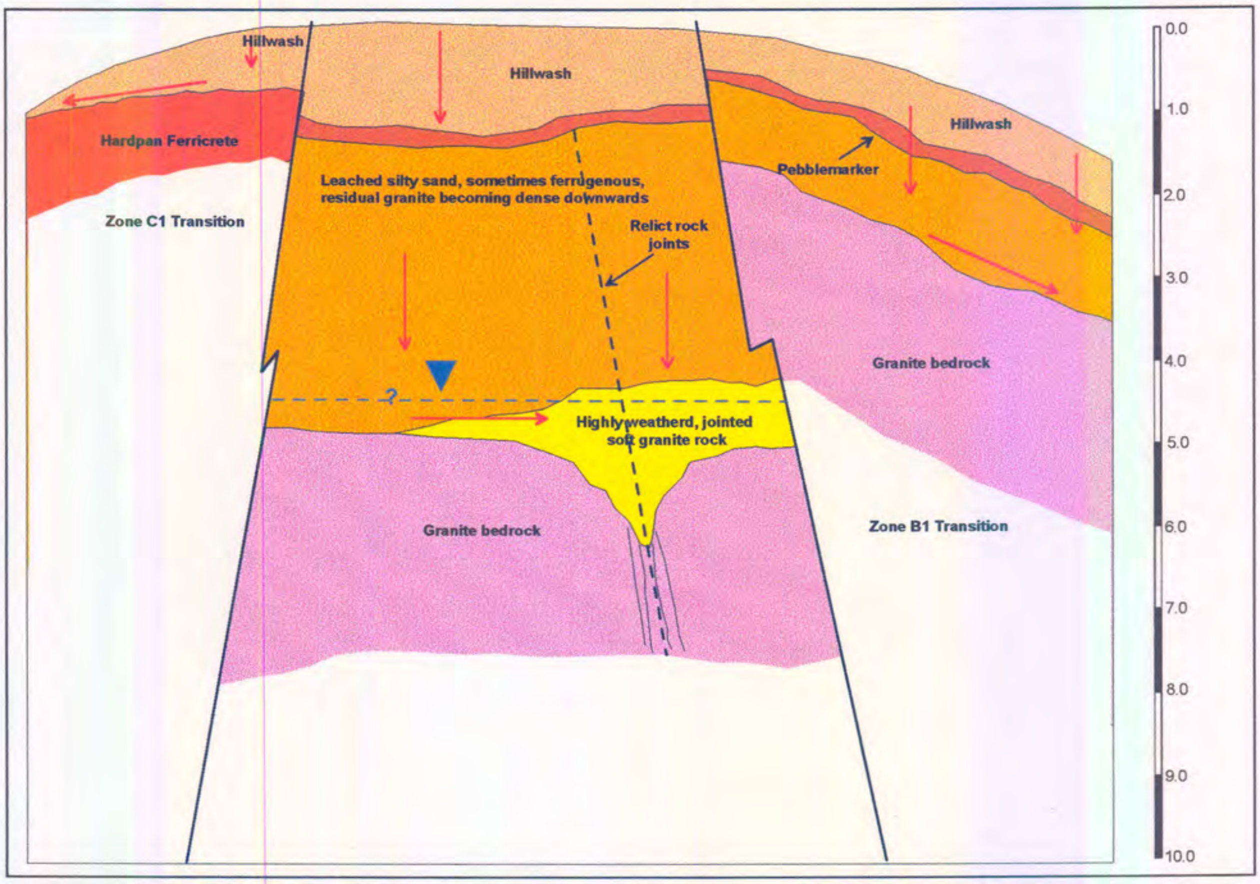

Figure 7.5: Typical soil profile and conceptual unsaturated groundwater model for Zone A2

Zone A3

Zone A3 represents the upper slopes occurring south of the dominant east-west ridge in the study area. The lower boundary of this zone is defined by the 1550m contour level and represents the approximate base of the African erosion surface. The zone is entirely underlain by foliated granodiorites (Hilliard, 1994) also known as the transitional zone (Anhaeusser, 1973). Zone A3 does not occur along the northern parts of the investigation area (underlain by banded gneisses), even though large parts occur above the 1550m contour line. The zone corresponds to KYAL0203 (Convex side slope, hillwash on residual granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also corresponds to the Scarp & Shelf (African Base with corestones) as proposed by McKnight (1997).

Only two soil profiles, representative of Zone A3, were obtained. The soil profiles have been recorded up to 2.0m in depth, which is not representative of a typical soil profile for Zone A3. Consequently, expected physical and hydrogeological characteristics of this zone are mostly based on work by McKnight (1997). The development of corestones and tors along the foliated granodiorite has been discussed in **Section 7.2.2**.

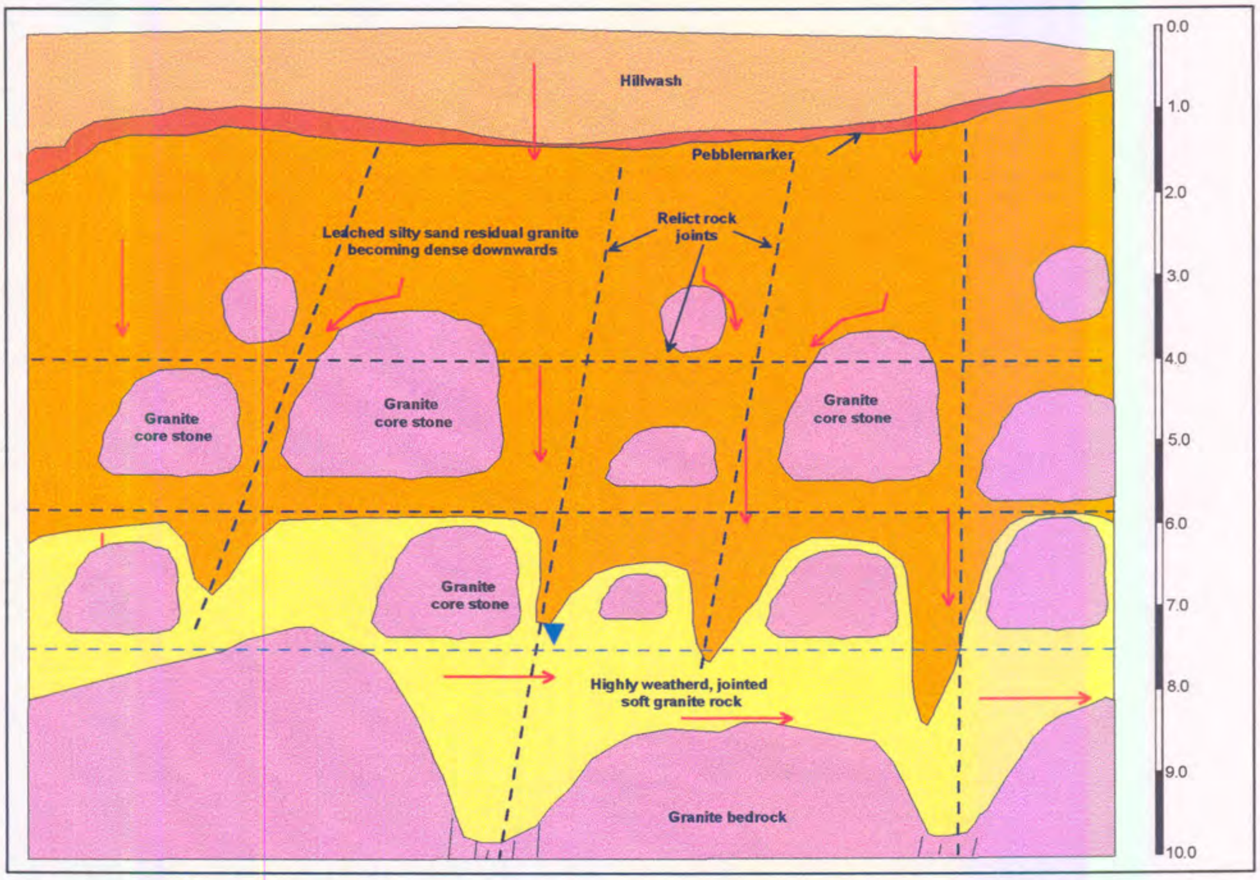

Figure 7.6: Typical soil profile and conceptual unsaturated groundwater model for Zone A3

Zone A3 is characterised by a deep, sometimes leached, soil profile. Corestones frequently occur in the profile. The size and frequency of corestones is highly variable and corresponds to the structure of the underlying bedrock. In essence, the weathering profile is similar to that of Zone A1, except that the extent of weathering is less pronounced. Consequently, top soil layers have in general not been as extensively leached and corestones have developed.

