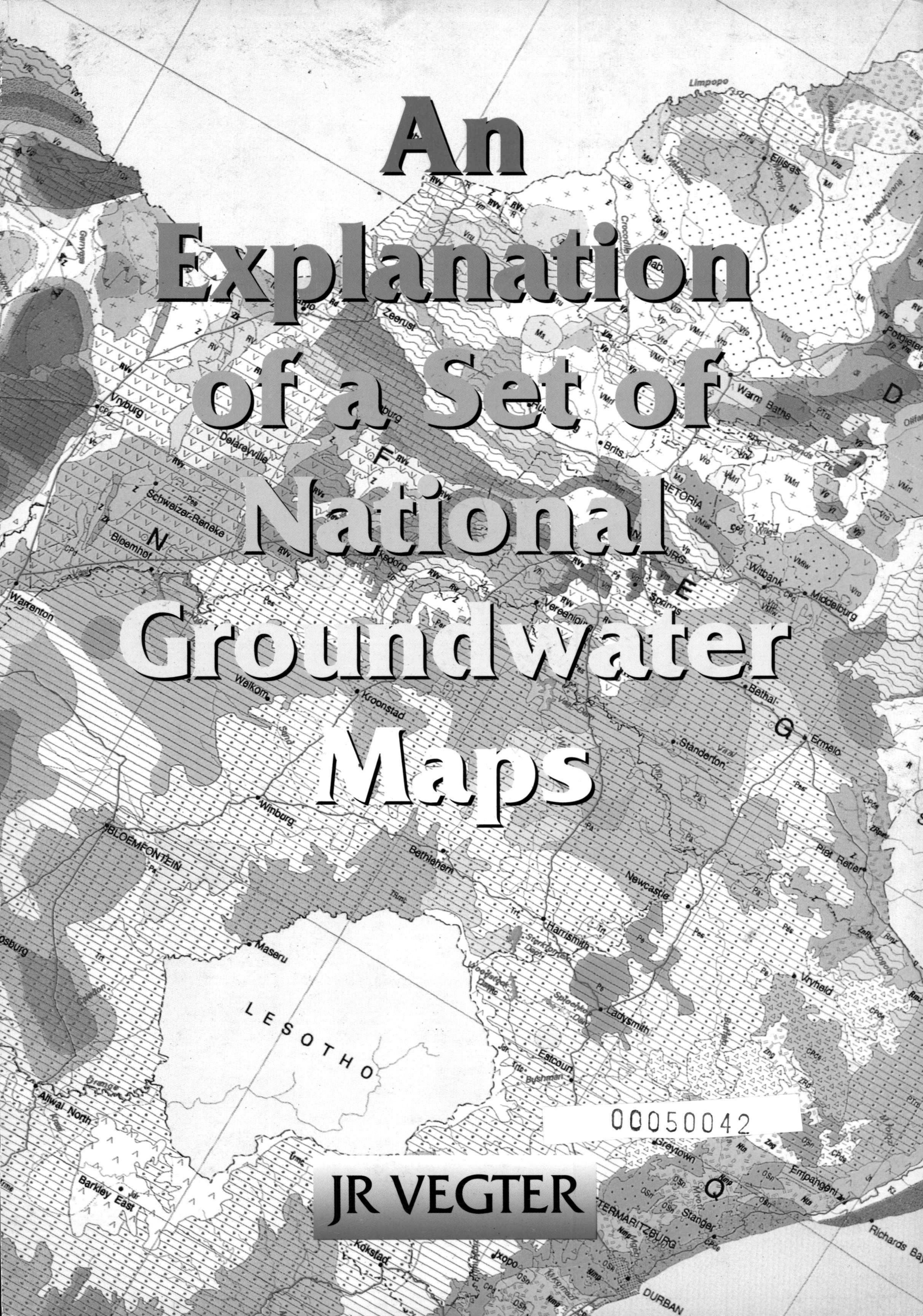
An Explanation of a Set of National Groundwater Maps



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JR VEGTER

PART A

GUIDE TO UNDERSTANDING THE MAPS

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PREFACE

The Department of Water Affairs* estimated that only 13 per cent of all water used in 1980 in South Africa (including the former independent TBVC and national self-governing states) was obtained from underground sources. This subordinate role has not changed materially over the past fifteen years. In spite of the quantitatively minor role played by groundwater in the country's water economy, it is the main or sole source of supply in most of the rural areas, particularly the drier western two-thirds of South Africa.

As a dearth of water severely limits the country's potential for population and economic growth, knowledge of its water resources is of paramount importance. Whereas the document *Surface Water Resources of South Africa* has been undergoing its third revision, nothing comparable exists for groundwater. The national groundwater maps that have now been produced is the first attempt at providing synoptic and visual information on the country's groundwater resources. It is hoped that these maps will not only meet some of the needs of planners, decision-makers, water supply engineers, and educated laymen, but will also provide groundwater scientists with a perspective on regional and national scales. This explanation therefore consists of two parts:

- A guide intended mainly for the layman, on how to read and understand these maps;
- A short exposition of hydrogeological principles on which the maps are based and how they were compiled.

The set of hydrogeological maps has been produced on two A0 sheets as follows:

- Sheet 1. Borehole Prospects in colours superimposed on a background of lithostratigraphy indicated by different hachuring and letter symbols (scale 1:2.5 million).
- Sheet 2.
  - Saturated Interstices providing a qualitative indication of groundwater storage (scale 1:4 million)
  - Depth of Groundwater Level (scale 1:7.5 million)
  - Mean Annual Groundwater Recharge (scale 1:7.5 million)
  - Groundwater Component of River Flow (Base Flow) (scale 1:7.5 million)
  - Groundwater Quality (scale 1:7.5 million)
  - Hydrochemical Types (scale 1:7.5 million).

From the outset it should be emphasised that these maps depict groundwater conditions on a regional scale. They are not site-specific and cannot be used for borehole siting or for deducing any other site-specific condition. Such an exercise requires local investigations and/or larger scale maps.

* Department of Water Affairs, 1986. *Management of the Water Resources of the Republic of South Africa*, Pretoria.

GLOSSARY

The list of terms is not exhaustive. Those which are defined in the text have not been repeated. The following references were consulted:

American Geological Institute (AGI), 1973. *Glossary of Geology.*
Tolman, C.F., 1937. *Groundwater.* McGraw-Hill Inc.
Billings, M.P., 1947. *Structural Geology.* Prentice-Hall Inc.

Aeration, Zone of. See **unsaturated zone**.

Anion. An electrically positively charged ion. See **ion**.

Aquiclude. See **aquitard**.

Aquifer. A stratum which contains intergranular interstices, or a fissure/fracture (as such) or a system of interconnected fissures/fractures (as such) capable of transmitting groundwater rapidly enough to directly supply a borehole or spring. The fissures/fractures are generally bound by either aquiclude/aquitard or aquifuge.

Aquifuge. A rock which contains no interconnected openings and therefore neither absorbs nor transmits water.

Aquitard. A body of poorly permeable rock that is capable of slowly absorbing water from and releasing water to an aquifer. It does not transmit groundwater rapidly enough by itself to directly supply a borehole or spring. Synonym **aquiclude.**

Base flow. That part of stream flow which is contributed by effluent groundwater.

Bedding fissility. The property possessed by sedimentary rocks, especially fine-grained, to split more or less parallel to the stratification (AGI 1973).

Capillarity. The action by which water (or other fluids) is drawn up (or depressed) in small interstices or tubes as a result of surface tension.

Cation. An electrically negatively charged ion. See **ion**.

Chronostratigraphy. Stratigraphy that interprets geologic history by determining the age and time sequence of the earth's strata (AGI 1973).

Crack. A partial or incomplete fracture (AGI 1973).

Confined groundwater. Groundwater under pressure significantly greater than that of the atmosphere and whose upper surface is the bottom of a layer of distinctly lower permeability than the material in which the water occurs (AGI 1973).

Effective rainfall. Rainfall on a given day minus interception loss minus storm runoff (Schulze et al. 1990), in other words, that part of the rainfall that wets the soil.

Evapotranspiration. Loss of water from a land area through transpiration of plants and evaporation from the soil (AGI 1973).

Fissure. A surface of fracture or crack in rock along which there is a distinct separation (AGI 1973).

Fracture. Any break in a rock whether or not it causes displacement, owing to mechanical failure by stress. Fracture includes cracks, joints, faults (AGI 1973).

Fracture cleavage. Cleavage based on closely spaced joints and fractures (AGI 1973). Minerals in the rock are not oriented parallel to the cleavage.

Flow cleavage. The parallel orientation of platy minerals such as mica and chlorite or of elongate minerals such as hornblende, as a result of plastic deformation. Cleavage planes are spaced a fraction of a millimetre apart (Billings 1947). Synonym **slaty cleavage.**

Free groundwater. See **unconfined groundwater.**

Geohydrology. The branch of hydrology dealing with subsurface water i.e. water in both the saturated and unsaturated zones. Also used interchangeably with hydrogeology.

Gneissosity. The coarse textural banding of the constituent minerals in a metamorphic rock, commonly a gneiss, into alternating light-(silicic) and darker-coloured (mafic) layers (AGI 1973).

Grike. A vertical fissure developed along a joint in limestone or dolomite through solution.

Groundwater. Water in the zone of saturation. It flows into boreholes/wells or debouches as springs. Synonym **underground** or **subterranean Water.**

Groundwater level. The water level in a borehole/well penetrating the zone of saturation and from which no water is being withdrawn. Synonym **static (water) level.**

Hard rock. A compact rock that lacks primary porosity.

Hydraulic conductivity. The rate of flow of water through a unit cross section of soil or rock, under unit hydraulic gradient.

Hydrogeology. The geology of groundwater.

Hydrologic cycle. All movement of water in its liquid, gaseous and solid phases, in the atmosphere, on the Earth's surface, and below the ground surface.

Hydrology. The science that deals with continental water on and under the Earth's surface.

Interception. The process by which water from precipitation is caught and stored on plant surfaces and eventually returned to the atmosphere without having reached the ground (AGI 1973).

Ion. An electrically positively or negatively charged particle into which salts are dissociated when dissolved in water.

Karst. A type of topography that is formed over limestone and dolomite by solution and that is characterised by closed depressions or sinkholes, caves and underground drainage (AGI 1973).

Karstification. The formation of the features of a karst topography (AGI 1973).

Lithology. The description of rocks on the basis of colour, structures, mineralogic composition and grain size.

Lithostratigraphy. Stratigraphy based only on lithologic composition. See **stratigraphy**.

Permeability. The capacity of rock and soil to transmit water.

Primary opening. Interstices that were made contemporaneously with the formation of the sedimentary deposit or rock that contains them (Tolman 1937). Hence the property of primary porosity.

Porosity. The property of a rock and soil of containing interstices.

Recharge. The processes involved in the absorption and addition of water to the zone of saturation (AGI 1973). Synonym **replenishment.**

Regolith. The mantle of fragmental and loose material of residual and/or transported origin, comprising rock debris, alluvium, aeolian deposits, soil and *in situ* weathered rock. It overlies or covers more solid rock, so-called bed rock.

Saprolite. *In situ* thoroughly decomposed rock.

Saturation, Zone of. The zone below the watertable in which all interstices are filled with groundwater.

Schistosity. Foliation in a schist owing to the parallel planar arrangement, mainly of the mineral mica.

Secondary openings. Interstices that were made by processes that affected the rocks after they were formed (Tolman 1937). Hence the property of secondary porosity.

Shear cleavage. A variety of fracture cleavage characterised by differential movement along the planes of rupture and by parallelism of platy minerals with the cleavage (Billings 1947).

Stratigraphy. The description of strata - sedimentary, igneous and metamorphic - in terms of lithologic composition, fossil content, age, origin, history.

Storm runoff. Runoff reaching stream channels immediately after rainfall.

Unconfined groundwater. Groundwater of which the upper surface is at atmospheric pressure, or in other words, its upper surface is the water-table.

Unsaturated zone. The zone between the land surface and the water-table in which interstices contain air or gases generally under atmospheric pressure as well as water under pressure less than that of the atmosphere. Synonym **zone of aeration.**

Water-table. The upper surface of the zone of saturation, in other words, the imaginary surface below which all openings are filled with water. On this surface the pressure is equal to atmospheric pressure.

GROUNDWATER RESOURCES OF SOUTH AFRICA

AN EXPLANATION OF A SET OF NATIONAL GROUNDWATER MAPS

Prepared for the
Water Research Commission
by

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Bart B: Mapping concepts.

DISCLAIMER

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The Steering Committee responsible for the project consisted originally of the following persons:

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Ms H. Ferreira
Ms F. Jonck
Mr A. Seymour
Mr M. Simonic
Mr F.P. Tennick.

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1. INTRODUCTION

Part A is meant as a guide for the layman. The next five chapters provide certain basic information on geology and groundwater that should assist the reader to a better understanding of the groundwater maps. The last chapter is devoted to the maps themselves.

2. SOME GEOLOGICAL CONCEPTS

As groundwater occurs in openings in rocks that form the earth's crust, it is necessary that one becomes familiar with the major groups of rocks. The materials penetrated in sinking boreholes consist in part of unconsolidated materials such as sand, clay and gravel and in part of consolidated rocks such as granite, sandstone, dolomite. For convenience all these materials are called "rocks".

Rocks are divided into three major groups:

- **Igneous rocks** that have formed from a molten or partially molten state. Some types of igneous rocks solidified at great depths below the surface and are referred to as intrusive igneous rocks examples of which are granite, gabbro, norite and dolerite. Other igneous rocks form from lava or volcanic ash ejected on the surface and are known as extrusive igneous rocks, examples of which are basalt, andesite, rhyolite, volcanic breccia, tuff.
- **Sedimentary rocks** are formed by deposition of sediment from water, ice or air. At the time of formation they are unconsolidated. Through deep burial, compression and chemical changes they become consolidated. Examples are sandstone, shale, mudstone, limestone and dolomite.
- **Metamorphic rocks** are formed from both igneous and sedimentary rocks when these are subjected to great heat and/or pressure at depth below the earth's surface. Amphibolite, granulite, (meta-)quartzite, marble and a variety of gneiss are examples of such rocks.

From the geologist's viewpoint and as is implied by the words intrusive, ejected, deposition and metamorphism, the earth's crust is dynamic and changing, albeit very slowly over millions of years. Its history is recorded by the rocks themselves. Whilst in certain parts of the earth, plateaux and mountains were being made and worn down, in other parts the land became submerged beneath the sea for long ages and continued to sink slowly while mud and sand derived from eroding land, built up deposits thousands of metres thick.

These loose materials were converted by compaction into rock, eventually to be uplifted above the sea as a result of vertically and/or horizontally operating forces to form either elevated plateaux or fold mountain ranges. This process of uplifting is generally accompanied by the intrusion and extrusion of molten rock. Thus another cycle of erosion and deposition, of sedimentary rock formation, igneous activity and uplifting commences - a process that was repeated many times during the earth's history.

By using the self-evident principle that the youngest sedimentary deposit is at the top and the oldest at the bottom of a pile of strata, and that a body of intrusive rock is younger than the strata it intrudes, and by dating rocks using the radioactive decay clock, geologists have been able to decipher the geological history of different parts of the country.

TABLE 1
CHRONOSTRATIGRAPHY (KENT 1980, VISSER 1989)

Million Years B.P.*	Eonothem (Eon)	Erathem (Era)	System (Period)	Symbol On Borehole Prospect Map
0				
	Phanerozoic	Cainozoic	Quaternary	Q
			Tertiary	T
63		Mesozoic	Cretaceous	K
			Jurassic	J
			Triassic	T
240		Paleozoic	Permian	P
			Carboniferous	C
			Devonian	D
			Silurian	S
			Ordovician	O
			Cambrian	
570	Proterozoic	Namibian		N
1 180		Mokolian		M
2 070		Vaalian		V
2 500	Achaeozoic			
2 620		Randian		R
3 090		Swazian		Z
3 800				
4 000				

* Before Present

Rocks have accordingly been grouped into major and minor natural divisions called lithostratigraphic units and placed in chronological order. See the lithostratigraphic column on the Borehole Prospects Map.

The fundamental formal unit in lithostratigraphic classification is the **Formation** (note spelled with a capital). It is generally characterised by some degree of lithologic uniformity or distinctive lithological features, by a prevailing but not necessarily tabular shape and of a minimum thickness and extent so as to be mappable on a scale of 1:50 000. It usually consists of a sedimentary stratum or strata. Igneous and metamorphic rocks are, however, not excluded from being termed Formations.

A **Group** is an assemblage of two or more successive Formations with significant unifying lithologic features in common. Formations need not be aggregated into Groups.

The term **Supergroup** is used when there is need to refer to several successive associated Groups and Formations with significant lithologic features in common. The term Subgroup is used to distinguish an assemblage of successive Formations from the rest of an already established Group.

Formal lithostratigraphic names normally comprise three elements; a geographic name of the type locality; a simple lithologic name; and the rank term, e.g. Ghaap Plateau Dolomite Formation. Groups and larger units are referred to by the geographic name and rank term only e.g. Pretoria Group.

The chronostratigraphic terms assigned to rocks of different eons, eras and periods are given in Table 1.

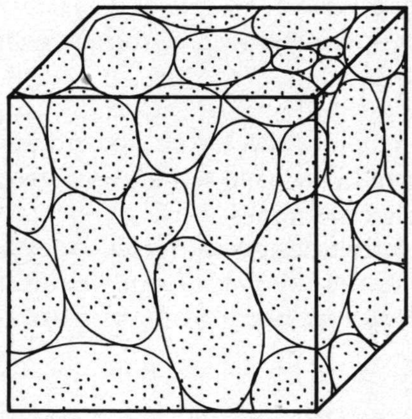
3. OPENINGS IN ROCKS

Figure 1 is a diagrammatic illustration of the types of openings found in rocks. In unconsolidated sedimentary deposits such as sand and clay, the openings are the pores between the mineral grains. As these openings originated simultaneously with deposition, they are termed primary openings.

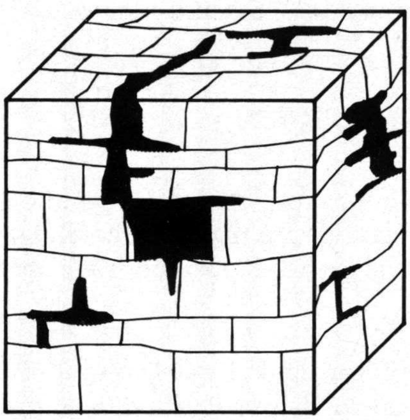
Upon burial these interstices are reduced in size through compaction by the weight of the overlying layers and through cementation with silica or calcite by circulating water. In older sedimentary rocks which have been deeply buried and have undergone some degree of metamorphism, the intergranular openings are completely destroyed.

Intrusive igneous and metamorphic rocks, having been formed at depth, do not contain any appreciable openings. Certain extrusive igneous rocks contain gas holes, tubes and cooling fractures; volcanic ash deposits contain pores. During the course of geologic time igneous, sedimentary and metamorphic rocks were subjected to vertical as well as horizontal compressive stresses which deformed, cleaved and ruptured them, and displaced blocks of the crust along so-called faults. As the overlying strata are gradually being removed by erosion, vertical and lateral stresses are being relieved, resulting in the opening of sets of horizontal, dipping and vertical fractures known as joints, faults and cleavage planes.

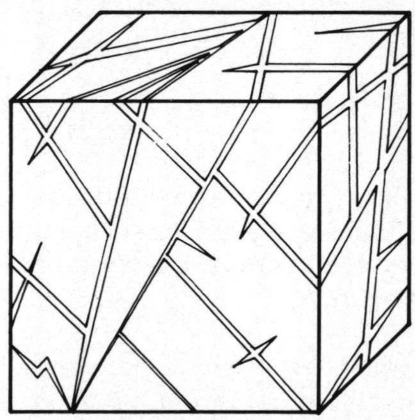
A joint is a parting plane which separates or tends to separate two parts of a once continuous block and along which there has been no visible movement parallel to that plane. The interval between joints of a particular set may vary from a few centimetres to hundreds of metres. Faults are ruptures along which the opposite walls have moved past each other. Faults may be accompanied by breccia which consist of angular to sub-angular fragments of crushed rock. If not cemented subsequent to faulting, these breccia may act as aquifers. Cleavage is the ability of rocks to break along closely-spaced parallel surfaces.



A. Pores in unconsolidated sedimentary deposits e.g. sand



B. Caverns and solution-enlarged openings in limestone and dolomite



C. Joints in hard rock e.g. granite, quartzite

Figure 1

Types of opening. Block A is a few millimetres to a few tens of centimetres wide, depending on the nature of the deposit. Blocks B and C are a few tens of metres wide. Openings in block A are of primary origin; those in B and C are of secondary origin.

The near-surface opening of fractures allows the ingress of air and moisture. Weathering commences, the end result being disintegration and decomposition of rocks.

The fractured rock, termed bedrock, may be exposed on the surface in places; elsewhere it is covered by a mantle of soil, clay, sand and gravel transported from elsewhere and/or by material derived through the *in-situ* disintegration and decomposition of the underlying bedrock. The thickness of this mantle is highly variable from less than a metre to tens of metres. Fractures and pores in the disintegrated and decomposed rocks are termed secondary openings as they were formed subsequent to the formation of the rock. The opened fractures and the pores in the disintegrated and decomposed rock provide space for the storage and movement of groundwater in what would otherwise be compact rock.

This mantle is known as the regolith. Typically it consists of several zones. Firstly a distinction may be made between the upper transported material and the underlying *in-situ* weathered rock or saprolite. A typical section is:

- soil frequently with a pebble layer at its base
- structureless regolith
- saprolite in which the structure of the underlying rock is recognisable
- saprolite as above but containing core stones
- saprolite consisting of angular interlocking boulders
- fresh rock.