The hillwash consist of approximately 0.4m of greyish brown, loose, intact silty sand with scattered sub-rounded quartz and granite gravel and roots. The soils are often friable, voided and leached. The hillwash is underlain by a pebblemarker, sometimes absent or poorly developed and sometimes well developed, with a thickness of approximately 0.1m. It typically consists of a tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of silty fine, medium and coarse sand. The overall consistency of the layer is medium dense to dense.

Flow through the unsaturated soil profile is mainly along preferential weathering zones. The conceptual unsaturated groundwater flow model is represented in **Figure 7.6**. The medium to high permeable nature of the soils implies that recharge events will closely be related to rainfall events. During infiltration, water flows predominantly along the more permeable preferential weathering zones. The infiltrating water is channelled pass the impermeable corestones as indicated in **Figure 7.6**. This results in extensive leaching between corestones.

The main pathway of water within the phreatic zone is along high-permeable medium to highly weathered jointed soft rock zones. Flow along these zones is mainly horizontal. This zone

i Provide base flow to streams

ii Results in seepage along lower slopes characterised by a shallow bedrock or ferricrete layers or iii could recharge deeper fractured aquifer systems.

Areas underlain by Zone A3 are mostly recharge areas. In general, it can be concluded that the shallow aquifer systems are vulnerable to pollution due to the low travelling times. Since fractured aquifer systems are generally associated with linear drainage features in the study area, it can be concluded that the potential for groundwater will be low. However, it has been stated that these zones could act as water storage and could recharge deeper aquifer systems.

Zone B1

Zone B1 represents straight to slightly convex slopes within the study area, excluding areas occurring south of the dominant east-west ridge above 1550m. Zone B1 covers the largest portion of the study area. The zone corresponds to KYAL0203 (Convex side slope, hillwash on residual granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also corresponds partly to the Concave Upper/Middle Slope (Zone C) as proposed by McKnight (1997). Zone B1 occurs on the Post African I erosion surface.

A total of 38 soil profiles, representative of Zone B1, were obtained in the study area. Most of these soil profiles formed part of geotechnical investigations for residential development and small office developments and consequently, soil profiles had been described only up to approximately 2.5m in depth.

Zone B1 soils are characterised by their variability in physical soil profile attributes. The soil profiles are deeply weathered, underlain by shallow granite rock or underlain by shallow hardpan ferricrete. In contrast to Zone A2 soils, there appears to be no correlation between the physical soil profile characteristics and its position in relation to other morphology units. This implies that the hydrogeological characteristics of this zone can not be predicted and will depend on site-specific situations.

The hillwash and pebble marker layers are similar in appearance to that observed in Zones A1, A2 and A3 soils.

A total of 42 per cent of all soil profiles did not record refusal up to approximately 2.5m. A typical soil profile comprises hillwash and pebble marker overlying reddish brown, voided, ferruginous, loose to dense, silty sand completely weathered granite (S.Afr: residual granite). Ferruginous layers occur in all these soil profiles. The ferruginous layers generally occur between 0.2 and 0.6m below ground surface and their thickness could range between 0.2m to 2.3m

The ferruginous zones comprises either scattered ferricrete nodules, weakly to well cemented ferricrete concretions, honeycomb ferricrete or boulder ferricrete. The boulder ferricrete indicates weathering of ferricrete layers. According to McKnight (1997), the residual ferruginised soil layers could have developed under wet paleo-climate conditions and because the ferricrete is slowly dissolving under present climatic conditions.

A total of 37 per cent of all soil profiles recorded refusal on pale brown to grey, soft to hard, highly weathered to moderately weathered granitoid rock. A typical soil profile comprises hillwash and pebble marker overlying a reddish brown to pale grey, sometimes ferruginous, medium dense to very dense, silty sand, residual granite (S.Afr: reworked residual granite). This layer is generally underlain by pale orange brown, dense to very dense, sometimes micaceous, relict jointed, silty sand, completely weathered granite (S.Afr: residual granite). Ferruginous soil layers were recorded in only three of these soil profiles. The ferruginous soil layers comprises either nodular ferricrete or boulder ferricrete.

A total of 21 per cent of all soil profiles recorded refusal on hardpan ferricrete. Refusal occurred between 0.2m and 1.3m from ground surface. The hardpan ferricrete comprises orange brown, mottled black and dark yellow, medium hard ferricrete. The hillwash and residual granite overlying the hardpan ferricrete are described as grey-brown, very loose to loose, voided, silty sand with sporadic quartz gravel. The residual granite and overlying pebble marker are often ferruginised.

The variability in soil profile descriptions closely resembles that of Zone A2. However, in contrast to Zone A2 soils, seepage was recorded in 37 per cent of all soil profiles described. This supports the hypothesis that water generally flows down-slope along Zone A2 towards Zone B1. The perched aquifers in Zone B1 are being recharged by rainfall, runoff and down-slope seepage originating from Zone A2. This net recharge effect exceeds evapotranspiration. However, given the seasonal rainfall patterns, it is expected that most water in the perched aquifer will either evaporate or discharge into drainage channels during the dry winter months. This hypothesis is supported by the fact that no seepage had been encountered in most soil profiles recorded during the dry season.

In the case of shallow bedrock, the highly weathered granite is generally absent from the profile and the shallow bedrock occurs at approximately at a depth of 2m. Water either flows down-slope to drainage areas or is removed by evapotranspiration processes. Flow within soils characterised by hardpan ferricrete layers will be similar to that of Zone C1 and will be described in the relevant section.

The conceptual unsaturated groundwater model for Zone B1 is shown in **Figure 7.7**. The medium to high permeability soils and the shallow weathering profile implies that recharge events will closely be related to rainfall events. As with Zone A2, the high permeability of soils also implies high evapotranspiration rates.

Areas underlain by Zone B1 are mostly recharge areas, the exceptions being very shallow soils where seepage can occur, thereby acting as discharge points. In general, it can be concluded that the shallow aquifer systems are vulnerable to pollution due to the low travelling times. Since fractured aquifer systems are generally associated with linear drainage features in the study area, it can be concluded that the potential for groundwater will be low. However, linear features, which may represent fractured zones with a high potential for groundwater, occasionally occur within Zone B1.