Typical weathering sections are illustrated in Figures 2, 3 and 4.

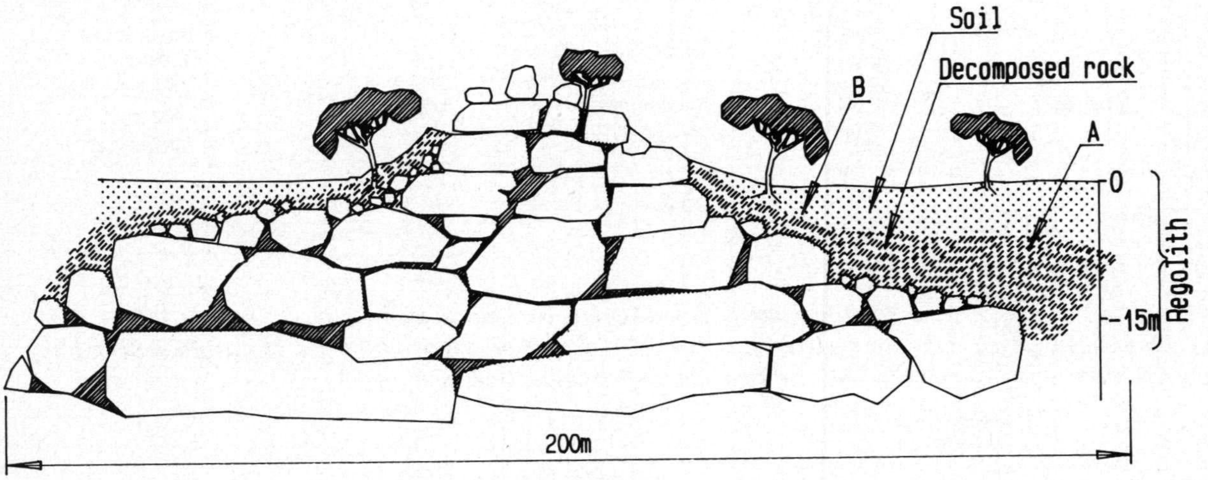


Figure 2

Regolith developed on massive igneous rock such as granite and gabbro. At A where the regolith is thick, transition from weathered to fresh rock is gradual. At B where the regolith is thin, the transition is sharp. Weathering encroaches on the fresh rock by the widening of joints.

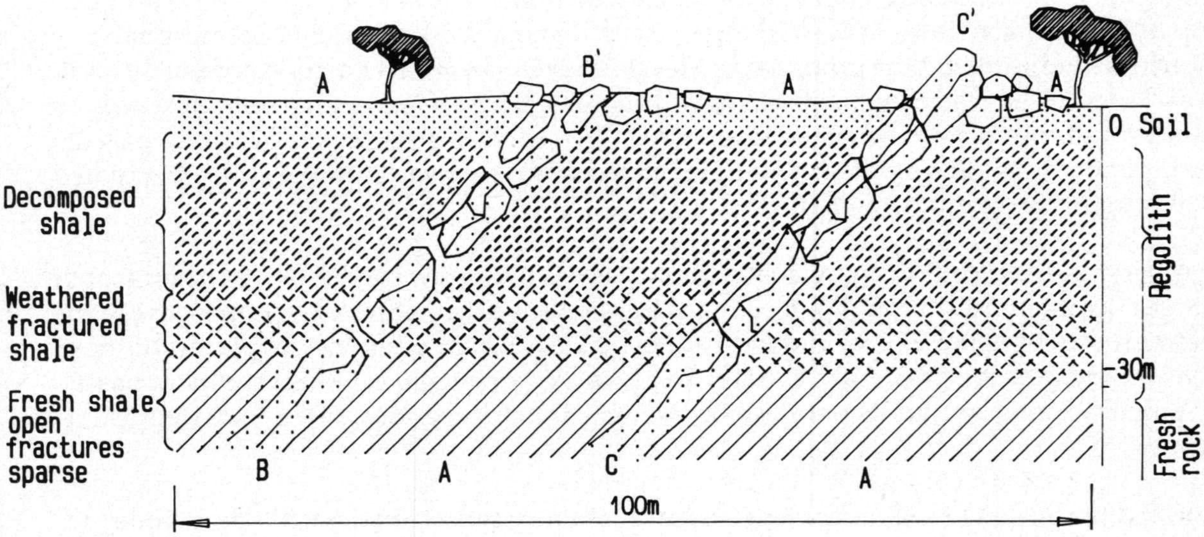


Figure 3

Regolith developed on sedimentary rocks. Note different modes of weathering exhibited by the different rock types. Shale (A) weathers easily with a gradual transition to fresh rock. The shale is not exposed on the surface. Sandstone (B) is more resistant, but joint weathering has broken the formation into residual blocks below the soil surface, so that the sandstone is only exposed as rubble at B′. Quartzite (C) is highly resistant to weathering so that, although there is a slight opening of joints below the soil surface, this formation is exposed in situ *at C′.*

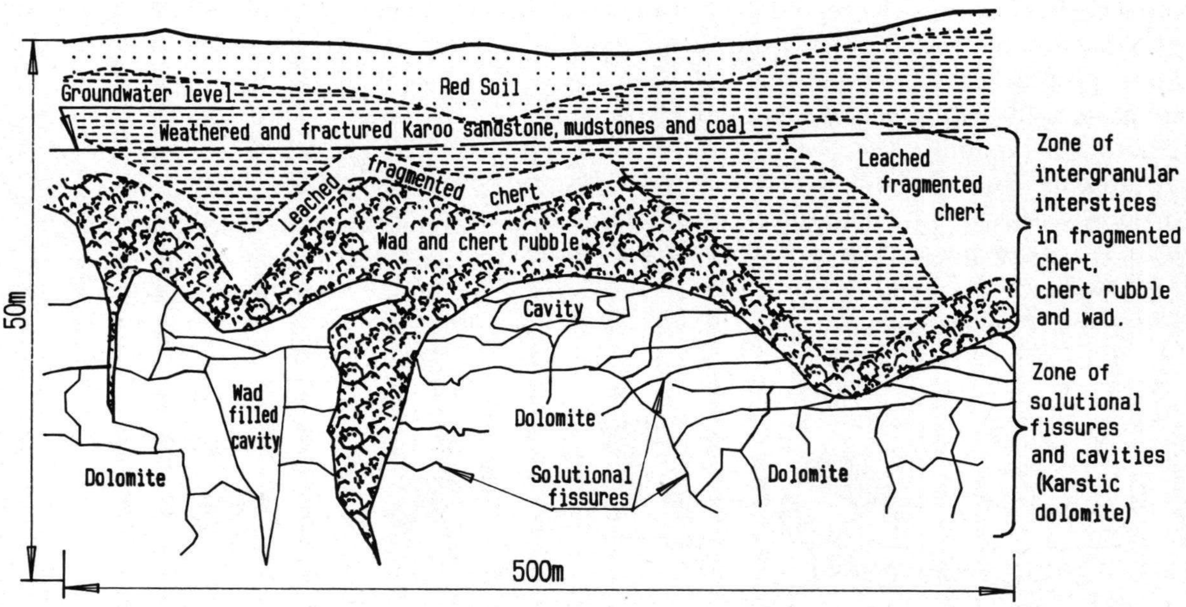


Figure 4
Regolith developed on dolomite, Far West Rand.
Note: (1) Subsidence is evident from the irregular disposition of the Karoo Beds. In their undisturbed state bedding would be close to horizontal. (2) Chert rubble and wad are residual solution products of the dolomitic strata.

4. BASIC GROUNDWATER CONCEPTS

Below the earth's surface water occurs in two distinct zones: an upper zone which contains both water and air, referred to as the unsaturated zone or zone of aeration; below this, in the saturated zone, interconnected openings contain water only. The water-table is the level near the top of the saturated zone at which water occurs under a pressure equal to atmospheric pressure. It is indicated by the groundwater level in boreholes/wells (certain confined conditions excluded). The water that is discharged through springs, seepage and from pumped boreholes/wells lies below the water-table and is referred to as groundwater. A small part of the precipitation that falls on the land surface, percolates downward through the unsaturated zone recharging the groundwater store.

The property of rocks to transmit water is known as the hydraulic conductivity or permeability. The larger the interstices through which the water flows, be they pores or fractures, the higher the permeability of that rock. For instance, although clay is highly porous, its permeability is very low because of the fineness of the clay particles. A coarse sand on the other hand has a lower porosity than clay, but its permeability is high. The driving force of groundwater is gravity.

A saturated porous rock unit, or a single or group of interconnected water-filled fractures, which are capable of transmitting groundwater and of yielding economically significant quantities of groundwater to boreholes/wells or springs are referred to as aquifers. The term "aquifer" should be used only in this sense to avoid vagueness and confusion. Primary aquifers consist of rock with primary openings e.g. alluvial deposits. Secondary aquifers consist of fractures or bodies of fractured and weathered rock. Bodies of saturated rock e.g. clay, which commonly are a hundred to a thousand times less permeable than aquifers are known as aquitards or confining layers. Although not capable of directly yielding water to boreholes/ wells or springs, they are important components of any groundwater system as they are capable of holding and slowly releasing water to aquifers.

Groundwater in transit through aquifers and confining layers, should be viewed as water in storage. The storage properties of rocks are as important as their hydraulic conductivities. Storage is expressed as a fraction i.e. volume of groundwater held per unit volume of rock. It should be noted that when a saturated rock is drained, some water will be retained as a film on grain and fracture surfaces. Groundwater is that part which drains out of the rock under the influence of gravity.

5. SALIENT CHARACTERISTICS OF SOUTH AFRICA'S HYDROGEOLOGY

With the exception of some localised occurrences of permeable porous Cretaceous and Karoo sandstones, pre-Tertiary Formations do not feature as primary aquifers. Over about 90% of the surface area of South Africa, groundwater occurs in secondary openings in so-called hard rocks.These igneous, metamorphic and sedimentary rocks, ranging in age from Swazian to Jurassic, lack adequate primary interstices to function as primary aquifers. Groundwater is contained mainly in fractures, and to some extent also in pores in weathered rock; and in dolomite and limestone in fissures and larger dissolution openings as well as in intergranular interstices in the insoluble residue and younger deposits filling dissolution openings (Figure 4).

The depth of weathering and depth to open fractures is generally not uniform in any particular area. Some rock-forming minerals are more susceptible to decomposition than others, which means that different rocks have different weathering properties (Figures 2, 3 and 4). Apart from mineral composition, structural features (the degree of jointing, faulting and folding) and the extent to which foliation i.e. bedding fissility, gneissosity, schistosity, flow fracture or shear cleavage, has developed, have an important effect on the weatherability of rocks. Other external factors which determine the thickness of the regolith are climate (weathering is more intense under humid conditions) and the rate of erosion in which steepness of surface slopes play an important role.

Judged on a country-wide and regional basis, groundwater can be found everywhere. Seen within local context, the occurrence of groundwater is generally restricted to zones or areas of deepest weathering and open fracturing (Figures 5 to 10).

Primary aquifers occur in:
- Kalahari beds of Tertiary age; principally in those filling pre-Kalahari valleys.
- Narrow discontinuous strips of alluvium along some rivers which are too limited in extent to be shown other than schematically, on the Borehole Prospects Map.
- Cainozoic deposits fringing the coast line. The nature of these deposits and of the aquifers contained in them is illustrated in Figures 11, 12 and 13.

Jurassic-Cretaceous deposits in Northern Zululand and in the Southern Cape contain sandstone and conglomerate beds which, it is surmised, may have adequate primary porosity and permeability to function as primary aquifers. Very little is known about the water-bearing

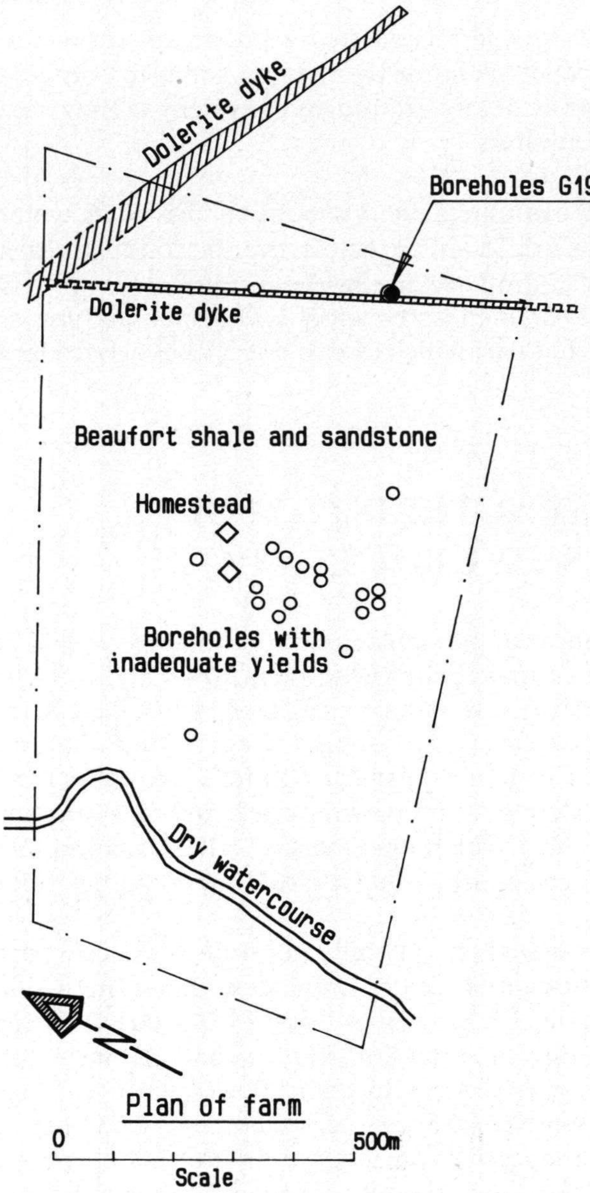


Figure 5
Occurrence of groundwater along dolerite dyke in Beaufort (Karoo) sedimentary rocks. Open fractures capable of yielding water are well developed in the contact zone of the dyke only. Elsewhere the Beaufort sedimentary rocks, although containing groundwater, are incapable of yielding a usable supply. This does not, however, apply to Beaufort rocks country-wide.

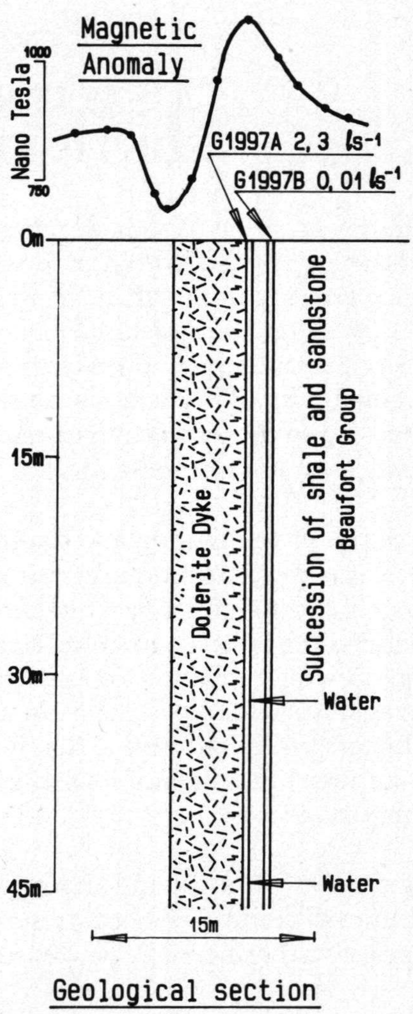
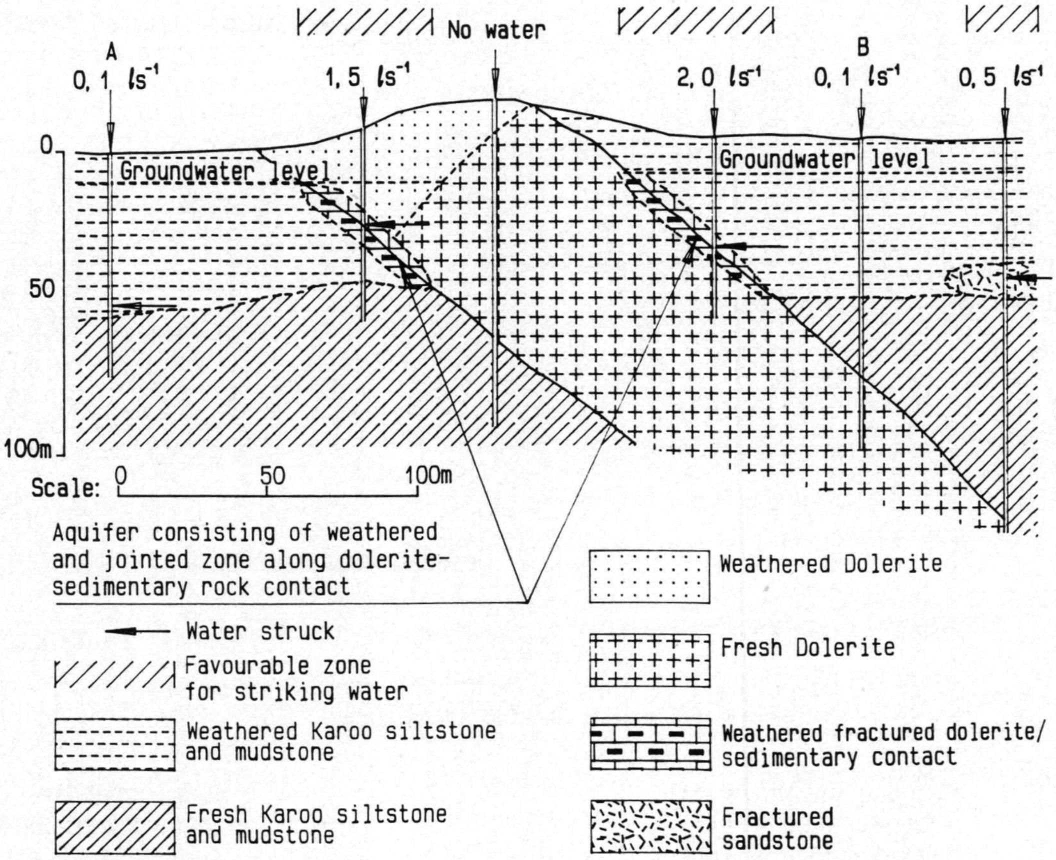
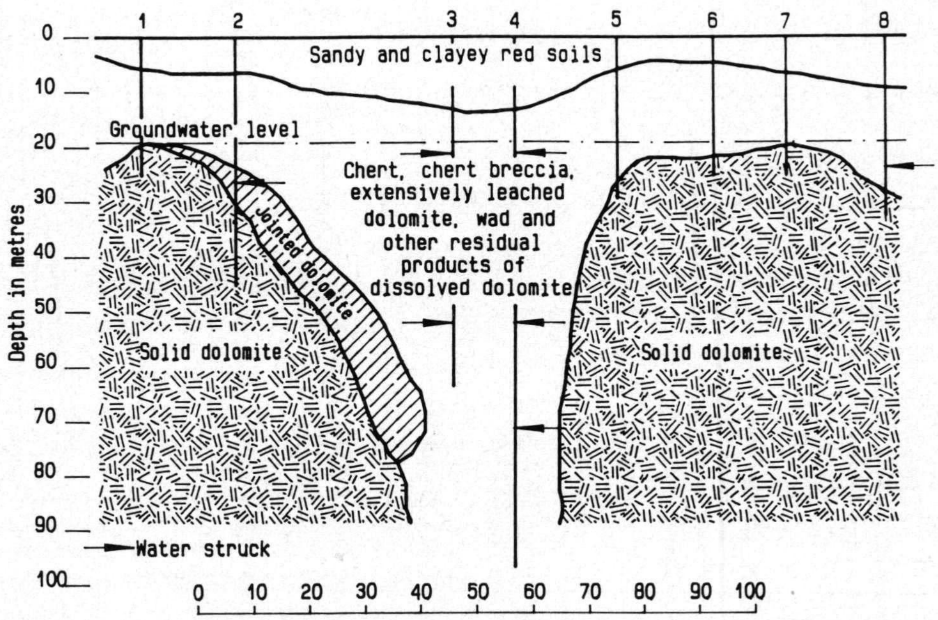


Figure 6 *(Top right)*
Schematic section through dipping dolerite sheet intrusive into an alternating succession of horizontally disposed Karoo siltstone and mudstone beds. Note: (1) As shown by the weak yields of boreholes A and B water-bearing fractures are poorly developed in both the weathered and fresh siltstone and mudstone. (2) The upper and lower contact zones of the dolerite sheet yield water only where fracturing has been opened by unloading and weathering.

Figure 7 *(Bottom right)*
Schematic section through water-bearing grike in dolomite i.e. a fissure widened by dissolution (after Enslin et al. 1976).