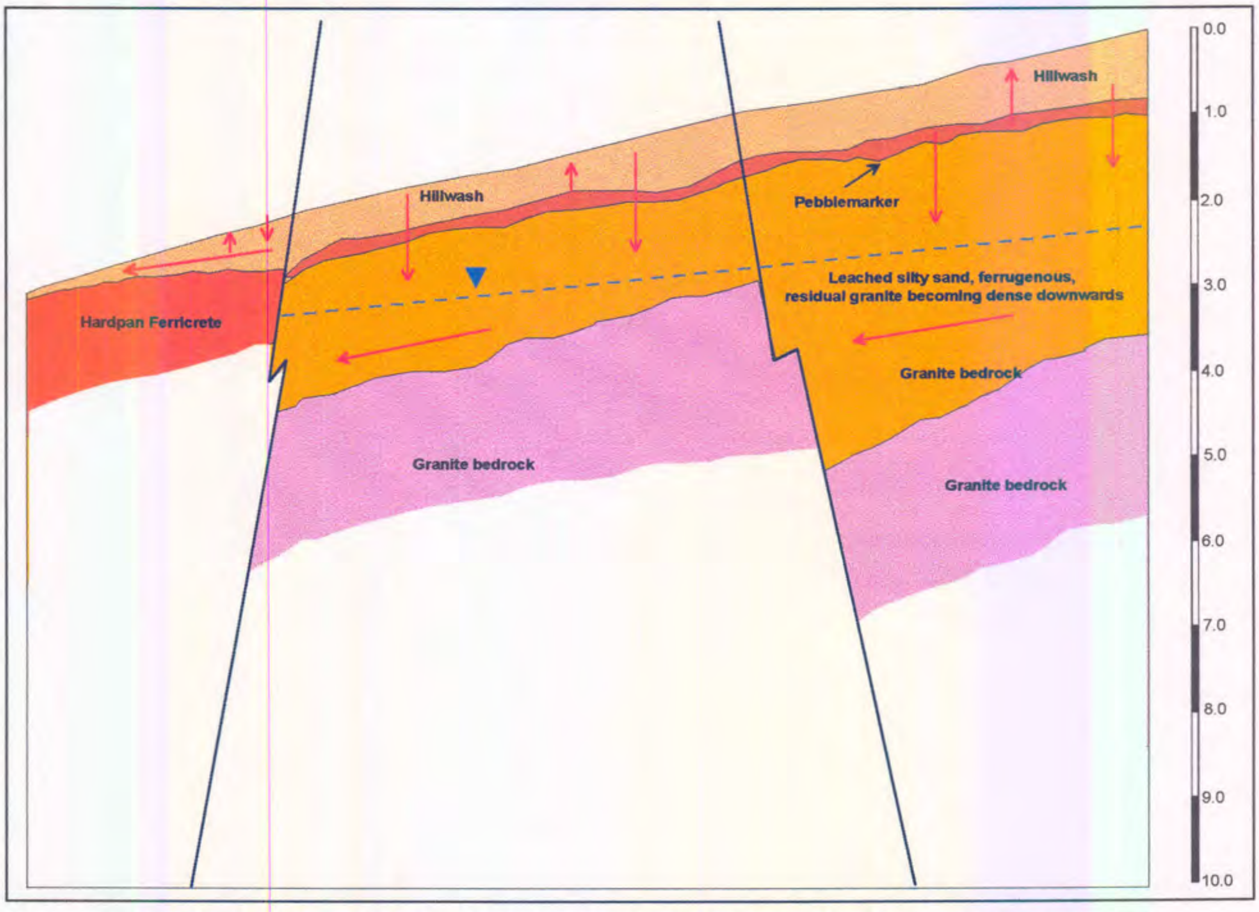

Figure 7.7: Typical soil profile and conceptual unsaturated groundwater model for Zone B1

Zone B2

Zone B2 represents a narrow band of slightly convex lower slopes, adjacent to drainage features within the study area. The zone corresponds to KYAL0203 (Convex side slope, hillwash on residual granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also partly corresponds to the Concave Upper/Middle Slope (Zone C) as proposed by McKnight (1997). Lower side slopes are not distinguished from middle and upper slopes for geotechnical purposes, except when possible flooding zones are indicated. This can be attributed to the fact that the soil profile characteristics are similar to that of the middle and upper slopes. However, it has been envisaged that the hydrogeological characteristics of Zone B2 will differ significantly from the upper slopes. Zone B2 occurs on the Post African I erosion surface.

A total of 6 soil profiles, representative of Zone B2, were obtained in the study area. Most of these soil profiles formed part of geotechnical investigations for residential development and small office developments and consequently, soil profiles have been described only up to approximately 2.5m in depth.

Hardpan ferricrete had been recorded in five of the six soil profiles. Although the sample number is too small to deduce valid conclusions, it would appear that shallow hardpan ferricrete is a prominent feature in Zone B2 soils.

The hillwash layers appears to be similar in appearance to that observed in other soil zones. However, the pebble marker appears to be either absent or poorly developed. Since Zone B2 soils are located at the forefront of active erosion processes, i.e., close to eroding drainage channels, it is possible that the pebble marker has been eroded away.

A typical soil profile consists of hillwash, between 0.2 and 0.7m in thickness, overlying light grey to yellowish grey loose to very loose, voided, silty sand. Occasional ferricrete nodules occur in the layer, which is approximately 0.5m in thickness. The loose residual granite is underlain by hardpan ferricrete, approximately 0.4 to 1.4m from ground surface.

Although no soil profiles were obtained in the southern parts of the study area, visual inspection revealed tor development along lower slopes, close to drainage features. It is postulated that significant erosion occurred along these areas, thereby exposing corestones that developed in the soil profile along Zone A3 areas. The Boulders shopping centre, built on top of large granitoid boulders, is partly located in a Zone B2 area. Tors were also identified along other areas within Zone B2 and alongside Zone A3 areas, though extensive development has shadowed many of the tors. It is significant that the observed large boulders are confined to the southern parts of the study area, underlain by foliated granodiorite, while no boulders were observed in the northern parts of the study area, which are underlain by banded gneiss.

No seepage was recorded in any of the test pits, contradictory to expectations. However, all of these soil profiles were recorded during the end of the dry season and it is postulated that the water had either been discharged in the drainage channel, or was removed by evapotranspiration processes during the dry season. It is expected that surface seepage will occur over large parts of the area during the rain season, especially after significant rainfall events. This presumption is supported by visual observations made during the borehole census in the area. Widespread seepage was observed along Zone B2 areas, especially in the region of borehole BH008. According to the residents, seepage generally occurs during the rainy season.

The conceptual unsaturated groundwater model for Zone B2 is shown in **Figure 7.8**. Water flows rapidly on top of impermeable ferricrete layers within the permeable loose residual granite and hillwash. The zone is recharged by rainfall, surface runoff and seepage originating from Zone B1. During wet weather conditions, surface seepage occurs and Zone B2 therefore acts as a discharge zone. Zone B2 is therefore a major contributor of base flow to small streams. Since sub-surface seepage is a major recharge factor for Zone B2 areas, long periods of surface seepage are expected after significant rainfall events.

Areas underlain by Zone B2 are generally recharge areas during dry weather conditions and may change to discharge areas during wet weather conditions. The impermeable ferricrete layer acts as a barrier against aquifer contamination but surface water features could be highly vulnerable to contamination since these areas are a major contributor of base flow to surface water bodies. Since secondary fractured aquifer zones are generally associated with drainage features, it can be concluded that these aquifers are also vulnerable to contamination.

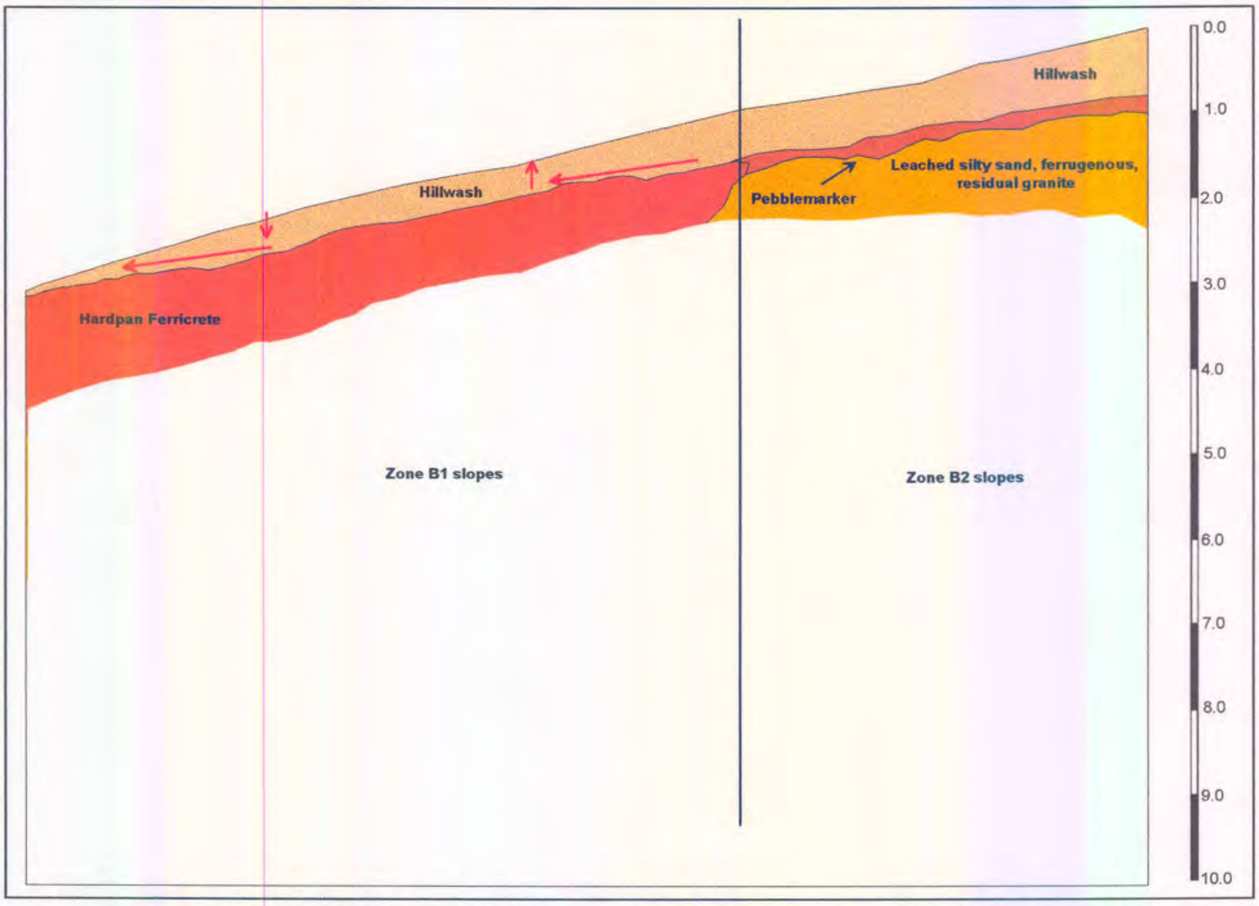

Figure 7.8: Typical soil profile and conceptual unsaturated groundwater model for Zone B2

Zone B3

Zone B3 represents slightly convex slopes occurring below the 1 500m contour line, and is representative of the Post African II erosion surface. The zone corresponds to KYAL0203 (Convex side slope, hillwash on residual granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also corresponds partly to the Middle/Lower Slope (Zone D) as proposed by McKnight (1997). Zone B3 is confined to the far northern and far southern areas in the study area.