Boreholes No's 1, 5, 6 and 7 no usable yield; No's 2 and 8 small usable yield; No's 3 and 4 high yielding holes

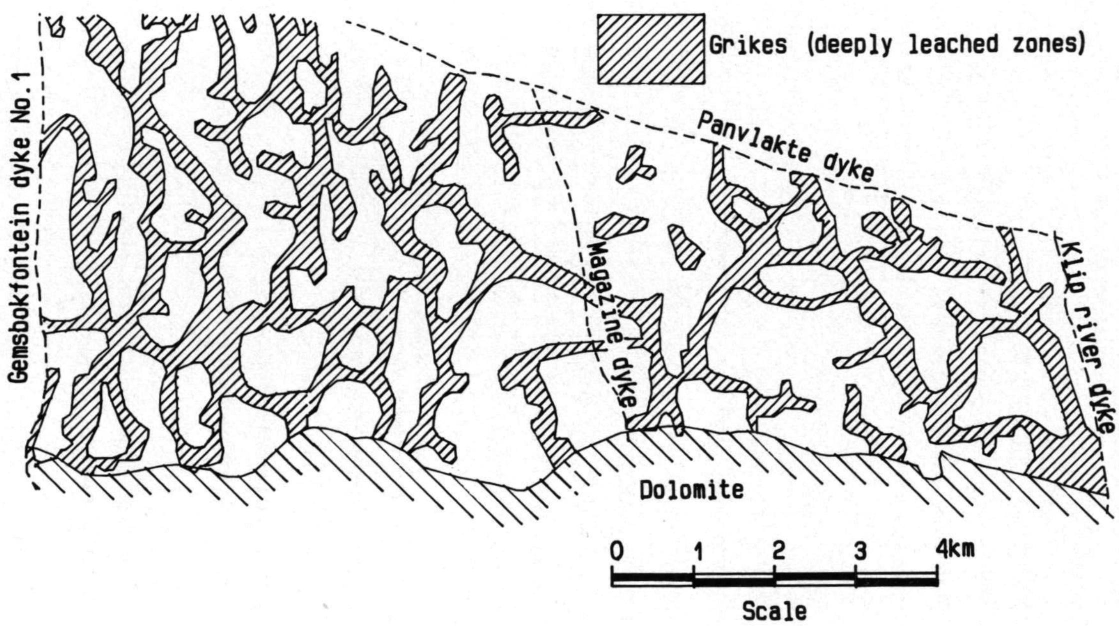


Figure 8
Grike pattern in the Gemsbokfontein dolomite compartment Far West Rand, as inferred from gravity data (after Enslin et al. 1976).

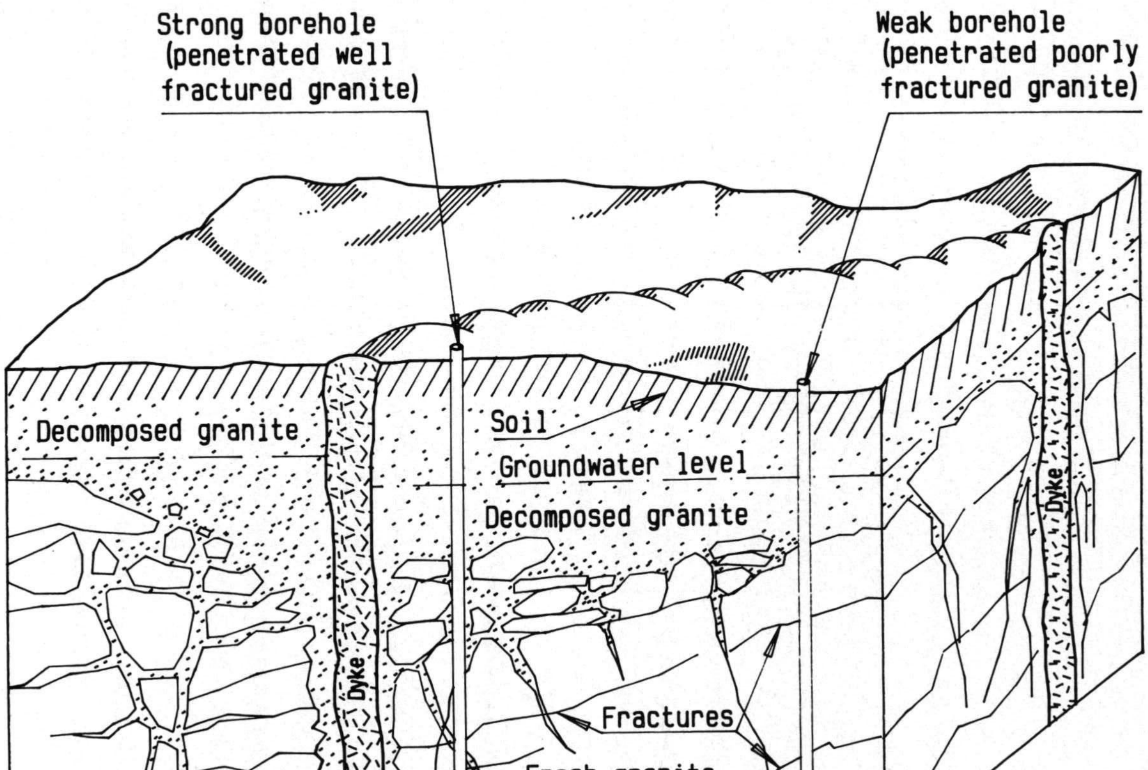


Figure 9
Block diagram illustrating deeper weathering and fracturing and more favourable water yielding conditions alongside a dolerite dyke intrusive into granite, than further away.

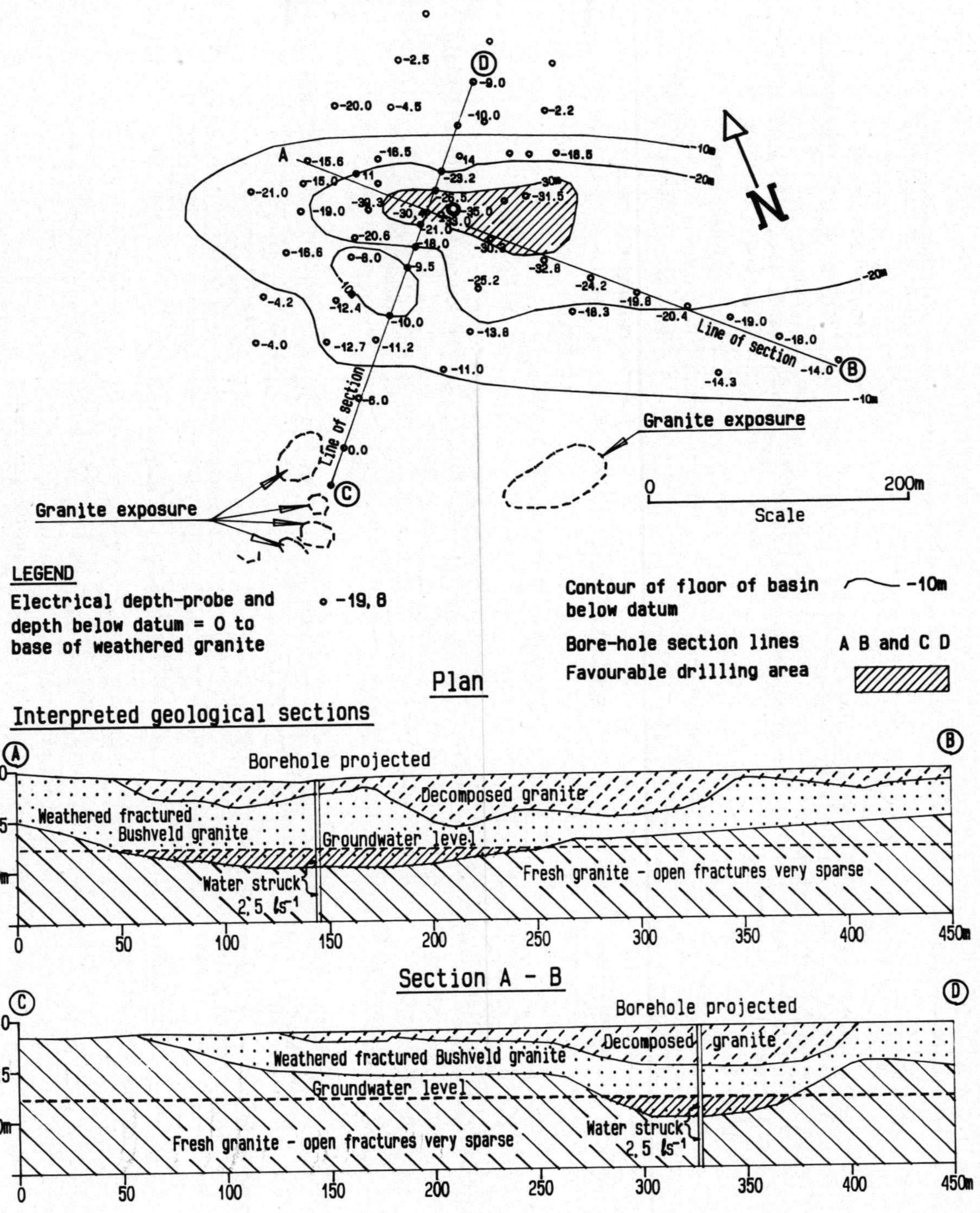


Figure 10

Basin of weathering in Bushveld granite illustrated by contour plan and two sections deduced from electrical depth probing. Note the small area where weathering extends to below the groundwater level and where conditions for striking water are favourable. The chances of striking water are small where the weathering is shallower than the groundwater level.

WELL No.	Yield ls^{-1}
4	10, 7
6	4, 0
G6778	10, 0
G6779	9, 8
G18881	15, 1

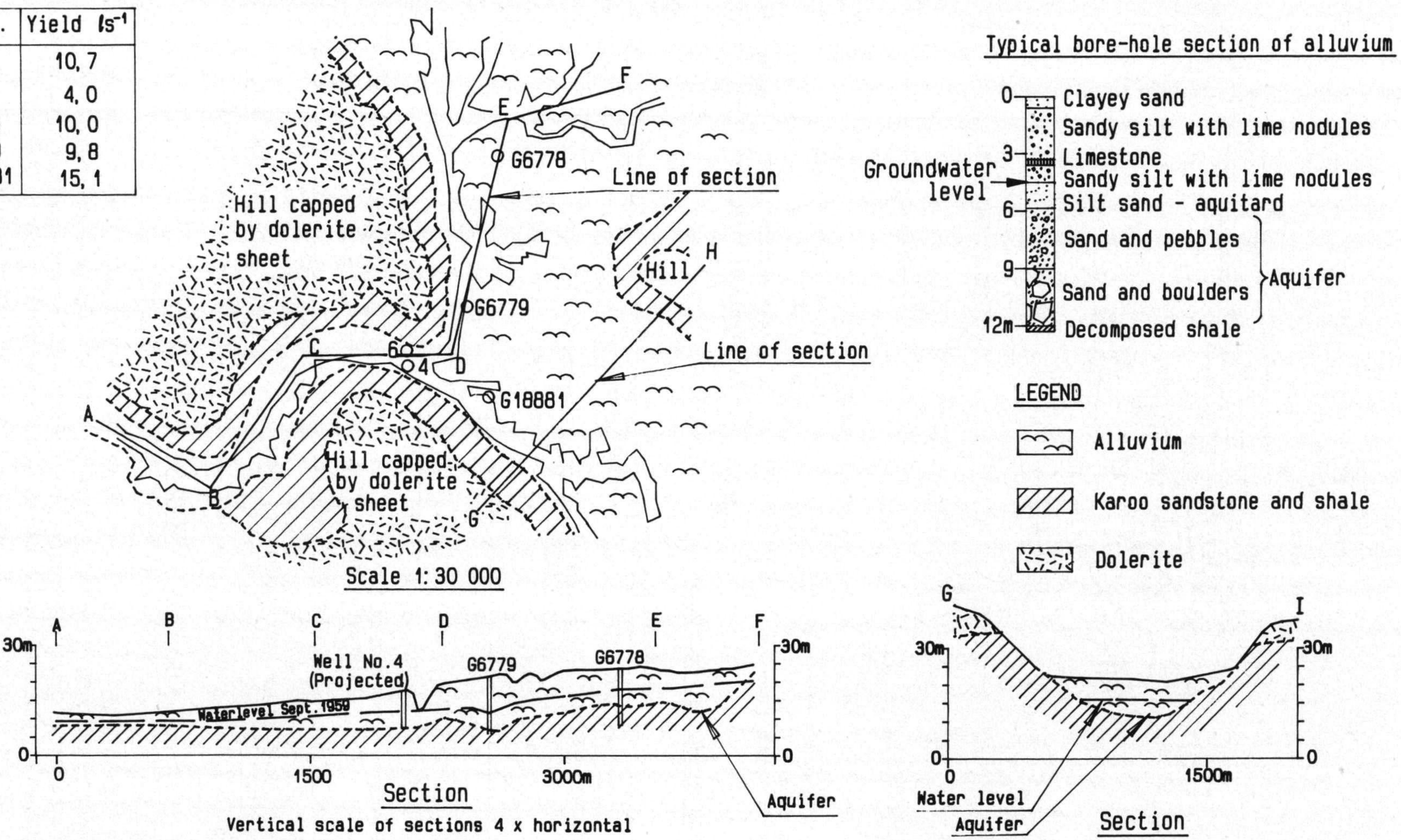


Figure 11
Water-bearing alluvial deposits along the Brak River at Caroluspoort, De Aar.

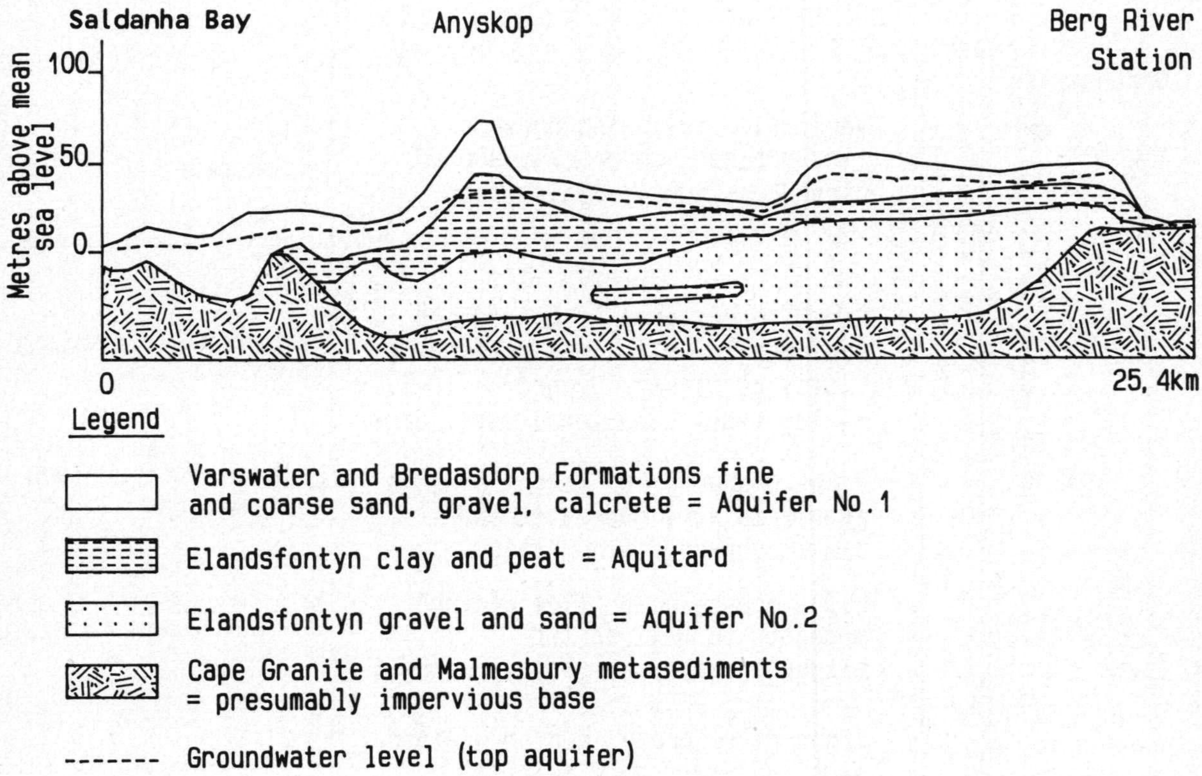


Figure 12
Section through water-bearing Neogene coastal deposits, Saldanha area (Timmerman et al. 1985).

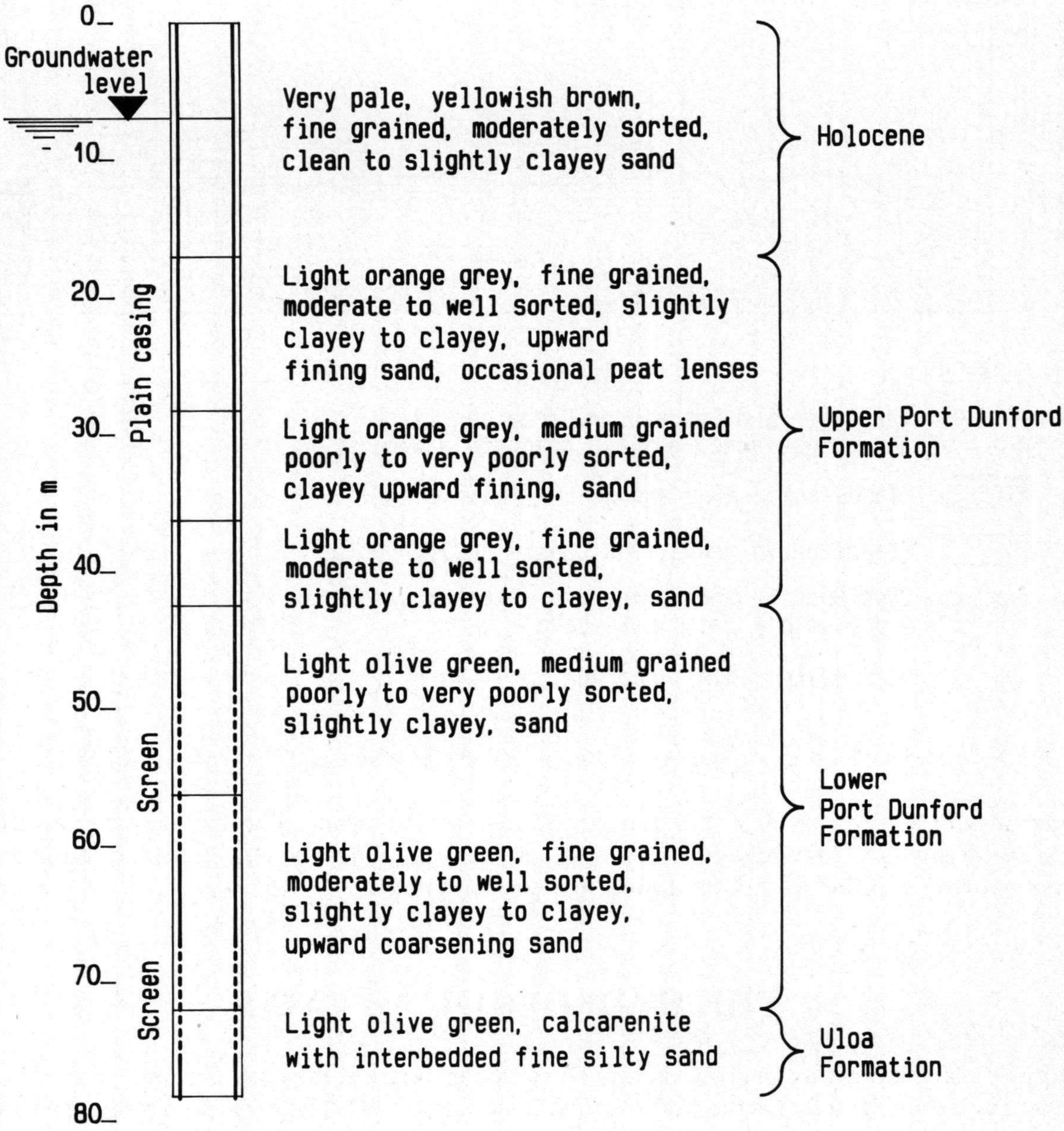
properties of these formations. With the exception of a very localised occurrence of Enon sandstone at the town of Uitenhage in which originally flowing holes have been drilled, apparently no noteworthy supplies have been found in these formations.

6. THE HYDROLOGICAL CYCLE

To appreciate the position of groundwater as an integral part of the earth's water resources, it is necessary to dwell briefly on the hydrological cycle (Figure 14). The earth's water in the form of liquid, ice and vapour is present in three zones, viz. in the atmosphere, on the surface and underground. There is an intermittent discharge of water from the atmosphere in the form of rain, snow and hail, and a continuous fluctuating addition of water into it through evaporation from the oceans and other open water-bodies as well as from land surfaces and through transpiration by plants.

A portion of the precipitation that falls on the land is intercepted by the vegetation from which it evaporates. Another part soaks into the ground, some of it being stored in surface depressions, and the rest gathering into streams and rivers and flowing back into the ocean and lakes from which it again evaporates. Evaporation also takes place from wet soil surfaces and water held in depressions. Part of the water which infiltrates into the soil and deeper, returns to the surface through capillarity and also evaporates.

Wherever the surface material, soil and rock, is permeable throughout so as to allow infiltration to depths beyond the combined action of capillarity and evaporation, and provided interstices



Screened sections 49 - 61m and 67 - 76m
Type of Screen: Johnson stainless steel wire wrapped
Gravel pack: Grain size 3mm placed around screen between 40 - 78m
Tested yield: 23,3 ls^{-1}
Drawdown: 4,3m after 4 hours

Figure 13

Borehole section through water-bearing coastal deposits, Northern Zululand
(Courtesy R. Meyer, EMATEK, CSIR)

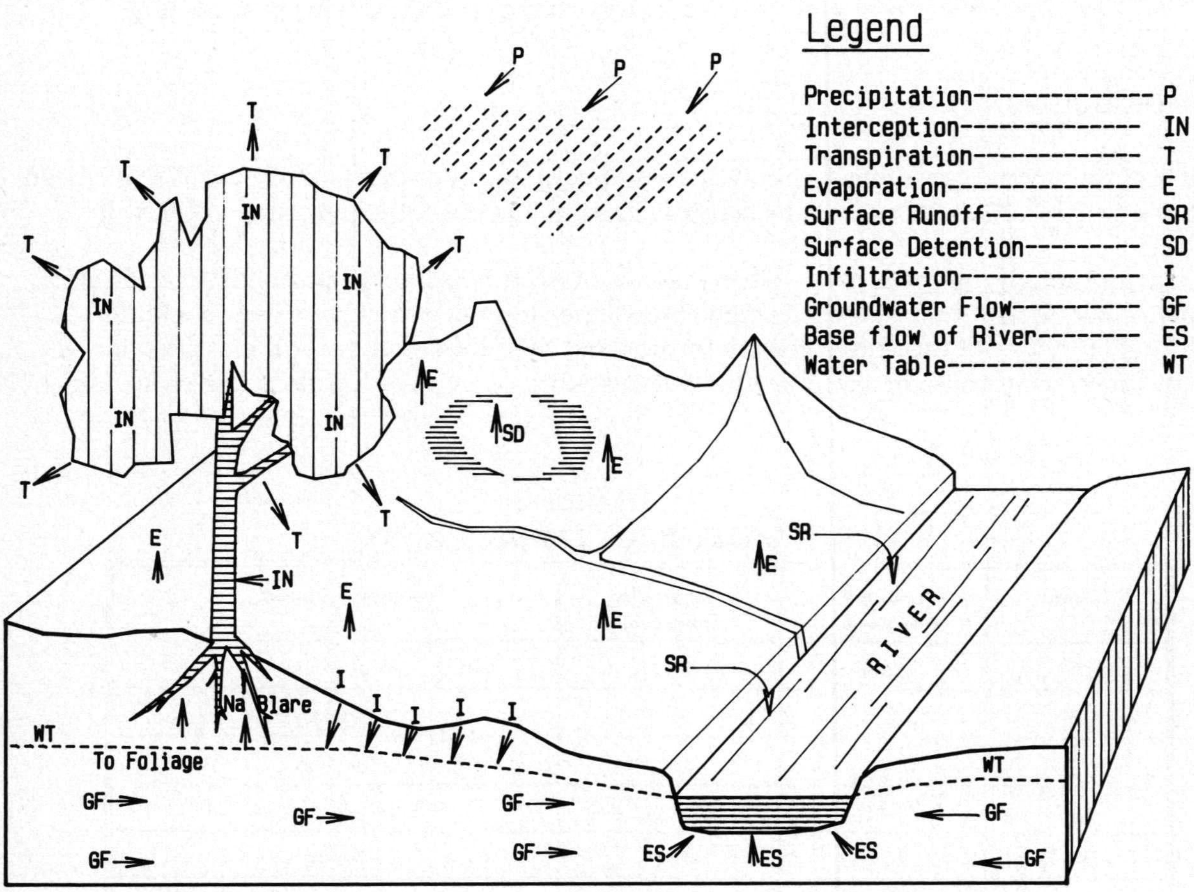


Figure 14
Disposition of rainfall on land.

in the subsurface are not filled with water, infiltration to greater depths takes place. The volume of water held in the saturated zone (see Chapter 3) is thus being replenished or recharged. As precipitation is intermittent, so is infiltration and recharge to groundwater.

Within the saturated zone the movement of water is lateral under the influence of gravity rather than vertical as in the unsaturated zone. As long as groundwater is being recharged albeit intermittently, it is also discharged on the surface, either as springs and seepage or into the air through evapotranspiration wherever it comes to within the reach of vegetation and/or evaporation aided by capillarity, where the water-table lies at or close to the surface. In the higher rainfall areas river flow is maintained during the dry season of the year, by groundwater which emerges in river channels in the form of seepage or springs. The groundwater component of runoff is termed base flow. By abstracting groundwater from boreholes/wells these natural discharges or losses are reduced or eliminated. Where the available space for holding groundwater is limited as is the case with shallow weathering and fracturing in certain hard rock areas, abstraction of groundwater by boreholes/wells may lead to more open storage in the zone of saturation, and thus to greater recharge than would normally occur under natural conditions.

From the foregoing it is evident that groundwater is not an independent resource. Its abstraction by boreholes/wells has an effect on spring flow, on surface runoff and on the environment.

7. HOW TO READ AND UNDERSTAND THE MAPS

7.1 INTRODUCTION

On each of the seven maps (Sheets 1 and 2) a number of localities designated A to W have been marked. These localities should not be considered as points but rather as centres of terrains.

Latitudes and longitudes of A to W and the names of neighbouring towns are listed in Table 2. The main rock types found in these terrains, the degree to which they have been metamorphosed, whether or not they have been deformed and their lithostratigraphic classification are given in Table 3. Information about groundwater conditions in these terrains is given in Tables 4 and 5.

TABLE 2
LOCATION OF TERRAINS A - W

Terrain	Latitude (degrees)	Longitude (degrees)	Neighbourhood
A	22.55	29.6	SW of Messina
B	22.9	29.0	S of Alldays
C	23.4	29.2	Dendron
D	24.5	29.2	S of Potgietersrus
E	26.15	28.7	Delmas
F	26.4	26.5	Coligny
G	26.55	29.75	Ermelo
H	27.45	21.6	NW of Olifantshoek
I	27,55	22.0	do
J	27.65	22.2	do
K	27.85	22.6	do
L	28.0	22.9	Between Sishen and Olifantshoek
M	27.5	23.8	Kuruman
N	27.5	25.45	Bloemhof
O	29.35	18.4	Between Springbok and Aggeneys
P	29.9	21.6	SE of Kenhardt
Q	29.13	31.03	SE of Kranskop, Natal
R	30.75	30.0	SE of Harding
S	31.3	19.1	Nieuwoudtville
T	31.5	23.3	Richmond (Cape)
U	33.0	21.6	Prince Albert Road
V	34.35	19.3	Hermanus
W	34.0	25.6	Port Elizabeth

The next nine sections 7.2 to 7.11 consist of
- general statements about each one of the set of maps on Sheets 1 and 2;
- a description of the geology and groundwater conditions of terrain A, as deduced from the maps. Terrain A is situated in the Northern Transvaal southwest of Messina.

7.2 GEOLOGY (SHEET 1)

The main types of rock are indicated on Sheet 1 by sixteen different hachuring of which the explanation is given in the legend, directly below the colour matrix. Further information about the rocks may be obtained from the lithostratigraphic symbols on the map i.e. letters such as TQk. These symbols are explained in the table titled "Lithostratigraphy of the Water-bearing Formations". Under "Notes" it is stated that the Figures 1, 2, 3 or 4 and the letter "D" or "U" which follow the symbol in the table, indicate respectively the degree of metamorphism to which a lithostratigraphic unit has been subjected and whether it was deformed by folding or not. The figures and letters are followed by the name(s) of the lithostratigraphic units and a list of the more important rock types which comprise the unit.

Terrain A
The hachuring of terrain A is described as an assemblage of compact sedimentary, extrusive and intrusive rocks. As can be seen on the map, the hachuring is designated by the letters ***Zl***. The symbol ***Zl*** appears near the bottom of the table "Lithostratigraphy of the Water-bearing Formations" where it is followed by a figure "4", a capital "D" and lithostratigraphic names: Limpopo Mobile Belt which embodies the Sand River Gneiss, the Beit Bridge Complex, the Messina Suite and the Bulai Gneiss. The Sand River unit consists of migmatite and gneiss; the Beit Bridge Complex comprises meta-quartzite, meta-pelite, marble, calc-silicate rocks and amphibolite; the Messina Suite is composed of meta-anorthosite, serpentinite, and meta-pyroxenite, and the Bulai unit consists of porphyroblastic biotite gneiss.

The figure "4" denotes high-grade metamorphism, whilst the letter "D" means that the rocks have been deformed by folding and that they are foliated. That the rocks of the Limpopo Mobile Belt have been metamorphosed and deformed is also indicated by the fact that the letters ***Zl*** on the map have been printed in bold italics.

Rock types at terrains A - W have been listed in Table 3.

7.3 BOREHOLE PROSPECTS (SHEET 1)

Borehole Prospects are depicted by means of a matrix of six colours each one in three shades (top right hand corner of sheet 1). The three shades are indicative of the probability of drilling a successful borehole, that is a hole yielding at least 0.1 ℓ/s.

The dark shades signify that of every 10 holes drilled 6 or more may yield at least 0.1 ℓ/s, i.e. a success rate of 60 per cent and more. The intermediate shades indicate a success rate of between 40 and 60 per cent and the pale shades a success rate of less than 40 per cent.

The six colours ranging from red to purple indicate the probability that a successful borehole may have a yield exceeding 2 ℓ/s.

A seventh colour has been used for unconsolidated to semi-consolidated coastal and alluvial deposits. Although boreholes in these porous formations generally have higher yields than

TABLE 3
GEOLOGY OF TERRAINS A - W*

Terrain	Lithostrat. unit	Lithology	Degree of meta-morphism	Deformed (D) Undeformed (U)
A	Zl	Migmatite, gneiss, meta-quartzite, metapelite, marble etc.	High grade	D
C	R	Biotite-muscovite granite, gneiss, leucogranite etc.	Low-high grade	U-D
O	Mn	Gneiss, granite meta-sediments etc.	Low-high grade	D
Q	Nmp	Gneiss, granulite etc.	Low-high grade	D
B	Jl	Basalt	None	U
D	Jl	Basalt	None	U
F	RVv	Volcanic rocks: andesite, quartz porphyry etc: sedimentary rocks: conglomerate, sandstone etc	Low grade	U
N	RVv	As for F above	Low grade	U
L	Vo	Andesite etc	Low grade	D
E	Vm	Dolomite, chert etc.	None	U
M	Vc	Dolomite, dolomitic limestone, chert etc.	Very low grade	U
G	Pes	Shale , sandstone intruded by dolerite dykes/sheets	None	U
T	Pa	Mudstone, sandstone intruded by dolerite dykes/sheets	None	U
U	Pa	Mudstone, sandstone (no dolerite)	None	D
H	CPd	Tillite with sandstone mudstone, shale intruded by dolerite	None	U
P	CPd	As for H above	None	U
R	CPd	As for H above	None	U
I	Mg	Schist, meta-quartzite, lava	Very low - low grade	D
J	Mv	Subgreywacke, quartzite, conglomerate	Very low	D
K	Mv	As for J above	Very low grade	D
S	OSt	Quartzitic sandstone, subordinate shale and tillite	Very low grade	D
42 V	OSt	As for V above	Very low - low grade	D
W	OSt	As for V above	Low grade	D

* Note: Terrains with more or less similar lithology have been grouped together. This also applies to Tables 4 and 5.

those in hard rock formations, adequate data are lacking for statistical analyses of probabilities. In addition borehole yields in these formations are much more dependent on the use of correctly sized borehole screens and development techniques than holes drilled in hard rock formations. In the case of the Kalahari Group which is also semi- to unconsolidated, the probabilities of drilling successful boreholes and the chances of yields exceeding 2 ℓ/s are shown.

Terrain A

According to the colour matrix, terrain A is situated in an area where the probability of drilling a successful hole is less than 40%. The chances that such a successful hole will yield more than 2.0 ℓ/s lie between 10 and 20%. In other words the chances of drilling a hole yielding more than 2.0 ℓ/s in terrain A are less than 40/100 times 20/100 i.e. less than 8%.

It should be noted that this probability is based on a statistical analysis of results on drilling sites that were not selected scientifically. It is believed that these statistics are a better reflection of the overall water-bearing properties than statistics of drilling results on scientifically selected sites. With scientific siting the tendency would be to rule out, as far as is possible, those parts where chances of striking water would be poorer.

Borehole Prospects at terrains A - W are listed in Table 4.

7.4 TYPES OF SATURATED INTERSTICES (SHEET 2)

Moving on to Sheet 2, the saturated interstices map and legend provide information about the types of opening in which groundwater is held and recommends optimal drilling depths below the water level on the basis of statistical analyses of water strikes in boreholes. As in the case of Borehole Prospects, it should be realised that these findings are regionalised averages and that they should be seen as guidelines for planning purposes. The optimal drilling depths are not hard and fast rules to be applied blindly. Ideally, a final decision on drilling depth should be taken at the drill site on the basis of the drill cuttings emerging from the hole.

Terrain A

The map shows that at terrain A groundwater is held in fractures in igneous and crystalline metamorphic rocks and that the optimal drilling depth is less than 20 m below the groundwater level. This does not mean that deeper fractures do not exist. Open fractures are generally more numerous directly below the groundwater level. They decrease in number with increasing depth to the stage where the chances of striking an open water-bearing one becomes too small for economical pursuit i.e. another borehole should rather be drilled than continuing to drill deeper.

The type(s) of saturated interstices at terrains A - W are listed in Table 4.

7.5 GROUNDWATER STORAGE (SHEET 2)

The volume of water divided by the volume of the rock in which it is held, is known as the storage coefficient. A storage coefficient of 0.001 means that one cubic metre of rock contains one thousandth part of a cubic metre of water i.e. a litre. The storage coefficients quoted in the legend are meant as very rough indications of the storage capacities of saturated rocks containing fractures only or fractures plus intergranular openings or pores. The pores may be primary (in unconsolidated and semi-consolidated formations) or secondary having been formed through weathering of hard rock.

TABLE 4
DRILLING CONDITIONS AND NATURE OF SATURATED INTERSTICES

Terrain	Borehole prospects		Type(s) of saturated interstices	Groundwater level (metres) (refer to note below)		Optimal drilling depth below groundwater level (metres)
	Probability of a successful borehole i.e. yield more than 0.1 ℓ/s	Probability of successful borehole yielding more than 2 ℓ/s		A	B	
A	< 40 %	10 - 20 %	Weathered fractures	20 - 30	15 - 20	20 - 30
C	> 60 %	> 50 %	Weathered fractures	30 - 40	>30	30 - 50
O	< 40 %	10 - 20 %	Weathered fractures	75 - 100	-	< 20
Q	40 - 60 %	10 - 20 %	Secondary pores & weathered fractures	20 - 30	>25	20 - 30
B	40 - 60 %	30 - 40%	Weathered fractures	10 - 20	8 - 15	20 - 30
D	> 60 %	> 50 %	Secondary pores & weathered fractures	10 - 20	8 - 15	20 - 30
F	> 60 %	20 - 30 %	Secondary pores & weathered fractures	10 - 20	8 - 15	20 - 30
N	40 - 60 %	10 - 20 %	weathered fractures	10 - 20	8 - 15	20 - 30
L	> 60 %	30 - 40 %	Weathered fractures	about 30	15 - 25	< 20
E	> 60 %	> 50 %	karst see Figures A 5, 8 & 9	30 - 40	>30	50 - 100
M	> 60 %	> 50 %	Fractures dissolution features not prominent	10 - 20	8 - 15	20 - 30
G	< 40 %	10 -20 %	Secondary pores & weathered fractures	10 - 20	8 - 15	30 - 50
T	> 60 %	40 - 50 %	Weathered fractures	< 10	-	20 - 30
U	> 60 %	40 - 50 %	Weathered fractures	10 - 20	8 - 15	20 - 30
H	< 40 %	< 10 %	Weathered fractures	> 125	-	< 20
P	< 40 %	20 - 30 %	Secondary pores and weathered fractures	20 - 30	<15	< 20
R	> 60 %	10 - 20 %	Secondary pores & weathered fractures	20 - 30	15 - 25	< 20

Terrain	Borehole prospects		Type(s) of saturated interstices	Groundwater level (metres) (refer to note below)		Optimal drilling depth below groundwater level (metres)
	Probability of a successful borehole i.e. yield more than 0.1 ℓ/s	Probability of successful borehole yielding more than 2 ℓ/s		A	B	
I	< 40 %	10 - 20 %	Weathered fractures	75 - 100	-	< 20
J	<40 %	10 - 20 %	Weathered fractures	> 125	-	< 20
K	> 60 %	10 - 20 %	Secondary pores & weathered fractures	about 30	20 - 30	< 20
S	40 - 60 %	20 -30 %	Fractures	10 - 20	>15	50 - 100
V	> 60 %	> 50 %	Fractures	30 - 40	20 - 30	50 - 100
W	40 - 60 %	< 10 %	Fractures	20 - 30	15 - 25	50 - 100

Note: A is the range within which the mean groundwater level lies B is the range by which groundwater levels fluctuate about the mean. With few exceptions groundwater levels in boreholes do not lie above the surface. Negative levels obtained by deducting B from A should be interpreted as levels at or close to the surface.

The mean thickness of that part of the saturated zone which contains the bulk of the most readily accessible groundwater may be taken on average as half the optimal drilling depth below the water level. From the fact that not every borehole in hard rock proves successful, it should be evident that a zone of saturated and favourably fractured rock is not omnipresent. One may visualise such conditions to exist over a fraction of a terrain only - along linear zones of more intense fracturing or patch-like at the intersection of two or more joint systems (see Figures 5 to 10). The extent to which these favourable water-bearing conditions obtain in a terrain, may be judged on the basis of the percentage successful holes that have been drilled in that particular area.

Terrain A

That part of the saturated zone that is well fractured, averages less than 10 m in thickness. Assuming that the storage coefficient is 0.001, and that the well-fractured zone is 5 m thick, one may conclude that 5 litres of groundwater are stored beneath a square metre of the surface.

The success rate of less than 40% indicates that this does not apply to every square metre of the terrain, but only to a rather small fraction of it. Over the greater part weathering and its well-developed zone of fracturing does not extend to below groundwater level. It is therefore clear that the volume of groundwater in terrain A is indeed very limited. During periods of little or no recharge, it may easily be depleted by abstraction through boreholes.

7.6 GROUNDWATER LEVEL AND DRILLING DEPTH (SHEET 2)

To estimate the total drilling depth, one has to know the depth of the water level below the surface in addition to the optimal drilling depth below the groundwater level. This information is provided by the depth to groundwater level map (Sheet 2).

Terrain A

A mean water level depth somewhere between 20 and 30 m is indicated. The groundwater level varies around this mean as a result of variable topography. This variation is of the order of between 15 and 25 m. At its shallowest the groundwater level could be close to or at the surface and at its deepest 50 m, if the mean level is taken to be 25 m deep. The total optimal drilling depth in terrain A therefore ranges between 20 m (0 plus 20 m) in the areas with the shallowest groundwater levels to 70 m (50 plus 20 m) in those parts where the groundwater level is deepest.

The mean depths of the groundwater level and their variability about the mean in terrains A -W are given in Table 4.

7.7 GROUNDWATER RECHARGE AND EFFECTIVE RAINFALL (SHEET 2)

Groundwater recharge is dependent in the first instance on rainfall. A measure of the rainfall that is available for recharge is provided by mean annual effective rainfall. Effective rainfall is that part of the daily rainfall which seeps into the ground after allowing for losses through interception by vegetation and by storm runoff. Of the effective rainfall, only a small fraction infiltrates down to the saturated zone. The major part is lost through evaporation from the soil and transpiration by the vegetation. The determination of that fraction of the rainfall which ultimately becomes groundwater is one of the most difficult quantities to measure.

A provisional indication of mean annual groundwater recharge may be found on Sheet 2. The fact that recharge is expressed in terms of millimetres per annum does not signify that recharge is an annual event throughout the country. In the eastern and southern higher rainfall parts of South Africa, groundwater contributes to the flow in rivers and streams. Here recharge, though variable, as is indicated in the legend accompanying the "Groundwater component of river flow" map (Sheet 2), may be assumed to take place annually. However the lower the rainfall, the more variable and uncertain it is. This applies even more so to recharge. Over the drier parts of the country recharge ranges from periodic to ephemeral i.e. in the more arid western parts of the Kalahari and the North-western Cape.

Terrain A

The mean annual effective rainfall is between 200 and 300 mm/a. According to the ground-water recharge map (Sheet 2) the mean annual recharge is less than 5 mm/a. At this low rate, it may be taken that recharge occurs periodically, not annually. Coupled with the very limited storage, one may conclude that the groundwater resources in terrain A are suitable for no more than limited stock-watering and domestic supplies. Under such circumstances the possibility of failure of supply during droughts is very likely.

Provisional groundwater recharge in terrains A - W are given together with indications of effective rainfall in Table 5.