No soil profiles representative of Zone B3 were obtained in the study area. As such, the physical and hydrogeological characteristics of this zone were deduced from soil profiles occurring outside the study area, within areas representative of Zone B3.

A large proportion of soil profiles occurring in Zone B3, recorded refusal on shallow, pale brown, soft to medium hard, highly to moderately weathered granitoid rock. Shallow bedrock is a prominent feature in Zone B3 soils.

The hillwash and pebble marker layers are similar in appearance to that observed in other soil zones. A typical soil profile consists of hillwash, between 0.1 and 0.4m in thickness, and a pebble marker consisting of tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of silty fine, medium and coarse sand. These layers are underlain by yellowish brown to orange brown, medium dense to very dense, relict jointed, micaceous, silty sand. Occasional ferricrete nodules occur in the top residual granite layer. Granite bedrock occurs approximately between 1.3m and 2.9m below ground surface.

Seepage was observed in some of the test pits, approximately 2m below ground surface.

The conceptual unsaturated groundwater model for Zone B3 is shown in **Figure 7.9**. Water flows rapidly on top of impermeable bedrock within the completely weathered granite (S.Afr: residual granite). The zone is recharged by rainfall, surface runoff and seepage originating from Zone B1.

Areas underlain by Zone B3 are mostly recharge areas, but surface seepage occurs in areas underlain by very shallow bedrock or bedrock outcrops. The perched aquifers in Zone B3 are being recharged by rainfall, runoff and down-slope seepage originating from Zone B1. This net recharge effect may exceed evapotranspiration, but given the highly seasonal nature of South African rainfall, it is expected that most water in the perched aquifer will either evaporate or discharge into drainage channels during the dry winter months.

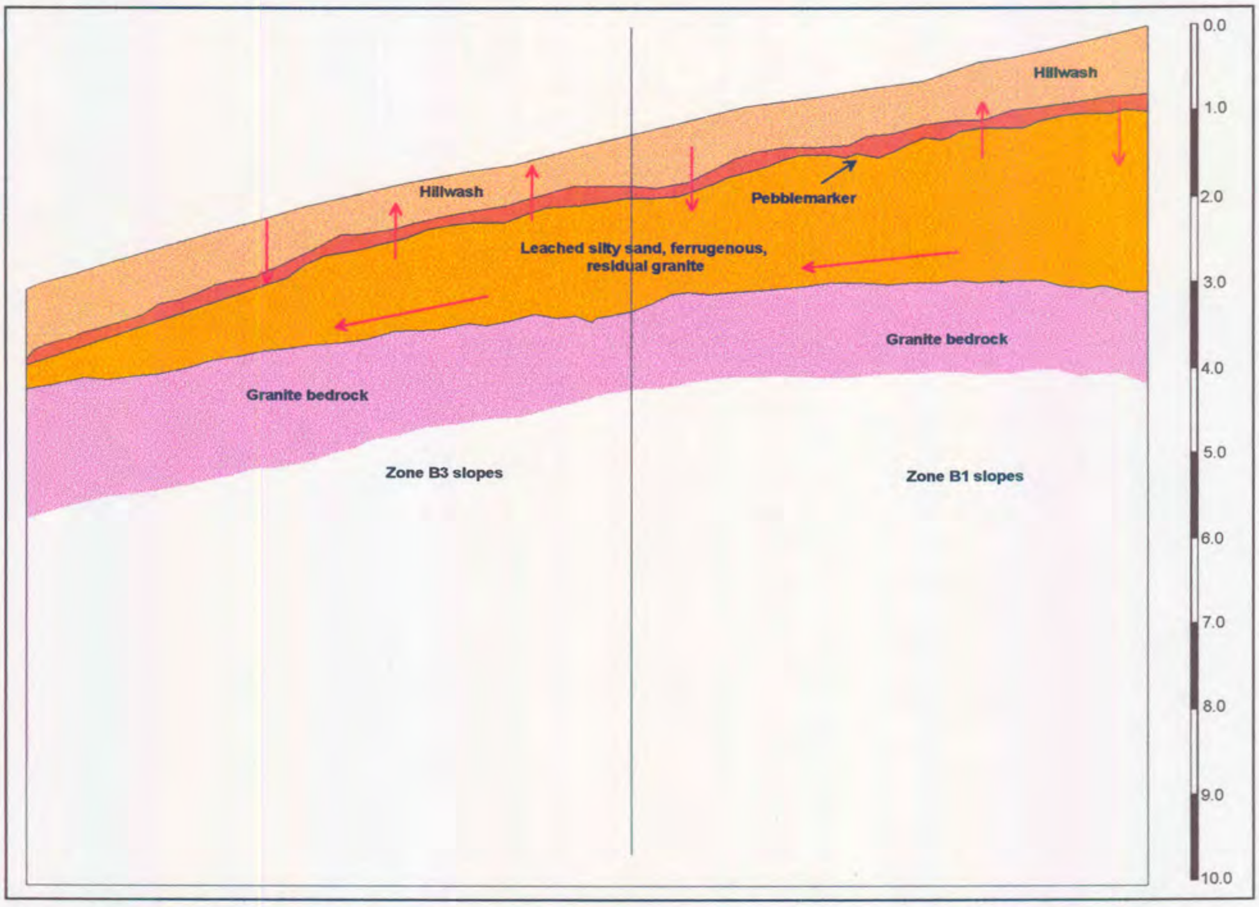

Figure 7.9: Typical soil profile and conceptual unsaturated groundwater model for Zone B3

Zone C1

Zone C1 represents areas occurring along stream heads in the investigation area. The zone corresponds to KYAL0501 (sandy gully wash derived from granite) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). It also corresponds partly to the Concave Middle/Lower Slope (Zone D) as proposed by McKnight (1997). Gully heads are readily identifiable in Aerial Photo Interpretation.