7.8 GROUNDWATER QUALITY (SHEET 2)

The quality criteria for judging the suitability of water for the different uses of water vary. For domestic use water has to comply with certain minimum physical, chemical and bacteriological requirements. This spectrum obviously cannot be covered within the context of the national hydrogeological map project. The total dissolved solids (TDS) content may be used as a pri-

TABLE 5
PROVISIONAL GROUNDWATER RECHARGE, GROUNDWATER QUALITY AND HYDROCHEMISTRY

Terrain	Mean effective rainfall (mm/a)	Mean groundwater recharge (mm/a)	Total dissolved solids (mg/ℓ) (refer note 1 below)		Fluoride above limit in more than 20 % of analyses	Nitrate above limit in more than 20 % of analyses	Dominant Hydro-chemical Type(s) (refer note 2 below)
			A	B			
A	200 - 300	< 5	500 - 1 000	1 500 - 2 000	No	Yes	bc
C	300 - 400	5 - 10	500 - 1 000	500 - 1 500	No	Yes	AB
O	50 - 100	< 1	1 000 - 1 500	> 3 500	Yes	No	D
Q	> 600	50 -75	< 300	500 - 1 000	No	Yes	D
B	300 - 400	5 - 10	< 500	1 000 - 1500	No	Yes	B
D	300 - 400	25 -50	< 500	1 000 - 1 500	No	Yes	A
F	400 - 500	25 -50	< 300	500 - 1 000	No	Yes	AB
N	300 - 400	15 -25	< 500	1 000 - 1500	No	Yes	AB
L	200 - 300	5 -10	< 300	500 - 1 000	No	No	B
E	500 - 600	about 50	< 300	500 - 1 000	No	No	B
M	300 - 400	> 25	< 300	500 - 1 000	No	Yes	B
G	500 - 600	< 50	< 300	500 - 1 000	No	No	B
T	150 - 200	10 - 15	< 500	1 000 - 1 500	No	No	A
U	50 - 100	< 5	< 500	1 000 - 1 500	No	No	a
H	100 - 150	< 1	> 1 500	> 4 000	Yes	Yes	D
P	100 - 150	> 5	> 1 500	> 4 000	Yes	Yes	D
R	> 600	50 - 75	< 300	< 500	No	No	d
I	100 - 150	< 1	500 - 1 000	2 000 - 3 500	No	Yes	AD
J	100 - 150	< 1	500 - 1 000	2 000 - 3 500	No	Yes	AD
K	About 200	1 - 5	< 300	500 - 1 000	No	Yes	A
S	300 - 400	> 15	< 500	1 500 - 2 000	No	No	D
V	300 - 400	about 75	< 300	500 - 1 000	No	No	D
W	300 - 400	> 50	< 500	1 000 - 1 500	No	No	D

Note 1: The lower and upper geometric standard deviations lie somewhere within the ranges as indicated by columns A and B. See Section 7.8 Terrain A for further explanation.
Note 2: For the meaning of the letters A, B, b, c etc. refer to Table 6. Upper case signifies a greater degree of dominance of the hydrochemical type than the lower case (refer to Groundwater Quality Map sheet 2). Two type dominance is indicated by letter pairs.

mary indication of suitability. As far as drinking water is concerned the situation may be summarised as follows (Department of Water Affairs 1986):
"The TDS limit, as recommended by the South African Bureau of Standards in Specification 241-1984 is expressed in terms of its electrical conductivity (EC) to facilitate analytic procedures and comparison of results. The conversion of EC to TDS depends on the chemical composition of the dissolved salts. The recommended EC limit of 70 Ms/m is equivalent to TDS concentrations of between 350 and 550 mg/ℓ depending on constituents. The maximum allowable limit for drinking water is given as 300 Ms/m which is equivalent to a TDS concentration of about 2 000 mg/ℓ".
A TDS concentration below 1 000 mg/ℓ is the World Health Organisation's guideline for drinking water.

Limits of 300, 500, 1 000 and 2 000 mg/ℓ which agree more or less with the above have been used in mapping TDS concentrations. The variability of TDS over short distances and the amount of data available do not allow demarcation of areas within which all TDS values will lie within the limits of less than 500, between 500 and 1 000, between 1 000 and 2 000 and over 2 000 mg/ℓ. With the exception of the 300 to 500 mg/ℓ range, the different categories on the map overlap these ranges. It should also be noted that the upper and lower geometric standard deviations comprise about 83 per cent of the analysed samples. Seventeen per cent fall outside the specified ranges, partly above and partly below the ranges.

Apart from TDS, the chemical suitability of groundwater has to be judged in terms of the concentrations of the ions it contains. Of these fluoride and nitrate have been singled out as constituents that are most commonly present in amounts exceeding the recommended limits of 1.5 mg/ℓ F and 10 mg/ℓ NO_3 (as N).

Areas where these limits are exceeded in more than 20 per cent of the samples analysed, are shown by two sets of diagonal lines. Excessive concentrations of fluoride and/or nitrate are, however, not necessarily a problem of each and every borehole in these areas. Unmarked areas on the other hand should not be viewed as devoid of borehole supplies with excessive concentrations of fluoride and/or nitrate. In other words, in the demarcated areas fluoride and nitrate are more commonly a problem than in the unmarked areas.

In certain areas nitrate may be a natural constituent of groundwater, in other instances its presence may be the result of the excessive use of nitrogen fertiliser, or it may be an indication of pollution by concentrations of animal excrement in stock pens and at watering places or by sewage. Fluoride is commonly, though not exclusively, associated with acidic and alkaline igneous rocks such as granite, rhyolite and foyaite. Within the scope of this project it is not possible to dwell on other constituents mentioned in the SABS specification, that are deleterious to health if present in amounts above permissible limits. The suitability of a water supply for drinking should in any case always be determined by analysis.

Terrain A
Excluding approximately 17% of analyses which have lower and higher values, TDS ranges from somewhere between 500 and 1 000 mg/ℓ (lower geometric standard deviation) to somewhere between 1 500 and 2 000 mg/ℓ (upper geometric standard deviation). Some of the groundwater would therefore, as far as TDS is concerned, comply with the World Health Organisation's guideline for drinking water while most of the remaining water does not exceed the maximum allowable limit of 2 000 mg/ℓ TDS.

Nitrate in excess of 10 mg/ℓ as N has been encountered in more than 20 per cent of the samples analysed. Fluoride in excess of 1.5 mg/ℓ, is likely to occur in less than in 20 per cent of analyses.

TDS ranges for terrains A - W are given in Table 5.

7.9 HYDROCHEMICAL TYPES (SHEET 2)

This classification is more of scientific than general practical interest. Four principal types of water may be distinguished in terms of the dominant dissolved constituents (Table 6).

TABLE 6
PRINCIPAL HYDROCHEMICAL TYPES

Dominant dissolved constituents	Piper quadrangle (see Sheet 2)
Calcium and/or magnesium bicarbonate/carbonate	B
Sodium and potassium bicarbonate/carbonate	C
Calcium and/or magnesium chloride and/or sulphate	A
Sodium and potassium chloride and/or sulphate	D

Groundwater from any particular borehole does not necessarily contain only one of the above-mentioned four groups of dissolved constituents. One of the four groups of constituents may be the dominant one. Usually lesser amounts of the other constituents are also present. A particular sample of groundwater is however characterised and classified in terms of the dominant group of dissolved constituents it contains e.g. a Calcium/Magnesium Bicarbonate water (type B).

In some parts of the country the majority of groundwater samples which have been analysed, are of one principal hydrochemical type; in other parts two principal types are about equally represented. The former areas are indicated on the Hydrochemical Types Map by a single colour assigned to that particular principal type; the latter parts of the country are depicted by an alternation of two colours, one for each of the two principal types. In each of these two cases two degrees of dominance are distinguished: dark colours indicate a greater degree of dominance and paler shades a lesser degree of dominance of the hydrochemical type(s).

Terrain A
Two principal hydrochemical types, each comprising between 30 and 40 per cent of the analysed samples, are dominant in terrain A: a sodium/potassium bicarbonate/carbonate and a calcium/magnesium chloride/sulphate type water.

The hydrochemical types of terrains A - W are given in Table 5.

7.10 GROUNDWATER COMPONENT OF RIVER FLOW (BASE FLOW, SHEET 2)

Reference was made in Chapter 6 to the groundwater component of river flow, also known as base flow. In the higher rainfall areas groundwater contributes to river flow. The contribution is expressed in terms of water depth i.e. the annual volume of groundwater in cubic metres derived from a particular catchment divided by the area of that catchment in square metres and multiplied by 1 000. Although base flow from some small catchments along the Eastern Transvaal Escarpment exceeds 50 per cent of the total annual runoff, it mostly constitutes between 10 and 25 per cent of the annual runoff from those catchments that produce measurable base flow volumes. It constitutes less than 4 per cent of the mean annual rainfall for the greater part of the base flow producing area. Because groundwater is dissipated also through evaporation from shallow water-table areas and by transpiration of vegetation, base flow underestimates recharge. As can be seen in the legend, base flow varies considerably from year to year.

Terrain A
Groundwater does not contribute to river flow.

7.11 CONCLUSION

To exercise and test his ability at map reading, the reader may follow the procedures described above for any or all of the marked terrains and check the results against Tables 3, 4 and 5. Note that in these tables terrains with more or less similar lithology have been grouped together as follows:

Terrains	**Lithology**
A, C, O and Q	Granitic rocks
B, D, F, N and L	Lavas
E and M	Dolomitic strata
G, T and U	Intercalated Karoo shales, mudstones and sandstones
H, P and R	Dwyka tillite
I, J and K	Mokolian quartzitic rocks
S, V and W	Table Mountain quartzitic sandstones

The reader may find it an interesting exercise to see how groundwater conditions in similar lithologies vary under different climatic conditions.

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APPENDIX I
GROUNDWATER EXPLOITATION

Towns with populations exceeding 2 500 which are either totally or partially dependent on groundwater supplies are shown on Figure 15 (see colour section) and listed in Tables 7 and 8. The more important irrigation areas based on groundwater are also depicted on Figure 15.

TABLE 7
MORE IMPORTANT MUNICIPAL SUPPLY SCHEMES BASED SOLELY ON GROUNDWATER (ONLY TOWNS WITH A POPULATION OF MORE THAN 2 500 LISTED)

Locality	No on Figure 15	Locality	No on Figure 15
MESSINA	1	PHILIPPOLIS - PHODING-TSEROLO	50
THABAZIMBI	4	TROMPSBURG	51
GRASKOP	9	SPRINGFONTEIN - MAPHODI	52
MmBATHO	10	SMITHFIELD - MOFULATSHEPE	53
KOSTER - REAGILE	11	ROUXVILLE - RWELELEYATHUNYA	54
SABIE	13	MATATIELE - ITSHOKOLELE	55
MIER	15	CEDARVILLE - MZINGISI	56
DELAREYVILE	16	HARDING	57
SANNIESHOF - AGISANG	17	CALVINIA	58
LICHTENBURG - BOIKHUTO	18	FRASERBURG	59
OTTOSDAL - LETSOPA	19	VICTORIA WEST	60
VENTERSDORP - TSHING	20	RICHMOND (CAPE)	61
DELMAS - BOTLENG	21	MURRAYSBURG	62
BALFOUR - SIYATHEMBA	22	HANOVER - NONPUMELELO	63
OLIFANTSHOEK	23	NOUPOORT - KWAZAMUXOLO	64
SISHEN-KATHU	24	MIDDELBURG - KWANONZAME (CAPE)	65
KURUMAN	25	HOFMEYR	66
VREDEFORT - MOKWALLO	27	STERKSTROOM	67
DANIELSKUIL	28	JAMESTOWN - MASKHANE	68
GRIQUATOWN	29	LAMBERTS BAY	69
BOSHOF - SERETSE	30	ABERDEEN - THEMBALESIZWE	71
HERTZOGVILLE -MALEBOGO	31	JANSENVILLE - KWAZAMUKUCINGA	73
EXCELSIOR	34	BEDFORD - NYARHA	75
PAUL ROUX	36	TARKASTAD - ZOLA	76
KESTELL - TLHOLONG	37	ATLANTIS	79

Locality	No on Figure 15	Locality	No on Figure 15
KENHARDT	38	DE DOORNS	80
PETRUSBURG - BOLOKANANG	39	LAINGSBURG	81
FAURESMITH - IPOPENG	40	PRINCE ALBERT	82
JAGERSFONTEIN -ITUMELENG	41	DYSSELDORP	83
EDENBURG	42	KLIPPLAAT - WONGALETHU	84
DEWETSDORP - MOROJANENG	43	STEYTLERVILLE	85
GREYTOWN - ENHLALAKAHLE	44	ALEXANDRIA -KWANONQUBELA	87
RICHMOND (NATAL)	45	KENTON-ON-SEA	88
CARNARVON	46	KOMGA -QUMHRA	89
BRITSTOWN - MZIWABANTU	47	ALBERTINIA	91
DE AAR - NONZWAKAZI	48	STIL BAY	92
PHILIPSTOWN	49	HUMANSDORP	93

TABLE 8
MORE IMPORTANT MUNICIPAL SUPPLY SCHEMES BASED ON SURFACE AND ON GROUNDWATER (ONLY TOWNS WITH A POPULATION OF MORE THAN 2 500 LISTED)

Locality	No on Figure 15	Locality	No on Figure 15
LOUIS TRICHARDT	2	BRANDFORT - MAJWEMOSWEU	33
PIETERSBURG - SESHEGO	3	CLOCOLAN - HLOHLOLWANE	35
WARM BATHS	5	BEAUFORT WEST - SIDESAVIVA	69
NYLSTROOM - PHAGAMENG	6	GRAAFF-REINET - UMASIZAKHE	72
NABOOMSPRUIT - MOOKGOPHONG	7	SOMERSET EAST - KWANOJOLI	74
POTGIETERSRUS	8	ADELAIDE - LINGELETHU	77
PRETORIA	12	FORT BEAUFORT	78
VRYBURG - HUHUDI	14	UITENHAGE - KWANOBUHLE	86
SCHWEIZER-RENEKE - IPELENG	26	BREDASDORP	90
BULTFONTEIN - PHAHAMENG	32	JEFFREY'S BAY	94

APPENDIX II
COLD SPRINGS

The positions of cold springs yielding more than 1 000 cubic metres per day are shown on the Groundwater Level Map (Sheet 2). Keys to the names of the numbered positions are given in Table 8.

TABLE 9
COLD SPRINGS YIELDING MORE THAN 1 000 m³/d

No. on groundwater level map	Name/Farm name	Latitude degrees south	Longitude degrees east
1	VERGENOEG EYE	25.633	25.986
2	RIETPOORT EYE	25.679	25.955
3	DOORNPLAAT EYE	25.776	25.99
4	PRETORIA FOUNTAINS	25.785	28.196
5	GROOTFONTEIN EYE (MARICO)	25.787	26.361
6	ERASMIA	25.815	28.063
7	RHENOSTERHOEK EYE	25.816	26.441
8	MALMANIE EYE	25.838	26.063
9	KAREEBOSCH EYE	25.840	25.99
10	MOLOPO EYE	25.869	26.036
11	GROOTFONTEIN EYE (MAFIKENG)	25.917	25.869
12	GROOTFONTEIN (RIETVLEI DAM NATURE RESERVE)	25.921	28.367
13	KROMDRAAI 520 JO	25.968	27.788
14	TWEEFONTEIN 19 IR	25.968	28.351
15	RIETVALLEI 195 IR	26.081	28.553
16	OLIFANTSFONTEIN 196 IR	26.123	28.607
17	LICHTENBURG EYE	26.127	26.166
18	near DELMAS	26.173	28.688
19	BOONSTE OOG VAN MOOIRIVIER	26.193	27.161
20	SCHOONSPRUIT EYE	26.273	26.867
21	near JACKSON'S DRIFT	26.336	28.027
22	TURFFONTEIN EYE	26.411	27.176
23	PAKHANE	26.435	23.530
24	GERHARD MINNEBRON	26.445	27.160
25	near ORKNEY	26.959	26.71
26	LOWER KURUMAN (TSINENG)	27.096	23.075

No. on groundwater level map	Name/Farm name	Latitude degrees south	Longitude degrees east
27	near SEHUBANE VILLAGE	27.287	23.306
28	near MOTLHWARE VILLAGE	27.340	23.355
29	KURUMAN 2nd EYE	27.446	23.503
30	KURUMAN COMMONAGE	27.458	23.445
31	MANYEDING	27.499	24.687
32	KONO A	27.643	23.570
33	GROOT VLAKFONTEIN	27.663	23.088
34	KONO B	27.683	23.604
35	GROOT BOETSAP	27.936	24.404
36	FARM No 261	28.132	23.398
37	DANIELSKUIL	28.184	23.548
38	RICHARD BAY	28.824	31.982
39	ALONGSIDE MODDER RIVER	28.899	25.979
40	NIEKERKSHOOP ALLOT AREA	29.322	22.892
41	CRYSTAL SPRING	30.507	29.411
42	BRANDWACHT 226	32.210	18.427
43	LANGEVLEI 243	32.346	18.684
44	KRUISFONTEIN 2	32.433	18.599
45	STUDTIS	33.546	23.964
46	SILWERSTROOM	33.585	18.365
47	UITENHAGE	33.700	25.438
48	ALEXANDRIA COAST RESERVE	33.77	26.463
49	ALBION SPRING	33.968	18.468
50	NEWLANDS SPRING	33.969	18.458
51	HUMANSDORPFONTEIN	34.000	24.759
52	STILBAAI	34.361	21.371
53	GROOTE FONTEIN 486	34.367	21.408
54	PLATTE BOSCH 485	34.370	21.409
55	WALKERS BAY (FOREST RESERVE NO 130)	34.544	19.375
56	DIE KELDERS	34.557	19.377
57	KLEYN HAGEL KRAAL 321	34.685	19.544

APPENDIX III
THERMAL SPRINGS

The positions of thermal springs are shown on the Groundwater Level Map (sheet 2). Keys to the names of the numbered positions are given in Table 9.

TABLE 10
THERMAL SPRINGS⁺

No. on water level map	Name	Latitude degrees south	Longitude degrees east
1	EVANGELINA*	22.417	29.183
2	KLEIN TSHIPISE**	22.533	30.667
3	TUGELA*	22.567	28.617
4	GORDONIA	22.583	30.167
5	TSHIPISE**	22.617	30.167
6	VETFONTEIN	22.783	29.383
7	MPEFU	22.917	30.167
8	SOUTINI*	23.416	30.924
9	LETABA*	23.650	30.667
10	EILAND*	23.653	30.717
11	RHODA	24.030	31.131
12	CONSTANTIA*	24.417	28.758
13	DIE OOG*	24.433	28.617
14	WELGEVONDEN	24.450	28.567
15	BUFFELSHOEK	24.567	27.60
16	VISCHGAT*	24.567	28.60
17	LOUBAD**	24.600	28.183
18	VOORTREKKERBAD	24.770	30.383
19	RIFFONTEIN	24.833	29.30
20	DE BAD	24.842	30.397
21	WARMBATHS**	24.883	28.30
22	RICHMOND*	24.997	30.983
23	BUFFELSKLOOF	25.017	29.890
24	SABIE R.MIN.BATH	25.023	31.167
25 A & B	BADFONTEIN	25.345 25.362	30.364 30.398
26	JARRABAD*	25.35	29.033
27	MACHADODORP	25.65	30.25

No. on water level map	Name	Latitude degrees south	Longitude degrees east
28	BADPLAAS**	25.95	30.583
29	SULPHUR SPRINGS**	27.183	31.10
30	FRISCHGEWAAGD	27.363	31.00
31	NATAL SPA*	27.533	30.867
32	BLACK UMFOLOSI	28.033	31.30
33	RIEMVASMAAK	28.45	20.33
34 A & B	SKUITDRIF OOS WARMBAD NOORD	28.50 28.53	19.717 19.55
35	BADEN-BADEN**	28.517	25.783
36	WINBURG	28.550	26.917
37	FLORISBAD**	28.762	26.080
38	ETEMBENI	28.85	30.483
39	TUGELA VALLEY*	28.867	31.00
40	LILANI*	29.117	30.85
41	KNEGHA DRIFT	30.467	28.65
42	ALIWAL NORTH	30.717	26.717
43	ROOIWAL	30.867	25.583
44	BADSFONTEIN	30.883	25.783
45	CRADOCK*	32.133	25.45
46	GRASRAND	32.317	24.45
47	STINKFONTEIN	32.667	21.983
48	DIE BAD	32.75	19.033
49	FORT BEAUFORT	32..833	26.667
50	TOWERWATER	33.40	23.167
51	MALMESBURY	33.467	18.717
52	GOUDINI**	33.667	19.267
53	GAMKA VALLEY	33.667	21.717
54	OLIFANTS VALLEY**	33.667	21.767
55	BADEN *	33.713	20.117
56	BRANDVLEI	33.717	19.417
57	WARMWATERBERG**	33.733	20.90
58	MONTAGU	33.75	20.10
59	CALEDON**	34.25	19.45

+ Larger and better known marked **
intermediate group *
weakest/least known no asterisk

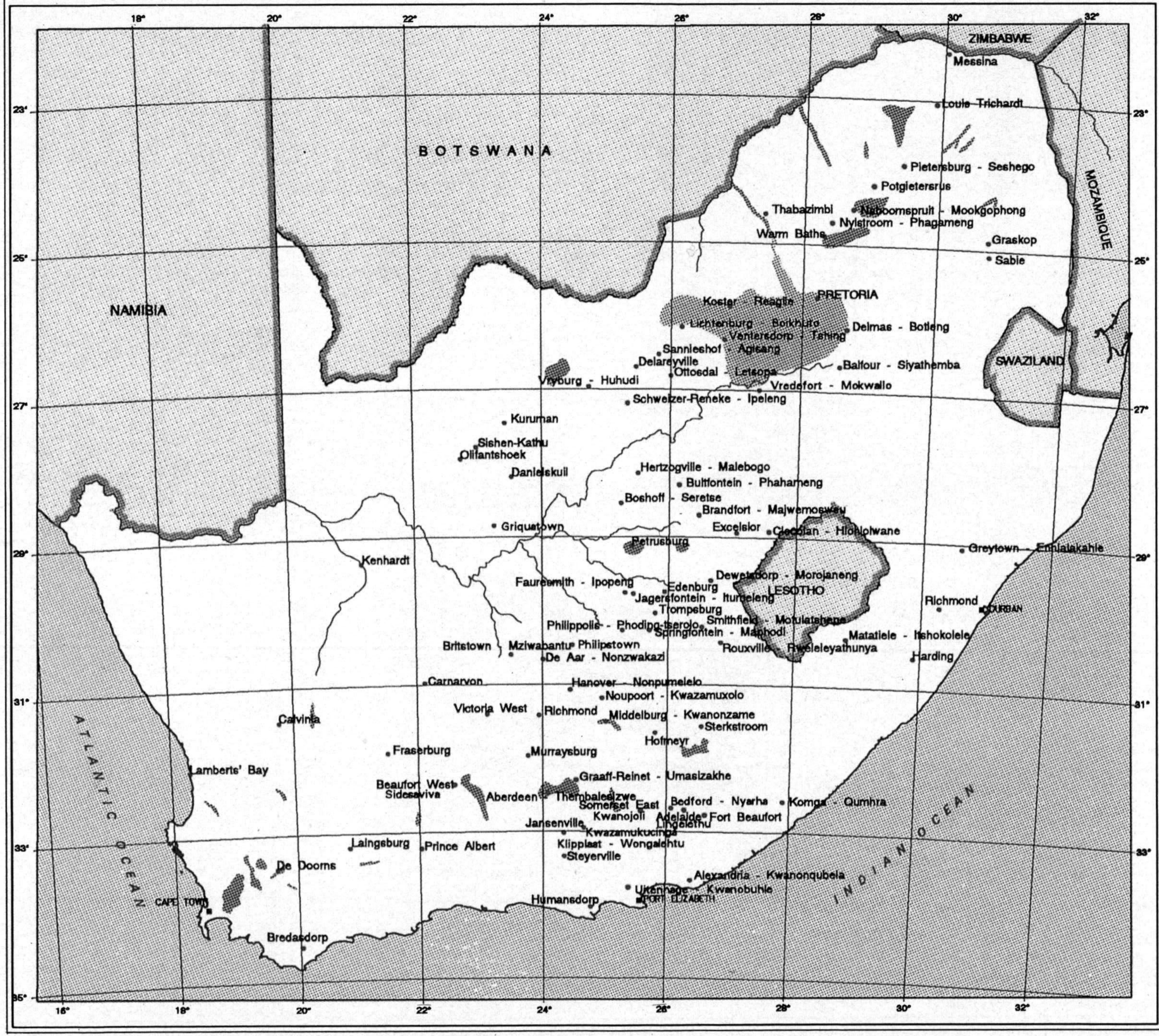


Figure 15

Groundwater Exploitation

- Dominant groundwater irrigation area
- Less dominant groundwater irrigation area
- Municipal Water Supply Scheme based on groundwater only for community of more than 2500 inhabitants
- Municipal Water Supply Scheme based on surface and groundwater for community of more than 2500 inhabitants

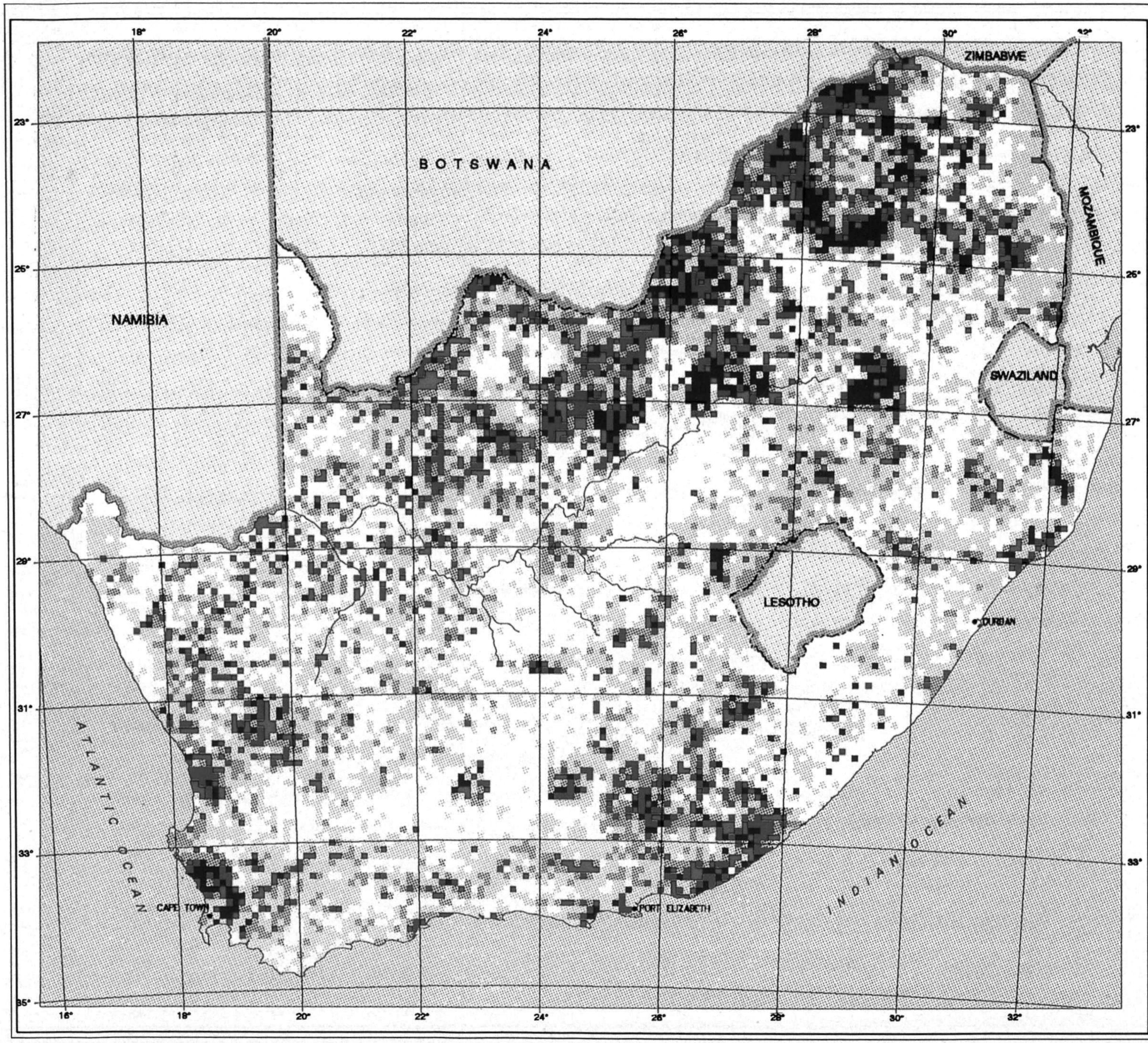
50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

Figure 1

Density of Borehole Data: Borehole Prospects Map



No boreholes

1 - 5

6 - 10

11 - 15

16 - 25

> 25

50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

COLOUR SECTION

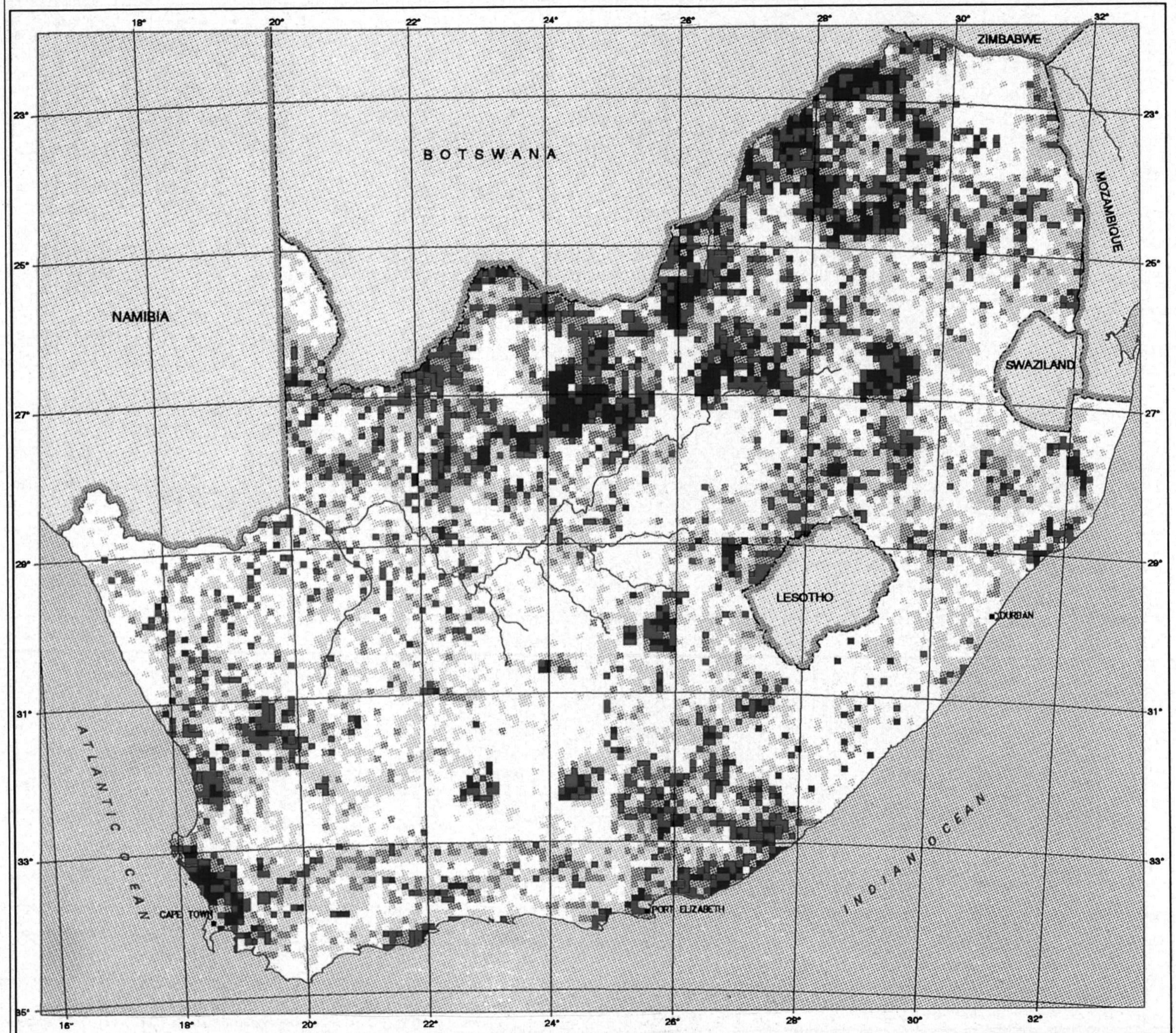


Figure 2

Density of Borehole Data: Depth of Groundwater Level Map

- No boreholes
- 1 - 5
- 6 - 10
- 11 - 15
- 16 - 25
- > 25

50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

Figure 3

Effective Rainfall (ACRU Model)

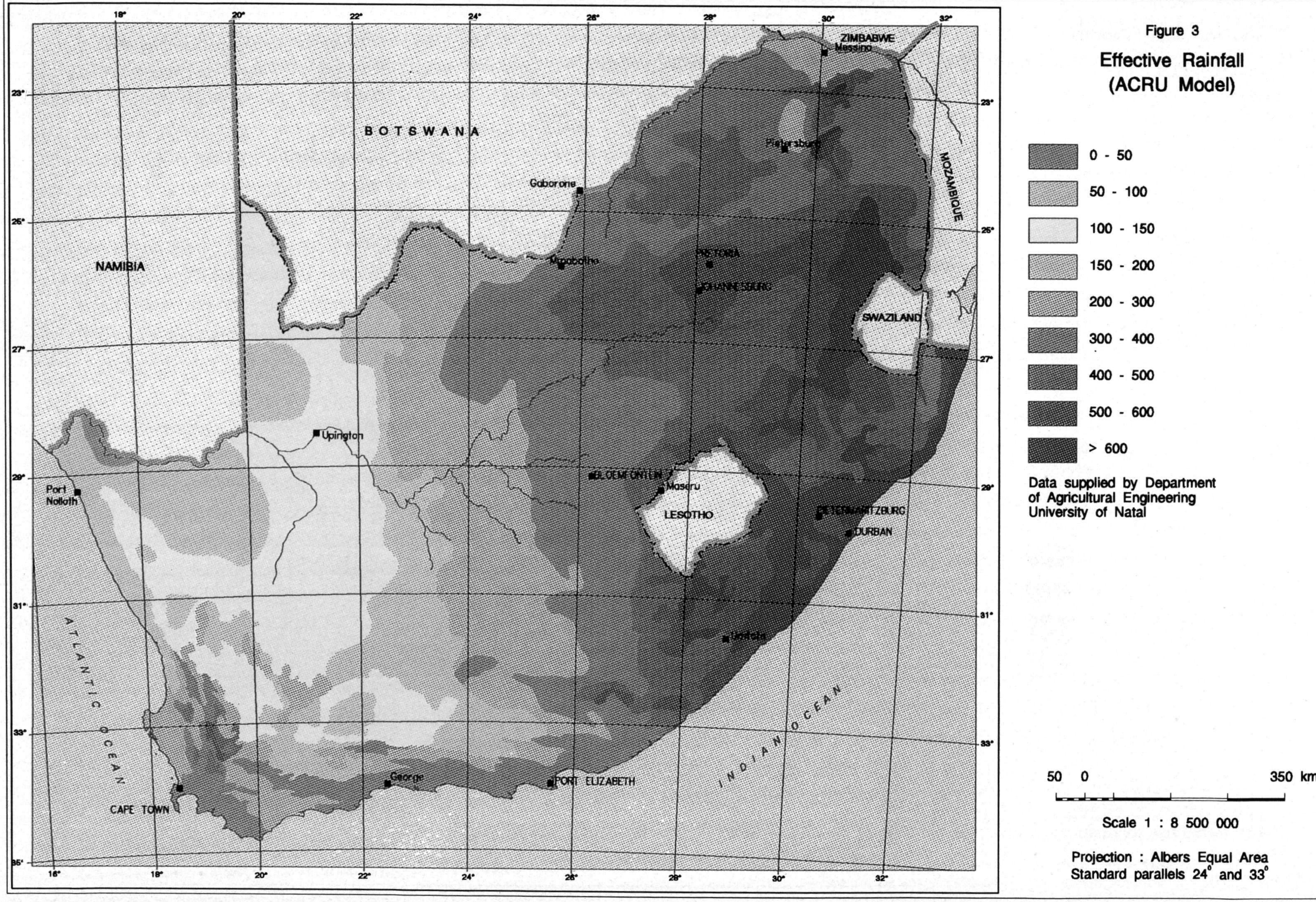
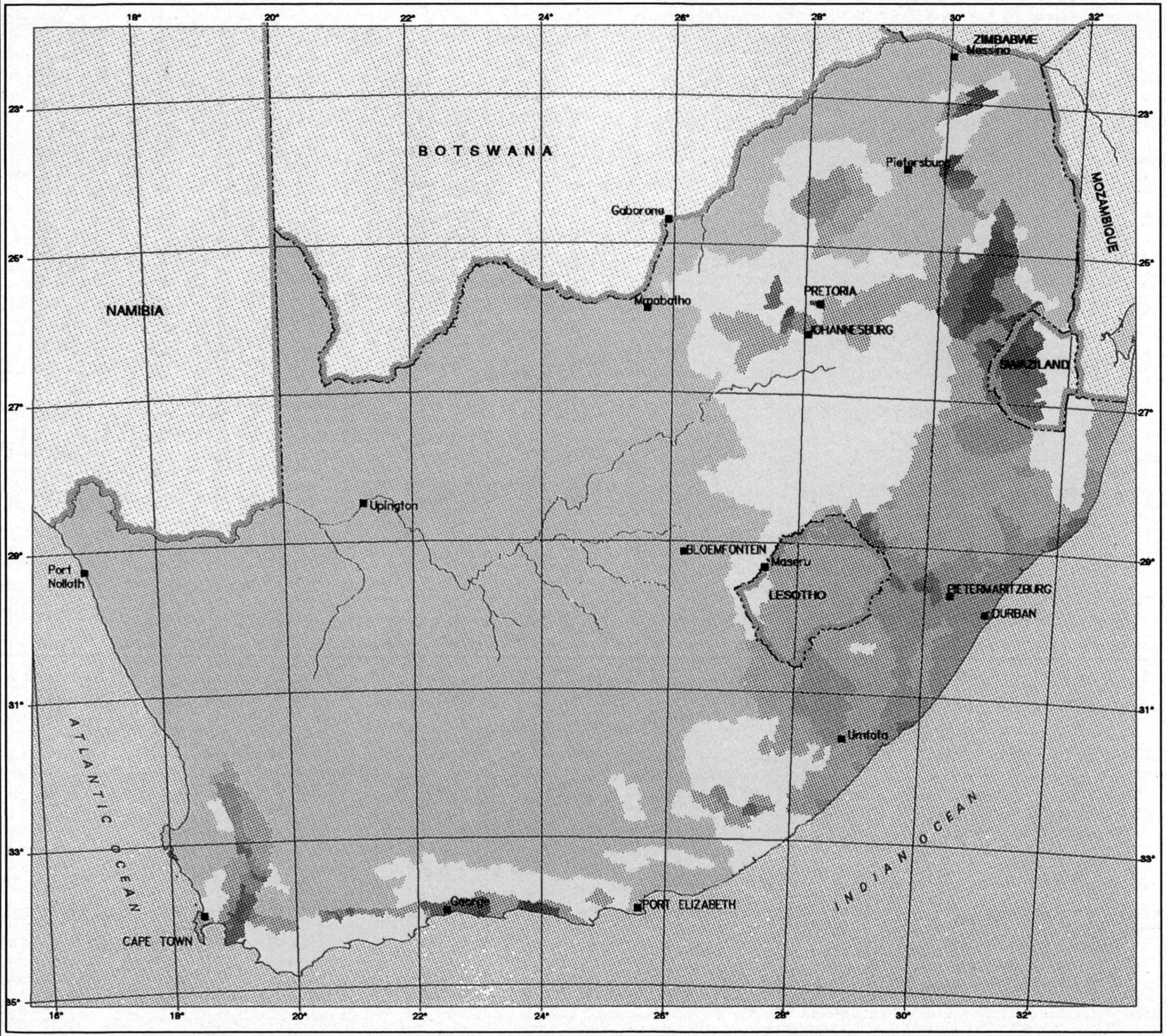