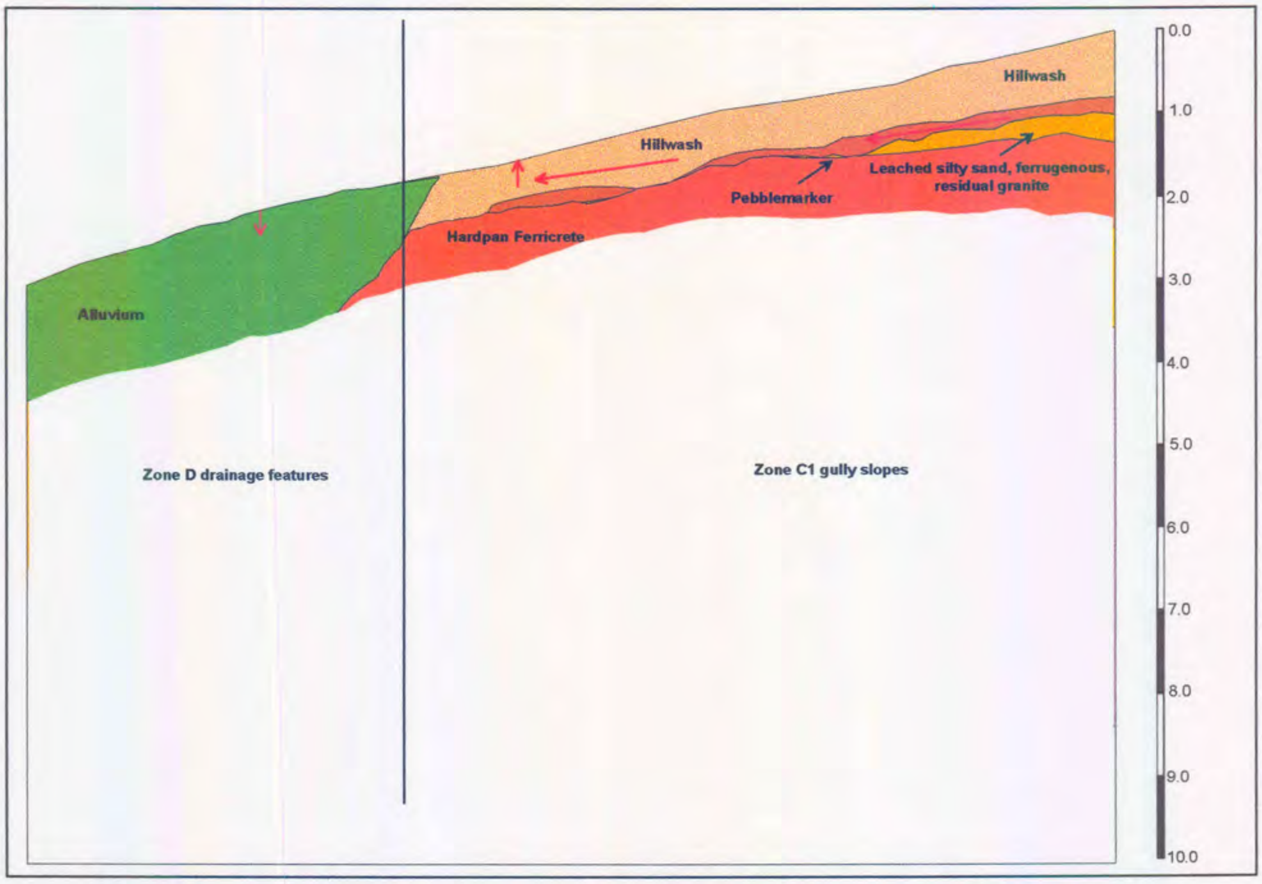

Figure 7.10: Typical soil profile and conceptual unsaturated groundwater model for Zone C1

Zones C2 and C3

It has been recognised that the depth to impermeable ferricrete/bedrock layers is one of most important aspects in assessing the hydrogeological characteristics of the vadose zone. As such, these factors had been incorporated in the GIS map and are indicated as Zones C2 and C3 in **Drawing 1**. Expected shallow soil profiles had been mapped during a regional geotechnical investigation, which includes the investigation area. Mapping was based on the soil profile descriptions and the frequency of bedrock outcrops in the area. Zones C2 and C3 differ from other hydrogeological units in that their boundaries were not derived from by means of aerial photo interpretation. The zones occur mainly adjacent to Zones B1, A2 and A3.

Zone C2 areas are characterised by occasional bedrock or ferricrete outcrops. Based on soil profiles in these zones, it is expected that hardpan ferricrete or granite bedrock will occur between 1.0 and 3.0m below ground surface. Zone C3 areas are characterised by frequent bedrock or ferricrete outcrops. Based on soil profiles within these zones, it is expected that hardpan ferricrete or granite bedrock will occur within 1.5m below ground surface.

A total of 11 soil profiles, representative of Zones C2 and C3 were obtained. All of these soil profiles formed part of geotechnical investigations for residential development and small office developments and consequently, soil profiles had been described only up to approximately 2.5m in depth.

Only 3 of the 11 soil profiles are representative of Zone C2. Of these three soil profiles, one was recorded in residual greenstone material, one recorded refusal at 0.7m on hardpan ferricrete and one recorded no refusal up to 1.8m in depth. The assumption that soil depths of between 1.0m and 3.0m occur within Zone C2 areas could therefore not be verified

A total of 8 soil profiles are representative of Zone C3. Hardpan ferricrete was recorded in 7 of the 8 profiles between 0.1m and 1.3m from ground surface. It would therefore appear that the presumption that shallow profiles can be expected in areas characterised by frequent hardpan ferricrete/bedrock outcrops is true.

The soil profile generally consists of hillwash, between 0.1m and 0.5m in thickness, overlying a pebblemarker. Residual granite is typically absent from the soil profile and the pebble marker is sometimes also absent in the case of very shallow soil profiles.

The hillwash typically consists of yellowish to greyish brown, loose to very loose, voided, silty to clayey sand with sporadic quartz gravel. The underlying pebble marker consists of tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of ferruginous, silty fine, medium and coarse sand.

The conceptual unsaturated groundwater model for Zones C2 and C3 is shown in **Figure 7.11**. The flow mechanisms are expected to be similar to that of Zones C1 and B2. Water flows rapidly on top of impermeable ferricrete layers within the high-permeability, loose, residual granite and hillwash. During wet weather conditions, surface seepage occurs and Zones C2 and C3 which act as a discharge zone.

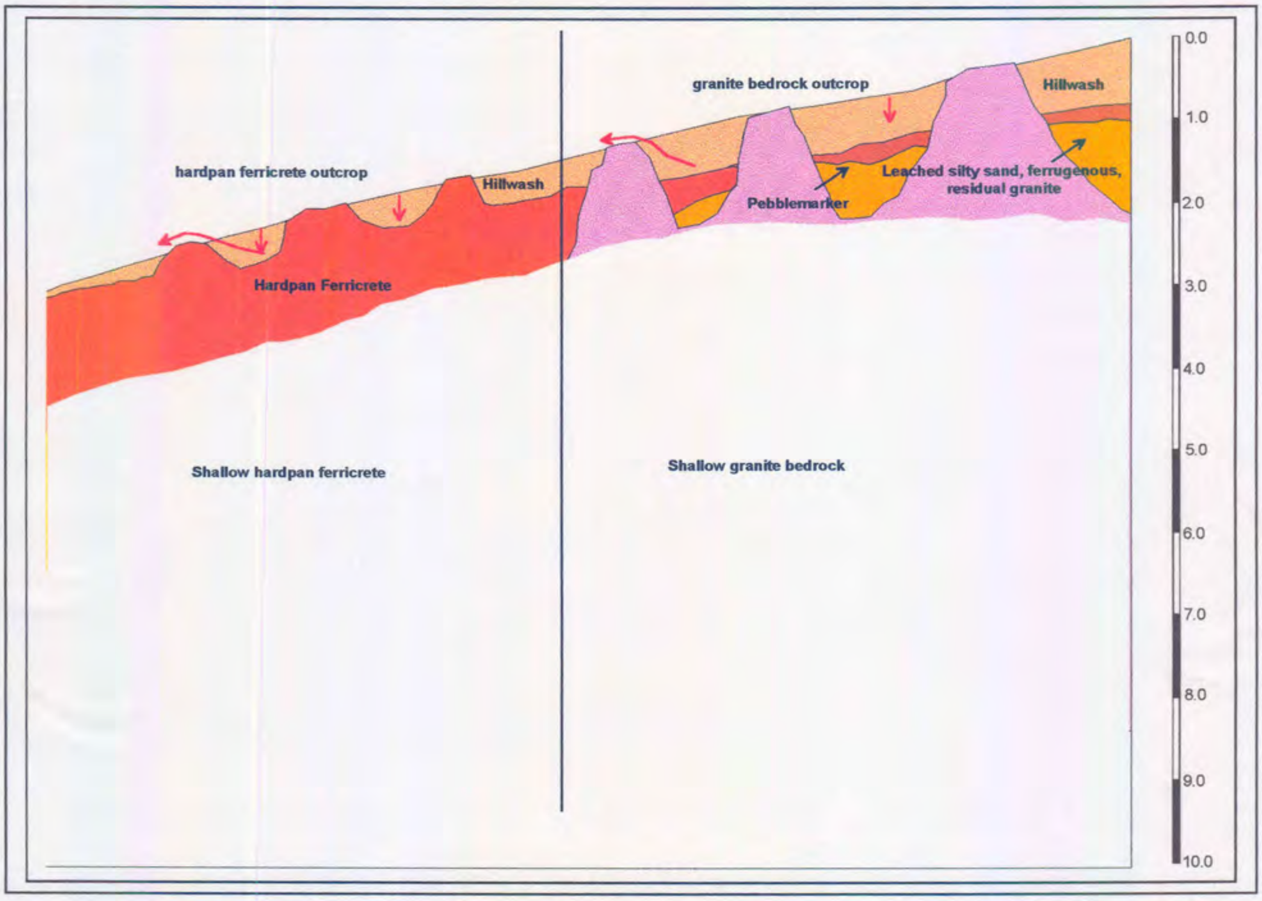

Figure 7.11: Typical soil profile and conceptual unsaturated groundwater model for Zones C2 and C3

Areas underlain by Zone C3 are generally recharge areas during dry weather conditions and could change to discharge areas during wet weather conditions. The impermeable ferricrete layer acts as a barrier to aquifer contamination. However, surface runoff will manifest in streams and it can be concluded that surface water features could be vulnerable to contamination.