Figure 5

Base flow as a percentage of mean annual precipitation



- 0
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- > 10

Data supplied by 1990
Water Resources Consortium

50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

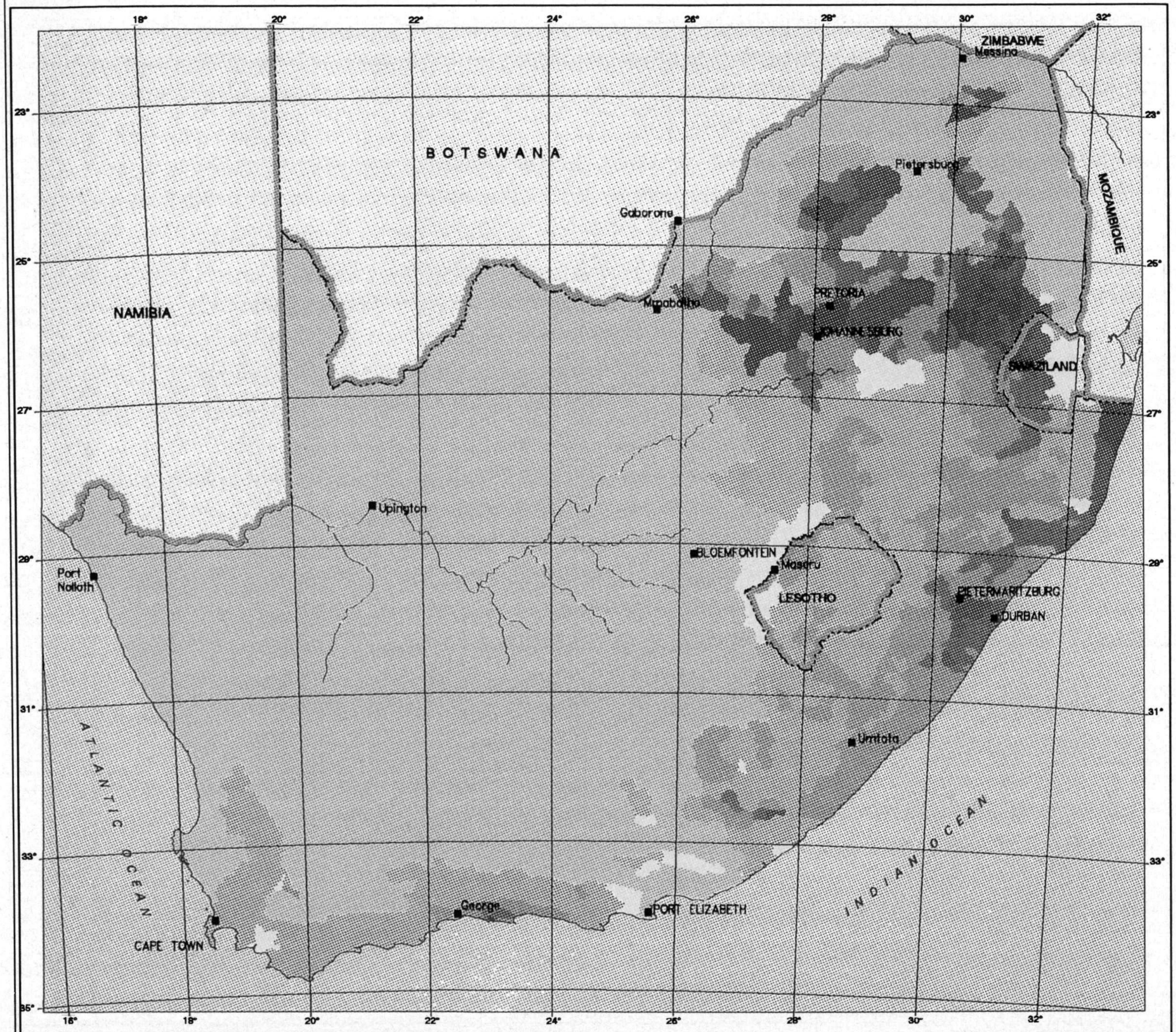


Figure 6

Base flow as a percentage of mean annual runoff

Legend
0
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
> 50

Data supplied by 1990 Water Resources Consortium

50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

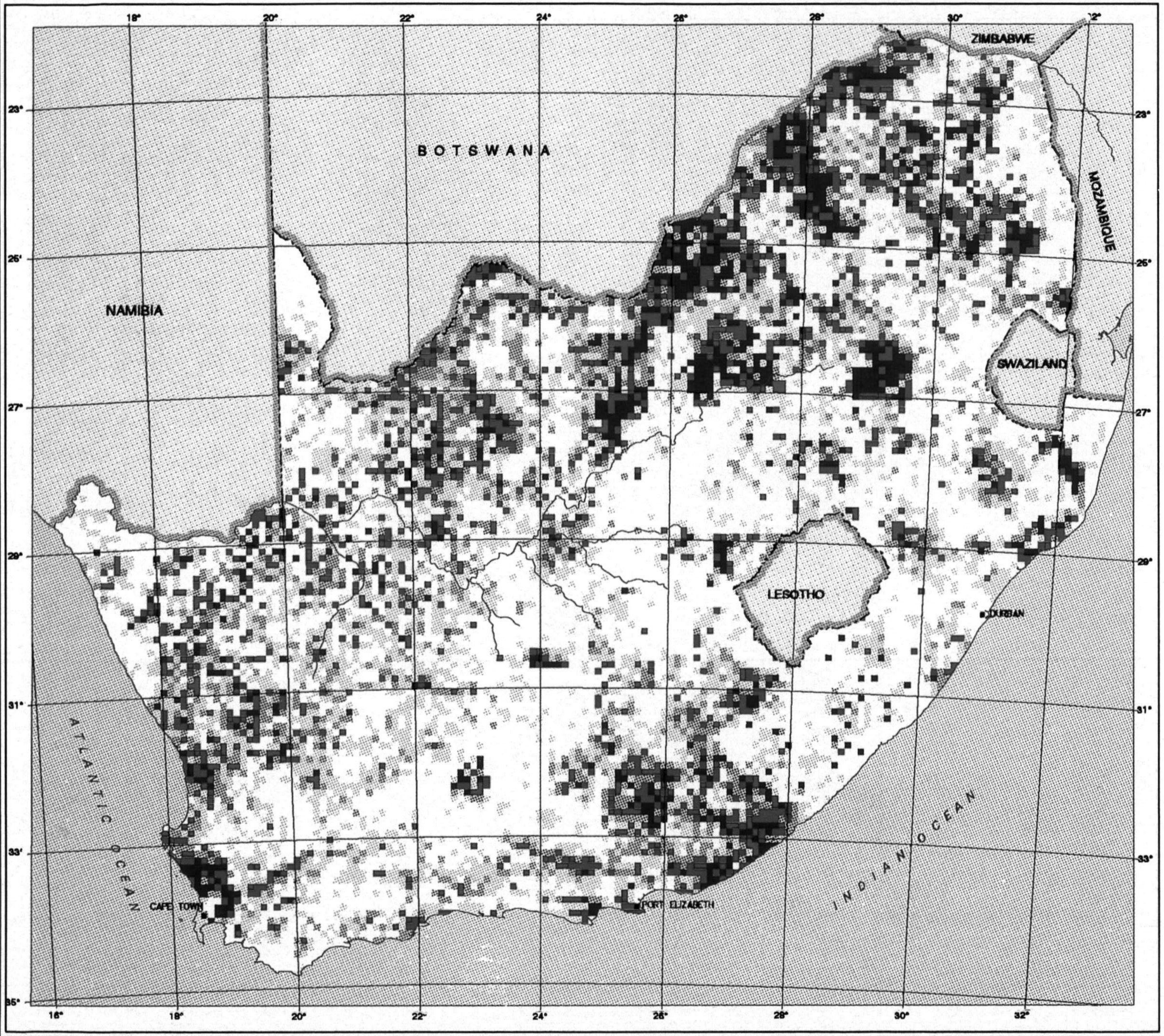


Figure 8

Density of Borehole Data: Strike Frequency Analysis

- No boreholes
- 1 - 5
- 6 - 10
- 11 - 15
- 16 - 25
- > 25

50 0 350 km

Scale 1 : 8500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

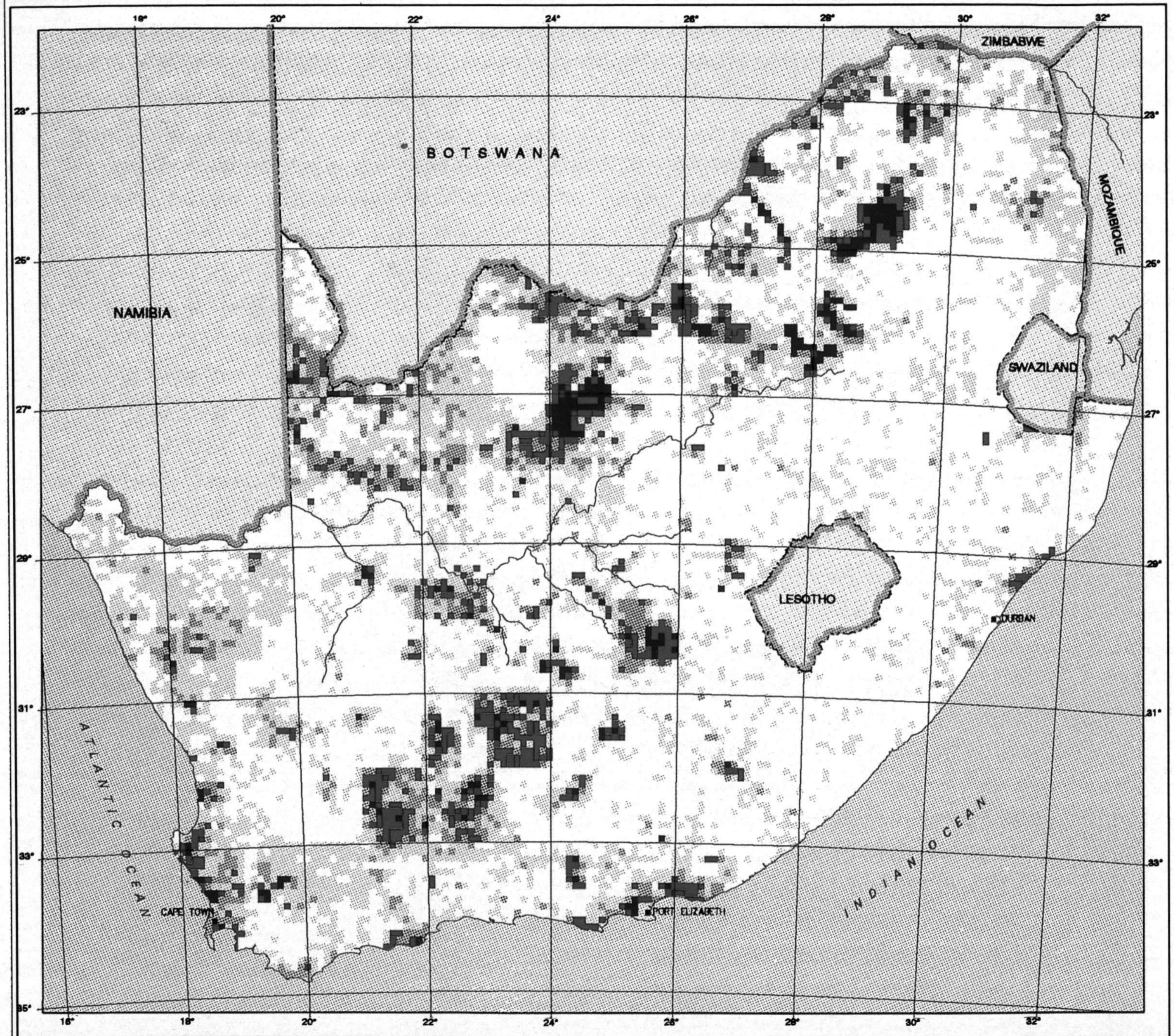


Figure 13

Density of Borehole Data: Groundwater Quality and Hydrochemistry

No boreholes
1 - 5
6 - 10
11 - 15
16 - 25
> 25

50 0 350 km

Scale 1 : 8 500 000

Projection : Albers Equal Area
Standard parallels 24° and 33°

PART B

MAPPING CONCEPTS

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LIST OF FIGURES

1. MODUS OPERANDI

The set of national-scale groundwater maps is based on statistical analyses of borehole data stored in the National Groundwater Data Base and of hydrochemical groundwater data contained in the Water Quality Data Base both at the Department of Water Affairs and Forestry. Both were supplemented with outside data. Borehole data were obtained from the former TBVC and self-governing national states. Hydrochemical data were augmented also from these sources, from published sources mainly Bond (1946) and with data supplied by the Atomic Energy Corporation and Watertek, CSIR. The density of data on which the different maps are based is shown in Figures 1 - 4 (see colour section & p. B16).

The Council for Geoscience (formerly Geological Survey) produced a simplified lithostratigraphic map in digital format from the 1:1 million Geological Map of the Republics of South Africa, Transkei, Bophuthatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland. The simplification of the lithostratigraphy was prescribed by the author.

A Geographic Information System (GIS) using Arc/Info computer software was employed to manipulate, analyse and display the geographically referenced data/information. Without GIS the compilation of the set of maps with the amount of detailed information on them, would have been a near impossible task. Some more details about the use of Arc/Info will be given in the discussion on the maps themselves.

2. REVIEW AND DISCUSSION OF INTERNATIONAL HYDROGEOLOGICAL MAPPING

2.1 GENERAL

According to Struckmeier (1989) hundreds of hydrogeological maps, which differ considerably in content, representation, scale, format and technical compilation have been prepared in many countries over the past 40 years or so. A good insight into many of these maps may be gathered from "Memoires of the International Symposium on Hydrogeological Maps as Tools for Economic and Social Development" (Hannover 1989) published by the International Association of Hydrogeologists. The intention is not to review the 83 papers in this publication but to concentrate on aspects which concern South Africa.

Despite the diversity of hydrogeological maps, Struckmeier recognises two main types:

- **Systematic general hydrogeological maps** which depict geological and hydrological data. Such maps are based on geological and topographical maps, information on climate plus hydrogeological data such as depth to groundwater, yields of boreholes, nature of water-bearing openings etc. These maps are often compiled according to the UNESCO International Legend for Hydrogeological Maps (see 2.2).
- **Derived maps** which are problem orientated and meet a particular demand of a well-defined group of users. They show for example groundwater exploitation potential, groundwater suitability, degree of vulnerability and required protection etc. These maps consequently vary widely in content and format. A recipe for their standardised presentation is out of the question and is not discussed further.

2.2 INTERNATIONAL LEGEND

Since 1954 the preparation of hydrogeological maps in an internationally standardised form has been receiving the attention of two international groups viz. the International Association of Scientific Hydrology (IASH) and the International Association of Hydrogeologists (IAH). The first draft of an international legend was published in 1962 in the Bulletin of the IASH, Volume VII No. 3 and was based largely on the legend of the hydrogeological map of Morocco by Ambroggi and Margat (1960).

Based on experience gained with its application, especially in the mapping of Sheet C 5 (Bern) as a prototype of the proposed International Hydrogeological Map of Europe, agreement was reached on an amended version which was published by UNESCO in 1970.

Subsequently, work on the European hydrogeological map series as well as mapping elsewhere in the world, has indicated the need for further modifications. In 1983 the IAH Commission on Hydrogeological Maps published a revised legend in English. The intention was to publish a fully revised version in colour with a multilingual text after a few years of practical experience. To date this has not materialised.

The 1983 version recognises three main hydrogeological categories, of which two are termed aquifers:

- **Intergranular aquifers** (linguistically more correctly "porous rock aquifer"); highly to moderately productive (1970 version: "porous formation"). These aquifers presumably consist of sedimentary strata with primary or syngenetic interstices. Intergranular porosity of secondary origin e.g. as in disintegrated granite, is presumably excluded.
- **Fissured aquifers** (i.e. "fissured rock aquifers") including karst aquifers; highly to moderately productive. Interstices are of secondary or epigenetic origin (1970 version: "fissured formation").
- Strata consisting of porous or fissured rock with local and limited or no groundwater resources (1970 version: "regions generally without groundwater or with very local groundwater").

The intergranular and fissured aquifers are further subdivided into (i) extensive and highly productive and (ii) local or discontinuous aquifers or extensive but only moderately productive aquifers. The third category is divided into strata with (i) local and limited groundwater and (ii) essentially containing no groundwater.

The legend unfortunately lacks clarity. The terms aquifer, extensive, local, discontinuous, highly and moderately productive and limited water resources are not defined. As the legend does not mention aquitards/aquicludes/aquifuges one must assume that the term aquifer is used in a wide sense analogous to Poland et al.'s (1972) "aquifer system" - a heterogeneous body of intercalated permeable and poorly permeable material that functions as a water-yielding hydraulic unit. Poland et al. apply the term to unconsolidated and semi-consolidated sediments. The term "aquifer system" could equally well apply to bodies of permeable fractured and semi-permeable weathered hard rock that act in a similar fashion. The use of the term aquifer for a hard rock formation that contains highly productive but widely spaced water-bearing fractures and in which consequently, a large percentage of boreholes fail to strike water, appears to be a misnomer. To avoid confusion, it is recommended that the term "aquifer" should be reserved for that stratum which contains the intergranular interstices, or for that fissure/fracture or interconnected system of fissures/fractures through which groundwater is transmitted into boreholes or to springs. The 1970 version of the legend is correct in using the term formation instead of aquifer.

The use of the terms "extensive", "local" etc. seems to imply that it is possible to identify individual hydraulic units. If this is the case, then the "aquifers" or rather "aquifer systems", surely could be mapped individually and their extent would be obvious from the map.

The meaning of the term "productivity" is obscure. The 1970 publication states that productivity should be defined in terms of borehole yield. In section 1 of the revised version it is stated that the distinction is made between large and lesser resources. The following questions arise:

What is large and what is lesser?
What is meant by "resources"?
Do resources refer to groundwater in storage or are both recharge and storage implied?
Are resources considered in terms of unit area or of the aquifer as a whole?

Without proper definition the terminology of the International Legend is open to different interpretations. This vagueness may be deliberate so that each map compiler can adopt the legend that best suits the hydrogeological conditions studied and map requirements. On the other hand the ideal of an internationally standardised way of compiling hydrogeological maps is defeated.

In view of these comments it appears profitable to examine the approach of some map compilers, especially those closer to home.

2.3 Hydrogeological Map of Australia

A hydrogeological map of Australia was published in 1987. According to Jacobson (1989) surficial aquifers in Cainozoic sediments cover 25 per cent of the continent and supply 60 per cent of the groundwater used. These aquifers overlie about 30 large sedimentary basins and many hard-rock aquifer provinces. The sedimentary basins which contain multi-layered aquifers cover about 65 per cent of the continent and supply about 30 per cent of the groundwater used in Australia. The fractured rock aquifer provinces cover about 35 per cent and supply about 10 per cent of the groundwater used.

On the hydrogeological map (scale 1:5 million) the surficial aquifers are not shown separately but are considered to be part of the twofold hydrogeological division - sedimentary basin and fractured rock province - which they overlie. Jacobson (1989) states that the UNESCO International Legend is not generally accepted in Australia. The salinity/yield matrix is preferred to the aquifer/yield classification of the International Legend as it stresses the Australian concern about salinity. Furthermore the International Legend is not geared to deal with layered systems; nor does it mention either recharge or discharge; productivity is not defined; it lacks emphasis on the very important aspect of salinity and makes no provision for aquifers that are both fissured and porous.

2.4 Hydrogeological Map of Mozambique

On the hydrogeological map of Mozambique, scale 1:1 million, the occurrence of groundwater is divided into the three classes of the International Legend. Subdivision of these classes however does not strictly follow the Legend. Each of the classes is subdivided into three instead of two groups according to probable borehole yields. The borehole yields are in turn translated in terms of the size of towns, villages, irrigation schemes and stock-watering that might be served. It should be noted that only the yield of boreholes is equated with magnitude of the resource. No account is taken of storage which is an important factor (see Chapter B 14).

The nine groups are represented by 32 lithological units. It is interesting to note that 19 units ranging in age from Precambrian to Quaternary are classified as areas of local aquifers of limited productivity (porous or fissured) or areas without significant groundwater resources. Five units are classified as fissured aquifers (discontinuous and consolidated), consisting mainly of Cretaceous and Tertiary limestones and calcarenites, Precambrian marbles and some Cretaceous and Tertiary sandstones and conglomerates. The porous aquifers are limited to Quaternary deposits.

2.5 Hydrogeological Map of Zimbabwe

The regional hydrogeological map of Zimbabwe, scale 1:500 000 was compiled with the specific purpose of identifying groundwater resources for rural development. The authors state that procedures as recommended in the International Legend were adhered to where applicable. The primary division is however in terms of so-called hydrogeologic units or rather lithostratigraphic units, and not in terms of the nature of the water-bearing interstices. Three classes of groundwater development potential are distinguished. It is not stated on what grounds the classification is done - apparently borehole yield and transmissivity. The colours assigned to the different development categories bear no relationship to the types of interstices and are therefore not in accordance with the International Legend e.g. primary aquifers are not shown in blue.

2.6 Hydrogeological Maps of Botswana

A series of eleven Hydrogeological Reconnaissance maps on a scale of 1:500 000 and a Groundwater Resources map on a scale of 1: 1 million were produced during the 1980s. The Reconnaissance map series depicts the groundwater development prospects in terms of borehole yields and their areal uniformity or variability. The lithology of the productive aquifers is indicated by hachuring. The Groundwater Resources map shows the groundwater resources potential, apparently combining the prospects of striking water with storage and recharge in a qualitative manner. This is, however, not defined or explained on the map.

According to Von Hoyer (1989) the Reconnaissance series were aimed at geoscientists and planners whereas the other map was directed at a broader spectrum: politicians, decision makers, water engineers, the educational sector and the general public.

As in the case of Zimbabwe, these maps are not systematic hydrogeological maps and were not compiled according to the International Legend.

2.7 Hydrogeological Map of Swaziland

The map on a scale of 1:250 000 depicts 24 major hydrogeological units. All major geological units are also considered to be hydrogeological units. The authors of the accompanying explanation (Piteau Associates 1992) define a hydrogeological unit as a formation, part of a formation or a group of formations in which there are similar hydrogeological characteristics that allow for grouping in aquifers or confining layers. Formation is not defined. The term appears to be used in its stratigraphic sense. Two letter codes are used to identify hydrogeological units e.g. Nhlangano gneiss is indicated by GL. The presence of extensive water-bearing faults or fracture zones is indicated by FZ i.e. GL/FZ. If portions of Gl also had significant weathering then the letters WE would be added - GL/FZ/WE.

2.8 HYDROGEOLOGICAL MAP OF LESOTHO

As in the case of Swaziland, the occurrence of groundwater has been mapped and described on the 1:300 000 map of Lesotho in terms of lithostratigraphic units. Four main categories are distinguished:

- Porous commonly unconsolidated rocks subdivided into:
  - gravelly to sandy ancient alluvial deposits
  - sandy to silty recent alluvial deposits
- Jointed rocks i.e. dolerite dykes and sills, kimberlite
- Fissured and jointed rocks i.e. massive amygdaloidal tholeitic basalt
- Fissured bedded and intergranular rocks subdivided on lithostratigraphic grounds into the Clarens, Elliot, Molteno and Burgersdorp Formations.

2.9 HYDROGEOLOGICAL MAPS OF NORTH AMERICA

The manner in which the groundwater resources of the United States of America have been mapped, differs completely from that prescribed by the International Legend. The U.S. has been divided into groundwater regions according to the following features of groundwater systems (Heath 1984):

- Components of the system and their arrangement i.e. the presence and character of aquifers and confining beds and the arrangement of these components.
- Nature of the water-bearing openings (whether of primary or secondary origin) of the dominant aquifer or aquifers.
- Mineral composition of the rock matrix of the dominant aquifer(s).
- Water storage and transmission characteristics of the dominant aquifer(s).
- Nature and location of recharge and discharge areas.

The first two features are primary criteria used in all delineations of the 12 groundwater regions of conterminous U.S. (Heath 1984) and the 26 regions of the North American continent (Heath 1988).The remaining three are useful in subdividing what might otherwise be unwieldy large areas.

Three hydrogeological maps of North America are included in volume O-2 "Hydrogeology" of the series "Geology of North America" (Back et al. 1988). The series marks the Centennial of the Geological Society of America. There is a close relationship between these maps and the groundwater regions. They may be said to complement each other.

The first map depicts the major rock units of the groundwater system. These are differentiated primarily on the nature and other aspects of their openings. Five categories are distinguished:

- Unconsolidated deposits (characterised by primary and solution interstices).
- Flat-lying to gently dipping consolidated (secondary interstices) and semi-consolidated rocks (primary openings).
- Folded consolidated rocks (secondary openings).
- Volcanic rocks (primary and secondary openings).
- Intrusive igneous and metamorphic rocks (secondary openings).

The second map shows the major units that comprise the surficial unsaturated zone. The zone ranges in thickness from less than one to more than 50 m. Seven types of unsaturated material are distinguished: stream, glacial, lake, wind and marine deposits, residuum and bed rock exposures. The third map depicts groundwater flow systems in the Great Basin.

2.10 BASE FLOW MAP OF CZECHOSLOVAKIA

Knezek and Krasny (1990) report on a groundwater runoff mapping program of the Czechoslovakian territory. It is of interest to note that groundwater runoff in the Bohemian Massif originates from a zone of weathered and fissured hard rocks not more than a few tens of metres thick. The runoff is not so much dependent on favourable water-bearing characteristics than on morphology and height above sea level, high precipitation and low evapotranspiration. Groundwater runoff ranges from more than 10 $\ell/s.km^{-2}$ (i.e. 315 mm/a) at the highest elevations with an annual precipitation of 1 000 to 1 200 mm, to between 3-7 $\ell/s.km^{-2}$ (95-220 mm/a) in the lower parts of the mountains with a precipitation of less than 800 mm/a. In the flatter areas groundwater runoff decreases to between 0.5- 2.0 $\ell/s.km^{-2}$ (16-63 mm/a). Conditions in South Africa appear to be analogous, although somewhat lesser groundwater runoff is obtained from the high rainfall mountainous tracts. As in Czechoslovakia a shallow zone of weathered and fractured hard rock is responsible for the groundwater component of runoff.