Zone D

Zone D represents drainage lines in the investigation area. The zone corresponds to KYAL07 (alluvial floodplain) as proposed by Brink & Partridge (1967) and modified by Stiff (1994). Drainage features are readily identifiable in aerial photo interpretation. The drainage lines generally occur as linear features and conform to the underlying structural geology.

Only 2 soil profiles, representative of Zone D, were obtained in the study area. These soil profiles form part of geotechnical investigations for residential development and small office developments and consequently, soil profiles had been described only up to approximately 2.5m in depth.

A field investigation revealed that major drainage lines are generally located on extensive alluvium. The alluvium generally comprises alternating dark grey, firm, sometimes fissured or micro-shattered, sandy clay and light grey, loose, fine sand.

Gully wash frequently underlies minor drainage lines. The gully wash generally comprises dark grey loose clayey sand becoming more clayey deeper in the soil profile.

Granitoid rock outcrops within the Rietspruit located in the northern parts of the investigation area. These areas are located on the Post African II erosion surface, characterised by shallow bedrock. According to McKnight (1997), granitoid bedrock frequently occurs in drainage channels located on the Post African II erosion surface.

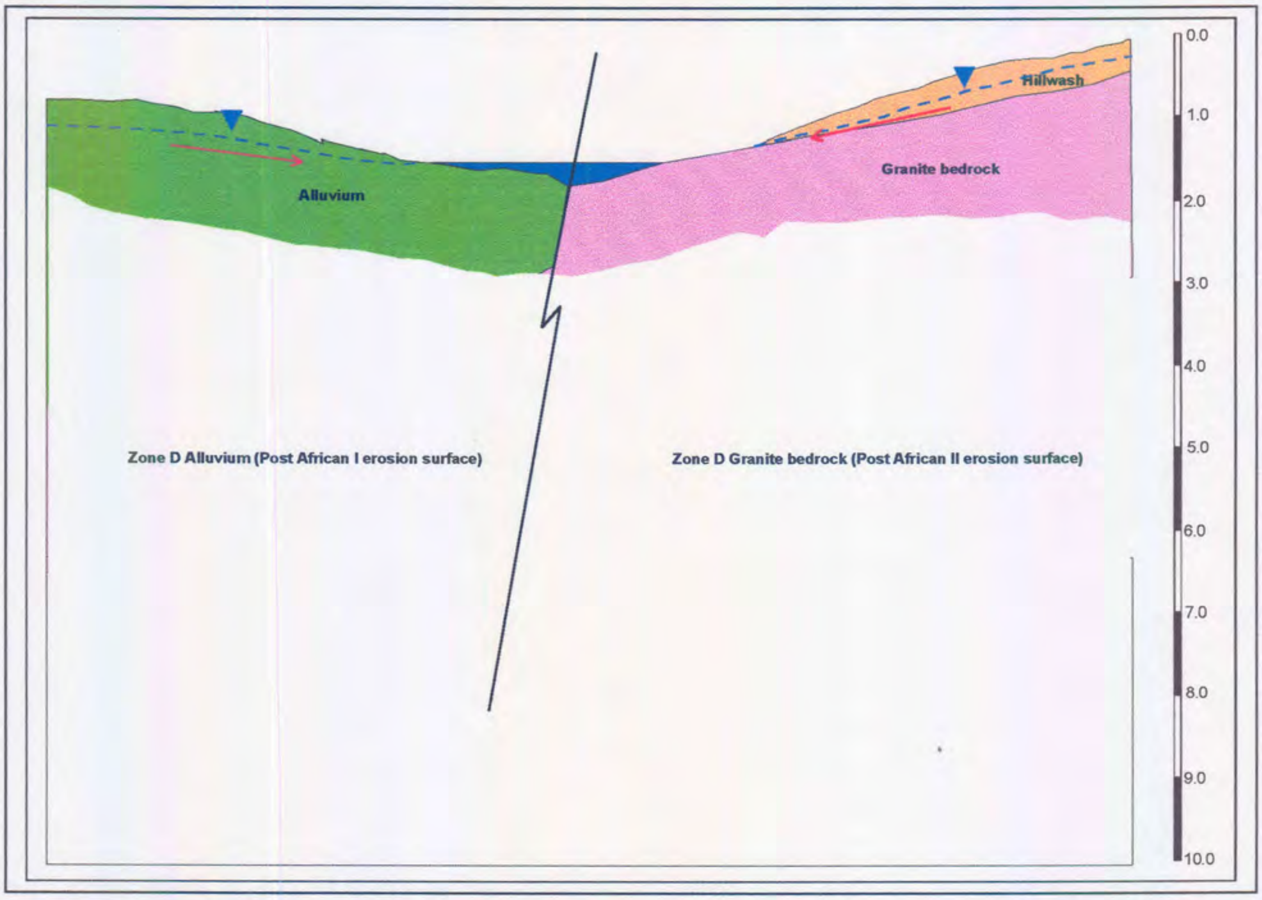

Figure 7.12: Typical soil profile and conceptual unsaturated groundwater model for Zone D

The conceptual unsaturated groundwater model for Zone D is shown in **Figure 7.12**. Zone D areas are generally discharge areas. Rainfall infiltrates soils in higher lying areas and flows down-slope after

A total of 10 soil profiles, representative of Zone C1, were obtained in the study area. Most of these soil profiles formed part of geotechnical investigations for residential development and small office developments and consequently, soil profiles were described only up to approximately 2.5m in depth.

Hardpan ferricrete was recorded in 8 of the 10 soil profiles. Although the sample number is too small to deduce valid conclusions, it appears that shallow hardpan ferricrete is a prominent feature in Zone C1 soils.

The hillwash layer is between 0.2m and 0.6m in thickness and typically consists of yellowish to greyish brown, loose to very loose, voided, silty sand with sporadic quartz gravel. The underlying pebble marker consists of tightly packed to loosely packed sub-rounded and sub-angular quartz and granite gravel in a matrix of ferruginous, silty fine, medium and coarse sand. The pebblemarker is frequently either absent or poorly developed.

In some cases, the hardpan ferricrete has developed directly underneath the pebblemarker or hillwash. In many cases, the transported soil is underlain by reddish to orange brown, very loose to medium dense, ferruginous, silty sand residual granite. The hardpan ferricrete occurs between 0.2m and 1.0m in depth below the ground surface.

No seepage was recorded in any of the test pits, contradictory to what was expected. However, all of these soil profiles had been recorded during the end of the dry season and it is postulated that the water was either discharged in the drainage channel, or removed by evapotranspiration processes during the dry season. It is expected that surface seepage will occur over large parts of the area during the rain season, especially after significant rainfall events. Widespread seepage was observed along Zone C1 areas during the rainy season.

The conceptual unsaturated groundwater model for Zone C1 is shown in **Figure 7.10**. In general, Zone C1 is similar in appearance to Zone B2. The flow mechanisms are also expected to be similar. Water flows rapidly on top of impermeable ferricrete layers within the permeable, loose, residual granite and hillwash. The zone is recharged by rainfall, surface runoff and seepage originating from Zone B1. During wet weather conditions, surface seepage occurs and Zone C1 therefore acts as a discharge zone. Zone C1 is therefore, like Zone B2, a major contributor of base flow to small streams. Since subsurface seepage is a major recharge factor in Zone C1 areas, long periods of surface seepage are expected after significant rainfall events.

Areas underlain by Zone C1 are generally recharge areas during the dry season and changes to discharge areas during the wet seasons. The impermeable ferricrete layer acts as a barrier against aquifer contamination but surface water features are highly vulnerable to contamination since these areas are a major contributor of base flow to surface water bodies. Since secondary fractured aquifer zones are generally associated with drainage features, it can be concluded that these aquifers are also vulnerable to contamination.

Springs originating from gully heads are sometimes used for feedstock watering, irrigation and domestic purposes.

which it discharges into streams. Minor streams are frequently seasonal in nature, implying that limited recharge occurs along these areas during dry weather conditions. In addition, fractured aquifer systems are frequently associated with the drainage features. As such, a lowering in groundwater levels in these areas can be expected during high borehole abstraction rates, resulting in the aquifer being recharged by the stream. In cases where surface water is contaminated, the fractured aquifer could also become contaminated.

The streams are obviously vulnerable to pollution.

CHAPTER 8

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

8.1 Discussion

The theoretical aspects regarding saturated and unsaturated flow are well researched. Most of the knowledge regarding the vadose zone has been collected by hydrogeologists, soil scientists and, more recently geotechnical (and geological) engineers and engineering geologists. However, this knowledge is mostly based on investigations in shallow transported soil and very little research has been conducted in deeper residual soils and rocks. Very little is known about the hydrogeological properties of deep residual soils and these aspects need further investigation.

Many practising geohydrologists and engineering geologists lack knowledge of flow processes in the vadose zone. As a result, important aspects in groundwater recharge and contamination investigations may be overlooked. These aspects may also be overlooked during investigation of engineering structures that may affect groundwater quality, such as waste disposal sites, cemeteries and low-cost housing.

Although preferential flow has been identified as an important contributor to groundwater recharge as early as 1882, it was only in the 1980's that preferential flow processes began to be investigated in detail. It is very difficult to estimate flow through preferential pathways. Much progress has been achieved in understanding preferential flow processes. Although conventional, Darcian-based one-dimensional flow equations have been verified in laboratory and field tests, little research has been conducted on flow through residual soils. From recharge studies conducted in South Africa, it is argued that preferential flow may be an important aspect in groundwater recharge and contamination of groundwater resources.

Many relationships between hydrogeological properties and hydrogeological data were found in literature. Soil profile descriptions are the most versatile of all geotechnical data sources and a number of hydrogeological properties can be derived. The literature study has shown that estimations of hydrogeological properties, especially hydraulic conductivity, are not very reliable. To the author's knowledge, no attempt has been made to describe soil profiles in terms of their hydrogeological characteristics. Such descriptions could greatly assist in the understanding of flow processes in field soils and may result in more accurate assessments of hydrogeological properties. This is especially true in the case of preferential flow processes.

Poor relationships between saturated hydraulic conductivity and soil-water retention characteristics have been observed. This can be ascribed to soil-water characteristics being largely a factor of the specific surface (and thus size) of the soil grains, while saturated hydraulic conductivity is largely a function of large soil pore conduits.

Soil-water retention characteristics can be estimated from geotechnical data, in particular from soil fractions and grain size distribution curves. The literature survey has revealed that the Van Genuchten (1980) and Fredlund and Xing (1994) functions can best describe soil water characteristic curves for a large range of soil types and these have been verified by the experimental results.

The relationships between soil-water characteristic curves and unsaturated hydraulic conductivity have been well researched. Excellent estimations of unsaturated hydraulic conductivity can be obtained, provided that the saturated hydraulic conductivity is known and that the soil-water characteristic curve is well described by the Van Genuchten (1980) and other functions. This has been confirmed by the experimental results showing that the Van Genuchten (1980) and Fredlund et al (1994) models can accurately predict the unsaturated hydraulic conductivity. It appears that the Van Genuchten (1980) model best describes sandy soils while the Fredlund *et al* (1994) model best describes clayey soils. These trends should be confirmed.

The results of saturated hydraulic conductivity achieved by Large-Diameter Double Ring Infiltrometer tests confirm the reliability of this test. In contrast, the high variability of saturated hydraulic conductivity achieved from laboratory tests proves that the samples tested were not representative of the field soils. The experiments indicate that saturated hydraulic conductivity can accurately be obtained by means of *in situ* tests. However, laboratory permeability test results indicate that accurate values of saturated hydraulic conductivity may be obtained, provided that a representative number of samples are tested and that these tests are conducted on undisturbed samples.

One major advantage of conducting large-scale *in situ* tests is that preferential pathways may be intercepted, thereby acknowledging the effect of preferential flow. The field experiments indicate that preferential flow, in particular macropore channelling, is probably not a significant factor in water flow through residual granite on the scale tested. However, limited preferential flow has been observed at all experimental sites.

It is important to note that experiments have been conducted on limited soil types and on limited scales. Fingering and funnelled preferential flow types have not been tested. Observations made at the experimental sites cannot be extrapolated to other soil types. Additional research has to be conducted on a wider range of soils and on larger scales in order to determine the effect of preferential flow in field soils. Preferential flow is probably more pronounced in fine-grained soils due to their low permeability. Layered and heterogeneous field soils may also be prone to preferential flow.

Internal Drainage methods may not yield accurate estimations of unsaturated hydraulic conductivity. In addition, unsaturated hydraulic conductivity can only be derived for a small data range, depending on the drainage rate of soils. Alternatively, unsaturated hydraulic conductivity can be obtained indirectly, provided that the soil-water characteristic curve for field soils can be obtained by simultaneously measuring the water content and soil suction of field soils during drainage or wetting (e.g. by means of neutron probes and tensiometers).

Land pattern techniques proved to be a successful tool in delineating field soils of similar hydrogeological characteristics. In both the geotechnical and soil science fraternities, these techniques have been used with success in identifying soils with similar characteristics. From the geotechnical point of view, land pattern classification techniques enable engineering geologists to identify possible problem soil areas. Although some examples have been found in literature where remote sensing techniques have been employed in hydrogeological investigations (of the vadose zone), these techniques are not as well entrenched as in geotechnical investigations. There exists excellent potential to exploit land pattern techniques for hydrogeological investigations.

Land pattern classification techniques have been applied successfully to differentiate between zones of similar hydrogeological properties for the test area in Midrand. Movement of water within the vadose zone is greatly affected by the distribution of shallow rock and hardpan ferricrete in the area and seasonal perched water levels often develop on these low permeable materials. Residual soil properties are remarkably similar throughout the study area, with the exception of alluvium located in drainage channels. This can be ascribed to the similar geology underlying these soils. Differentiation between zones of similar hydrogeological properties is mainly based on the distribution of shallow rock and hardpan ferricrete. It is anticipated that these factors will control flow of water through the vadose zone in other hard rock environments.

8.2 Conclusions

The research has shown that the geohydrological characteristics of residual soils in the vadose zone can be determined from frequently available geotechnical data and by applying modified geotechnical methods. Three aspects, important in flow of water through the vadose zone, have been addressed during the course of the study namely:

- Saturated and unsaturated flow through the soil matrix
- Preferential flow
- The spatial distribution and delineation of zones with similar hydrogeological characteristics.

These aspects account for scaling in the vadose zone. Unsaturated flow through the soil matrix represents characteristics of a particular soil horizon. Preferential flow represents flow through a soil profile and can generally be observed in testpits and trenches. The spatial distribution of the hydrogeological units can be identified via land classification techniques such as aerial photo interpretation.

8.2.1 Saturated and unsaturated flow through the soil matrix

The research focussed in predicting the following hydrogeological properties:

- Porosity
- Saturated hydraulic conductivity
- Soil-water retention characteristics
- Unsaturated hydraulic conductivity

The porosity of field soils can be estimated from soil profile descriptions, soil fractions and soil classification systems. In many cases, porosity can be estimated within the range of predicted values. However, the tables and empirical equations, which are used to predict porosity, allow for a wide range of porosity values, especially for fine-grained material. This renders predicted porosity values of little use for site-specific investigations. Porosity and saturated volumetric water content (which are almost equal to each other) are important aspects to be considered in the estimation of soil-water retention characteristics, saturated hydraulic conductivity and unsaturated hydraulic conductivity, as had been indicated from sensitivity analyses by Vereecken *et al.* (1989). Accurate estimations of these parameters are only possible on condition that the *in situ* porosity has been determined experimentally. If not, it is suggested that a probabilistic approach should be followed to account for uncertainties regarding porosity. Estimated porosity values can be used during the feasibility stage or for the compilation of regional groundwater recharge or vulnerability maps.

No other soil property varies as greatly as the saturated hydraulic conductivity, which may vary by more than ten orders of magnitude for field soils ranging from coarse gravel to clay. Considering that flow through the saturated soils is directly proportional to saturated hydraulic conductivity, it is obvious that an accurate determination of *in situ* saturated hydraulic is crucial in the assessment of flow through soils.

Saturated hydraulic conductivity can be estimated from soil profile descriptions, soil fractions, particle size distribution curves, Atterberg limits and soil classification systems. As with porosity, saturated hydraulic conductivity is frequently estimated within the range of predicted values. However, as with porosity, the tables and empirical equations which are used to predict saturated hydraulic conductivity, allow for a wide range of saturated hydraulic conductivity values. Considering the variability of saturated hydraulic conductivity and the sensitivity of this parameter in the assessment of flow through soils, predicted values are of no use for site-specific investigations and of little use during the feasibility stage.

The fact that saturated hydraulic conductivity had been estimated within the range of predicted values suggests that it is related to the grain-size distribution of field soils. However, many other factors, such as packing, the shape of the grains and pore channel geometry, affects saturated hydraulic conductivity and accounts for approximately two orders of magnitude variation of the predicted value.

Since saturated hydraulic conductivity is related to grain-size distribution, its value will be affected by variations in grain-size distributions. Soil samples, which are used to determine grain-size distributions, are not necessarily representative of the soil matrix, as is shown by the variability of sand, silt and clay fractions, obtained from similar soil horizons. The same reasons may account for the variations in laboratory permeability tests conducted on undisturbed soil samples, besides experimental error. Accurate determination of saturated hydraulic conductivity can only be achieved by conducting applicable *in situ* tests, and only if a representative soil area is tested. Small-diameter infiltrometer tests may not yield accurate determination of *in situ* hydraulic conductivity.

Predictions of soil-water retention characteristics from geotechnical data proved to be more accurate compared to saturated hydraulic conductivity and porosity. The accuracy of these predictions depends on the porosity value. The accuracy of these predictions can be improved if the porosity has been determined experimentally. Good predictions are possible in the high suction range, where soil-water retention is mainly a factor of specific soil surfaces, and therefore grain-size distributions. Poor predictions are usually associated along the low suction ranges, where water retention is affected by the pore-size distribution.

As with saturated hydraulic conductivity, predictions of soil-water retention characteristics are affected by variations in grain size distribution. Soil samples used to determine grain-size distribution are not necessarily representative of the specific soil horizon and as such, predicted soil-water retention characteristics may also not be representative. Predictions of soil-water retention characteristics can be used during the feasibility stages of the investigation or in the compilation of groundwater recharge and vulnerability maps.

Variations in unsaturated hydraulic conductivity are even more pronounced compared to saturated hydraulic conductivity and variations of up to twenty orders of magnitude can occur within a single soil horizon. These variations may occur within a small soil suction range, as is the case with a sandy soil. Most empirical models used to predict unsaturated hydraulic conductivity are based on the assumption that saturated hydraulic conductivity and some aspects of soil water retention characteristics are known. Predictions of unsaturated hydraulic conductivity, based on estimated saturated hydraulic conductivity, are useless considering the inherent variability of both properties and that errors in predicted saturated hydraulic conductivity are amplified when used to predict unsaturated hydraulic conductivity. Experimentally derived saturated hydraulic conductivity and a good estimation of soil-water characteristics are a prerequisite for accurate predictions of unsaturated hydraulic conductivity.

In the case that saturated hydraulic conductivity and soil-water retention characteristics are known, unsaturated hydraulic conductivity can be estimated by statistical methods. Accurate predictions of unsaturated hydraulic conductivity can be made, provided that the soil-water characteristic curve accurately describes soil-water retention characteristics. Sigmoidal functions, such as the Van Genuchten (1980) and Fredlund & Xing (1994) functions, accurately describe soil-water retention characteristics. The former function is more accurate in sandy soils and the latter is more accurate in clayey soils. Accurate predictions of unsaturated hydraulic conductivity can be achieved with the exception of soils characterised by a bi-modal pore-size distribution and soils where preferential flow is dominant. These predictions can be used during site-specific investigations, thereby eliminating the need for time-consuming and expensive laboratory tests.

8.2.2 Preferential flow

Preferential flow was observed in three of the five field-tests, substantiating the opinion held by several authors that preferential flow occurs in most soil types. The field experiments focussed in addressing macropore channelling and other preferential flow mechanisms, such as fingering and funnelled flow were not addressed.

Preferential flow observed during the field experiments occurred mainly in bio-pores, specifically relict plant root holes. These flow paths occurred at depths between approximately 1.0 and 2.0 metres below ground surface, suggesting that preferential flow may extent much deeper than previously thought. The complexity of preferential flow was also highlighted during the field experiments. The connectivity of preferential flow paths is an important aspect, with preferential flow taking place in very few flow paths.

Preferential flow is more pronounced in fine-grained soils, which are usually characterised by low permeability. Preferential flow may constitute a larger portion of flow through the soil profile compared to coarse-grained soils. In addition, certain preferential flow paths are caused by desiccation cracking and aggregation and these processes are more pronounced in fine-grained soils.

The quantification of preferential flow is extremely difficult, if not impossible. However, the research has shown that the preferential flow paths, in particular macropore channels, can be identified by inspection of the soil profile. Soils prone to preferential flow can then be identified. Very little is known on preferential flow mechanisms and it is suggested that a probabilistic approach should be followed in quantifying preferential flow

8.2.3 The spatial distribution and delineation of zones with similar hydrogeological characteristics

The delineation of zones with similar geotechnical characteristics, using land pattern techniques, is hailed as an important milestone in the engineering geological science. The research has shown that the same principles can be applied for delineating zones of similar hydrogeological characteristics, and that these techniques can arguably be used with greater effect for differentiating between zones of similar geohydrological characteristics.

The hydrogeological characteristics of units within the study area were successfully identified using the land system classification approach. Geohydrological characteristics of some units can be much more accurately predicted than those of other units. Shortcomings were identified in the accurate delineation of boundaries along the identified units. The geohydrological characteristics of areas located close to these boundaries should be interpreted with caution.

The research have shown that the geohydrological characteristics are functions mainly of underlying geology, geomorphologic history and pedogenic processes. The spatial distribution areas characterised by similarities of any of these aspects can be identified using land pattern classification techniques. The research has shown that accurate predictions of geohydrological characteristics is possible, based on:

- An understanding on weathering processes for different geological materials
- An understanding of the geomorphologic history to which these rocks were subjected
- An understanding of pedogenic processes

The hydrogeological characteristics can be predicted fairly accurately using mainly aerial photos, geological and topographical maps. The hydrogeological properties can be confirmed by conducting a field investigation in specific areas and these properties can then be extrapolated to areas with similar land patterns.

The construction of conceptual hydrogeological models for each identified hydrogeological unit is essential in understanding the hydrogeological setting. For example, the main variables affecting flow in the vadose zone within the study area include:

- Occurrence and depth of shallow bedrock
- Depth to groundwater surface
- Occurrence of ferruginised layers and hardpan ferricrete
- Occurrence of perched aquifers.

The geohydrological properties of the materials are not as important to differentiate between the geohydrological units within the study area and this can be mainly be attributed to the fact that these soils have been derived only from granitoid bedrock. However, the geohydrological properties can be an important aspect in areas underlain by complex geology.

8.3 Recommendations

It is proposed that additional research should be conducted on the following aspects:

- Methods to identify soils prone to preferential flow. The research should be aimed at methods for quantifying the water moving through the vadose zone. It has been shown that preferential flow, in particular macropore channelling, occurs in the soils tested. Although it has been shown that the extent of preferential flow in the soils tested is probably not significant, little has been achieved in quantifying preferential flow. It is postulated that preferential flow may be the main mode of transport in many South African soils, especially fine-grained soils.

- Unsaturated zone modelling. With the knowledge gained during the course of this investigation, current unsaturated flow models can be improved to include methods for estimating groundwater flow and recharge from geotechnical data sources. These models may be included in conventional groundwater models in order to derive more accurate estimations of recharge. Currently, large uncertainties revolve around the values of recharge to be attributed to specific soil types.

- Integrated groundwater and surface water models. At present, little is known about the unique relationship between surface and groundwater systems. The research has shown that, in the case of the study area, perched aquifer systems are an important aspect in contributing to surface water base flow. It is also highly vulnerable to contamination. These aspects should be further investigated.

- Solute transport and attenuation in the vadose zone. Solutes are mainly transported by means of advection. The results of this research enable researchers to more accurately describe the flow through the vadose zone based on geotechnical data. However, little is known about solute transport and attenuation processes in the vadose zone.

- Vadose zone monitoring. The international trend in investigations regarding features that may impact negatively on the groundwater is to monitor soil moisture in the vadose zone in order to detect constituents before they enter the groundwater regime. It is proposed that vadose monitoring programmes should be implemented in South Africa in order to prevent expensive remediation programmes after groundwater contamination has already taken place.