2.11 CONCLUSION

It is evident that the degree of sophistication in hydrogeological mapping depends on a number of factors: firstly the need for a hydrogeological map; secondly the type of problems that have to be resolved; thirdly the availability of data and of time and funds for generating data where these are lacking. Map makers accordingly have not strictly followed the International Legend.

The research proposal regarding the compilation of a Hydrogeological Map of South Africa envisaged that the map would be compiled according to an adapted version of the UNESCO International Legend. The end-product has, however, completely deviated from the recommendations of that document. The reasons may be summarised as follows:

- The International Legend has not been designed for distinguishing a diversity of shallow weathered and fractured hard rock conditions that occur in South Africa.
- According to Struckmeier's definition the end-product is a derived and not a basic hydrogeological map.

Non-adherence to the International Legend was therefore justifiable especially if its shortcomings, as discussed above, are taken into account. A general hydrogeological map in terms of the International Legend would be of less practical use, especially for the non-hydrogeologist.

3. HYDROGEOLOGICAL MAPPING CONCEPTS

In its strictest sense the term hydrogeological mapping implies depiction of geological and hydrological aspects. Conventionally, geology is mapped in terms of litho-stratigraphic units which consist of a certain rock type or combination of types. The criterion is composition or other characteristics of the solid material comprising the rock. The composition of the solid rock material is not necessarily an indication of its water-bearing properties. The latter depend on the type, size, degree and extent of interconnected openings. These may vary widely for the same type of rock and even within the same hard rock body. This applies even more so to lithostratigraphic units which usually consist of more than one rock type, not to speak of the further complication of facies changes.

In hydrogeological mapping rock bodies should ideally be divided into hydrogeological rather than lithostratigraphic units. These would be defined by the number, size, shape, arrangement and interconnection of their interstices. Hydrogeological units should consist of one type of saturated earth material or an association of different types, each distinguished and characterised on the basis of interstice properties only (Seaber 1989).

Mapping according to this principle would be much more detailed than merely distinguishing between porous and fractured/fissured rock as set out in the International Legend for Hydrogeological Maps (I.A.H.S./I.A.H. 1970 and 1983 and published by UNESCO). It will require the development of a code for classifying, ranking and naming hydrogeological units, similar to the lithostratigraphic code. For the present therefore mapping on this basis is not possible.

Apart from vaguely undefined terminology, the International Legend does not provide for finer classification in the case of hard rock aquifers as are found in South Africa. With a few exceptions there are no extensive hard rock aquifers and the bulk of the country's groundwater would have to be assigned to the classification of strata with local and limited groundwater resources. This is unacceptable as there is definitely considerable variation of the local and limited resource potential. (It should be remembered that by world standards, South Africa's groundwater resources are indeed limited).

TABLE 1
MAPPING CRITERIA ACCORDING TO ORIGIN AND NATURE OF SATURATED INTERSTICES

Time of formation	Geologic process		Type of openings	Rock type
Syngenetic (primary openings)	Sedimentary deposition		Intergranular, interfragmental	Consolidated-Unconsolidated clastic rocks
	Extrusion of magma		Vesicles, tubes shrinkage cracks	Vesicular lavas
Epigenetic (secondary openings)	Tectonic deformation (warping, folding, faulting with or without intrusion effects) below influence of weathering		Fractures, interstices in brecciated and granulated rock	All hard rock types: sedimentary, igneous and metamorphic
	Tectonic deformation plus weathering and unloading	Enhancement of incipient fractures	Fractures	All types of hard rock
		Disintegration and decomposition	Fractures, micro-fracture and pores	Susceptible hard rock types e.g. granite, basalt, shale, sandstone
		Dissolution	Fractures, solution cavities, pores in insoluble residue and infilling of sinkholes	Carbonate rocks

As a first step it is suggested that classification of saturated interstices according to origin and nature as set out in Table 1 serves as a mapping criterion.

It is thought that by further subdivision a scheme for the classification of different types and ranks of hydrogeological units could be developed. In the case of hard rocks for instance, further subdivision might be in terms of rock type and according to the pattern and intensity of fracturing, the thickness of the zone in which there is a fair abundance of open water-bearing fractures, the association of fractures with particular features such as folds, dykes contact zones etc.

4. SIMPLIFIED LITHOSTRATIGRAPHY

At this stage the ideal of a national map showing hydrogeological units of different ranks is unattainable. One possibility is to depict lithostratigraphy on hydrogeological maps (hydrology or groundwater being the other map component). As noted before, this is not ideal as lithology/lithostratigraphy does not uniquely determine the water-bearing properties.

On the 1:1 million geological map of the Republic of South Africa and the former Republics of Transkei, Bophuthatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland, 358 different lithostratigraphic units (mainly Formations but also Groups, Intrusive Suites and Complexes) are shown by means of some 80 colour combinations. As the hydrological component (Borehole Prospects) is to be shown in colour, lithostratigraphic units have to be depicted by different hachuring. Considering in addition, the smaller scale on which the hydrogeological maps are to be produced, it is clear that considerable simplification of the 1:1 million lithostratigraphy is necessary in order to produce a legible map. By adhering to the main lithostratigraphic units and by combining where feasible, adjacent units with similar lithologies, the number of units have been reduced to 86. These are distinguished from each other by 86 letter symbols and 16 different hachuring on the 1:2.5 million Borehole Prospects Map. Although certain lithostratigraphic units have the same symbols as on 1:1 million Geological Map, there are important differences as a result of the simplification. The legend on the Borehole Prospects map stands on its own and should not be confused with that of the 1:1 million Geological Map.

The map reader should note that each lithostratigraphic unit comprises a number of different rock types, that only the more important and dominant types are mentioned in the legend and that furthermore, at any particular locality the full complement of rock types is not necessarily present.

A close look at the lithostratigraphic legend will reveal that, with the exception of assemblages consisting of sedimentary, intrusive and extrusive rocks, intrusive rocks have been classified separately from sedimentary and extrusive lithostratigraphic units. Because of their multiplicity and the small map scale, dykes and sheets/sills are not shown on the map. Wherever they are of importance, mention is made of them in the legend.

As metamorphic rocks are either of sedimentary or igneous origin and as these have undergone varying degrees of metamorphism, there is no separate category for these rocks. Metamorphic rocks are mentioned by name under the lithostratigraphic units in which they occur. An indication of the degree of metamorphism to which the unit was subjected is indicated in the legend as well as on the map.

Finally it should be noted that the lithostratigraphy shown is that of the saturated formations. The overlying formations above the water-table, as for instance Kalahari beds have been stripped off.

5. GROUNDWATER RESOURCE POTENTIAL

Groundwater resource potential is of particular concern to the planner, developer and groundwater exploiter. According to Struckmeier (1989) groundwater resources potential embraces the following:

- Accessibility - aquifer depth and drilling risk
- Exploitability - yield and pumping height
- Availability - resource (i.e. groundwater in storage) and recharge
- Suitability - chemistry and risk of pollution
- Conservation - size and hydrodynamic situation.

The set of South African maps cover as far as is possible at this stage, the first four aspects of Struckmeier's concept of groundwater resource potential.

6. BOREHOLE PROSPECTS

The extent to which hard rock formations act as aquifers, or in other words the prospects of obtaining a supply from them, may be judged by an analysis of the yield distribution of an adequate number of randomly spaced boreholes. The results of country-wide government-sponsored drilling operations over the past eighty years on non-scientifically selected sites are considered the best available for this purpose. The results of some 120 000 of these boreholes have been taken up in the National Groundwater Data Base. Owing to the limited test-pumping equipment that has been available most of the time and the fact that boreholes yielding less than 0.1 ℓ/s are considered unsuccessful, (lower yields were generally not recorded) complete yield distribution analyses were not possible.

In emulation of Struckmeier's concept, the probability of drilling a successful borehole having a yield of at least 0.1 ℓ/s has been termed accessibility, whilst the probability of obtaining a yield equal to or exceeding 2.0 ℓ/s, has been termed exploitability. As only the risk and yield are taken into account this is strictly speaking not in accordance with Struckmeier's definition. However, from the South African point of view with its limited groundwater resources, these two factors appear to be of greater importance than aquifer depth and pumping height.

Aquifer depth and pumping height are accounted for separately. The Saturated Interstices Map (Chapter 16) gives an indication of the depth below the water level to which drilling may be continued gainfully. A separate map shows the depth to groundwater level (Chapter 6). A good indication of the maximum depth to aquifer as well as pumping height may be deduced from these two maps.

The Borehole Prospects map was generated as follows:
Contours were generated of the percentage successful boreholes (accessibility) and of the percentage successful holes yielding more than 2.0 ℓ/s (exploitability), using statistical inverse

TABLE 2
BOREHOLE PROSPECTS MAPPING MATRIX

Percentage probability of a borehole yielding 0.1 ℓ/s and more (viewed as successful and indicated by shade differences	Percentage probability of a successful borehole yielding 2.0 ℓ/s or more					
	< 10	10 < 20	20 < 30	30 < 40	40 < 50	≥ 50
	Red	Orange	Yellow	Green	Blue	Purple
< 40 pale	x	x	x	x	x	x
40 < 60 medium	x	x	x	x	x	x
> 60 dark	x	x	x	x	x	x

weighting. The contouring grid was set at 10 x 10 km and the search radius at 18 km. The reason for this approach was to eliminate at least initially geological bias. The generated contour lines were critically evaluated and adjusted where necessary. This was done either by directly sampling and re-evaluating borehole statistics of small map segments with problematic contouring, using the interactive spatial data base or by using statistical data generated for a particular lithostratigraphic unit. The modified contour lines set the framework for further adjustments where warranted in terms of lithostratigraphic boundaries and for extrapolation into regions of low sample density. Figure 1 (see colour section) shows the density of borehole data.

The Borehole Prospects Map was generated by combining the accessibility and exploitability maps, each of which was compiled separately. Some smoothing of boundaries between the different classes of borehole prospects was found to be necessary to eliminate small anomalous-looking polygons. Where these were lithostratigraphically based, they were however not smoothed.

Borehole Prospects are depicted in colours against a background of simplified lithostratigraphy indicated by a combination of symbols and different hachuring. The map user should not confuse borehole prospects with magnitude of the groundwater resource, in other words, groundwater availability (see Chapter 8). The Borehole Prospects Map provides a measure of the ease or difficulty with which groundwater may be struck by drilling and not of the volume of water held in storage nor of its replenishment.

Although certain borehole prospects boundaries coincide with lithostratigraphic ones, they should, in general, not be seen as precisely fixed but rather as gradational changes.This statement should not be construed to mean that a successive upward or downward change in colours and shades should be evident everywhere. Borehole prospects boundaries are largely a product of the choice of polygons for which the statistics were determined. The map offers a broad panoramic view rather than site-specific detail.

7. DEPTH OF GROUNDWATER LEVEL

The map depicts the ranges of mean groundwater level depth below the surface and the standard deviations from the mean levels. For example a standard deviation of x metres implies that just over 68 per cent of the sampled groundwater levels lies within x metres above or below the mean value. Groundwater levels were mapped according to the categories in Table 3.

TABLE 3
DEPTH OF GROUNDWATER LEVEL - MAPPING INTERVALS

Mean water level range (metres)	One standard deviation range (metres)
> 0 < 10	-
> 10 < 20	> 8 < 15
> 10 < 20	> 15
> 20 < 30	< 15
> 20 < 30	> 15 < 25
> 20 < 30	> 25
> 30 < 50	< 20
> 30 < 50	> 20 < 30
> 30 < 50	> 30
> 50 < 75	-
> 75 < 100	-
> 100 < 125	-
> 125	-

The first step in the compilation of this map was the generation of a depth to groundwater level contour map. By superimposing the contour map on the exploitability map quasi-homogeneous regions or polygons were generated. The mean groundwater level depth and the standard deviation were subsequently calculated for each polygon.

8. AVAILABILITY

Depending on whether or not groundwater resources are replenished periodically, groundwater may be exploited either as a renewable perennial or a non-renewable resource. Replenishment, also termed recharge, sets the ultimate limit to a perennial supply. Groundwater in storage has to bridge the gaps between recharge events, in the same fashion as a dam which supplies water during times when a river is not flowing. Storage is the ultimate limit to which a non-renewable resource can be exploited.

Under natural virgin conditions recharge to the groundwater "reservoir" is balanced by natural losses through spring flow, seepage, evaporation and transpiration from areas where the watertable lies close to the surface. Exploitation of groundwater by means of boreholes/wells implies that groundwater is being partially or wholly diverted from being discharged naturally.

Besides the limiting factors of recharge and storage mentioned above, availability is actually constrained further by practical and economic considerations such as irrecoverable natural losses, demand dictating pumping regime, minimum economic borehole yield, installation and pumping costs.

9. FACTORS INFLUENCING/DETERMINING RECHARGE

Groundwater is recharged by infiltration from stream and river flow and by direct infiltration of rainfall/precipitation.

9.1 Recharge from Streams and Rivers

This is probably the most difficult and costly aspect to assess. Infiltration from surface water occurs either directly into the saturated zone where the water-table coincides with the stream bed, or through the aeration or unsaturated zone. Very few studies on recharge from rivers have been undertaken in South Africa. It would appear however, that conditions over much of the country, militate against rivers being all but minor, localised sources of recharge for the following reasons:

- The hard rock environment and dearth of laterally extensive alluvial deposits below river-bed level.
- The fact that the water-table is a subdued replica of the topography over the greater part of South Africa, inhibits the lateral expansion of the recharge mound that is being built up below the river by infiltrating water.
- Rocky beds and silty channels limit infiltration.

In spite of their minor role in the overall replenishment picture, river valleys are generally more favourable for groundwater development, as a result of both groundwater flow towards them and augmentation by river recharge. This is particularly the case where extensive alluvial deposits are present such as those along the Crocodile River in the Thabazimbi District and along stretches of the Limpopo River. Some streams or river valleys follow fracture zones and thus provide favourable conditions for striking water in boreholes.

Under arid conditions, where there is very little recharge from rainfall, e.g. in parts of the North-western Cape and in the Kalahari, ephemeral streams such as the Kuruman River, are important sources of replenishment, and sand-filled river beds are the only significant aquifers.

9.2 Recharge from Rainfall

This is a highly complex process in which numerous factors and their interaction play a role. Aside from mentioning the following more important aspects affecting recharge from rainfall, no further discussion is intended:

- the amount, type, intensity, duration and temporal distribution of rainfall
- climate:potential evaporation
- surface slope and type of vegetative cover: storm runoff, interception and transpiration losses
- infiltration capacity of the materials at the surface be it rock or soil and subsoil; the presence of so-called macropores and fractured rock is of major importance; capillary movement
- the moisture retention capacity of the aeration or unsaturated zone and temporal fluctuations of moisture.

A rise in the water-table is positive evidence of recharge. Groundwater level records prove that over the greater part of South Africa groundwater is being recharged from time to time. This knowledge by itself is however not enough for the proper utilisation and management of the resource. Recharge has to be quantified. Worldwide a variety of methods have been developed and are being employed. The interested reader may refer to Lerner et al. (1990) for an exposition of these methods.

10. EFFECTIVE RAINFALL

The major source of recharge is rainfall. How much of it eventually becomes groundwater is determined by the various factors mentioned in the previous chapter. The distribution of rainfall, in particular effective rainfall over South Africa provides a rough indication of the variation in recharge. Effective rainfall as derived by the ACRU model (Schulze 1989) is shown in Figure 3. The term "effective rainfall" is defined by Schulze et al. (1990) to be equal to rainfall minus interception loss minus storm flow for a given day. Effective rainfall is that part of the total rainfall which is available for wetting the soil, and of which a small fraction may infiltrate deeper beyond the reach of evapotranspiration. The ACRU model was run for each of the 712 relatively homogeneous rainfall response zones (Dent et al. 1990) into which the country has been subdivided. A very rough estimate of how much rainfall reaches the groundwater body may be obtained by comparing effective rainfall with the point recharge estimates also shown in Figure 3 (colour section)(see Chapter 11).

The temporal variability of effective rainfall is least in the eastern higher rainfall areas and greatest in the western semi-arid to arid parts of the country. Recharge, though variable from year to year, may be expected to occur every rainfall season in the east, in the area where base flow occurs (see Chapter 12). In the west, recharge is not necessarily an annual event; in fact there is evidence that in certain parts recharge is restricted to abnormally high rainfall events.

11. GROUNDWATER RECHARGE ESTIMATES

Recharge studies as part of groundwater resource evaluations, have been undertaken in South Africa at a number of places. A selection of recharge estimates is given in Table 4. The localities and values are also indicated in Figure 5 (see colour section) and on the Provisional Groundwater Recharge Map (Sheet 2).

For a variety of reasons, the reliability of many of the recharge estimates remains questionable. Estimates for the same locality by different methods vary appreciably. For more detail Bredenkamp et al. (1994) may be consulted. In addition various reports of the Directorate Geohydrology, Department of Water Affairs and Forestry, not referred to by Bredenkamp et al. (1994), contain estimates of recharge and pumpage at localities where groundwater development apparently has reached its critical limit i.e. where groundwater abstraction more or less equals recharge.

TABLE 4
GROUNDWATER RECHARGE ESTIMATES

Locality (Reference No)	Longitude degrees east	Latitude degrees south	Mean annual rainfall mm	Mean annual recharge (mm)	Number on recharge map
Dendron (17)	29.31	23.36	440	8.6	1
Limburg (10)	28.88	23.81	485	18.7	2
Dorpsrivier (8)	29.06	24.2	580	Range from 9.2- 17.8; mean 13.1	3
Sabie (15)	30.75	25.08	1250	288	4
Rietpoort (1)	25.95	25.70	530	Range from 48-67.2; mean 56.7	5
Pretoria Fountains (15)	28.13	25.83	675	74.3	6
Upper Molopo (6, 8)	25.88	25.88	570	Range from 46-49.3; mean 47.8	7
Steenkoppies (3, 11, 12 & 13)	27.63	26.05	650	Range from 70.4-87.5; mean 81.1	8
Schoonspruit (15, 18)	26.75	26.16	660	82.1	9
Vicinity Leandra (23)	28.92	26.38	700	35	10
Louwna- Coetzersdam (2)	24.23	26.85	450	12	11
Kuruman (7, 20)	23.63	27.63	460	15	12
Hlobane (21)	31.0	27.72	720	117	13
Marydale (19)	22.08	29.42	185	0.8	14
Bloemendal (15)	30.50	29.55	910	65.4	15
Dewetsdorp (14)	26.68	29.56	530	21.3	16
Reddersburg (15)	26.25	29.67	480	38.1	17
Trompsburg (15)	25.80	30.03	370	25.2	18
Kokstad (15)	29.42	30.55	760	55	19
De Aar (14,22)	24.0	30.65	280	16.4	20
New Bethesda (15)	24.62	32.28	315	21.9	21
Bedford (15)	26.10	32.67	605	36.2	22
Bosberg (15)	25.95	32.73	700	50.4	23
Klein Swartberg (16)	21.3	33.36	245	12.5	24
Atlantis (5, 8, 15)	18.40	33.56	375	Range from 32-70; mean 42.5	25
Koo (9)	19.85	33.68	535	47.7	26
Cape Padrone (15)	26.4	33.75	640	53	27
Bredasdorp (15)	20.12	34.52	460	22	28

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12. GROUNDWATER COMPONENT OF RIVER FLOW

Perennial (and to a lesser extent intermittent) river flow consists of both a surface and a groundwater component (subsurface storm flow is included in the surface component). Through an analysis of river flow hydrographs it is possible to quantitatively separate these two components from each other.

When there is no surface runoff from rainfall, stream flow is derived entirely from groundwater. That portion of a hydrograph that represents only groundwater flow is a depletion curve of the form (Wisler and Brater 1949),

$$\log Q = \log Q_0 - cd^n \log e$$

in which Q is the discharge at the end of d days after cessation of surface runoff, Q_0 the discharge when d = 0, c and n are constants and e the Napierian base. Groundwater flow is thus represented by the straight line portion of a hydrograph plotted on semi-log paper.

In areas where there is no abstraction of groundwater from boreholes and wells, the groundwater component of river flow or base flow provides a minimum estimate of recharge because some groundwater is lost through evapotranspiration along the river course. Figure 5 (see colour section) illustrates the separation of the ground- and surface water components of the Quaternary Catchment X31A (Sabie River). The monthly flow is expressed in millimetres i.e. the depth water would stand if the monthly volume were spread over the catchment.

As an adjunct to the Water Research Commission's project 298 "The Surface Water Resources of South Africa" the groundwater component of river flow was determined in each of the approximately 2 000 quaternary catchments into which the country (with the inclusion of Swaziland and Lesotho), has been divided. Appendix I may be consulted for more detail.

For the production of the map the quaternary catchments were classified according to the categories in Table 5.

In the summer rainfall region no base flow is found where the mean annual rainfall is less than about 550 mm/a. Also note that the area where base flow occurs, coincides with a region of greater relief. In the winter and year-round rainfall regions i.e. the mountainous tract starting

TABLE 5
MAPPING CATEGORIES FOR BASE FLOW

Mean annual groundwater runoff (mm)	Range	
	Lowest as percentage of mean	Highest as percentage of mean
> 0 - 10	25	310
> 10 - 25	35	260
> 25 - 50	40	240
> 50 - 100	45	200
> 100	55	180

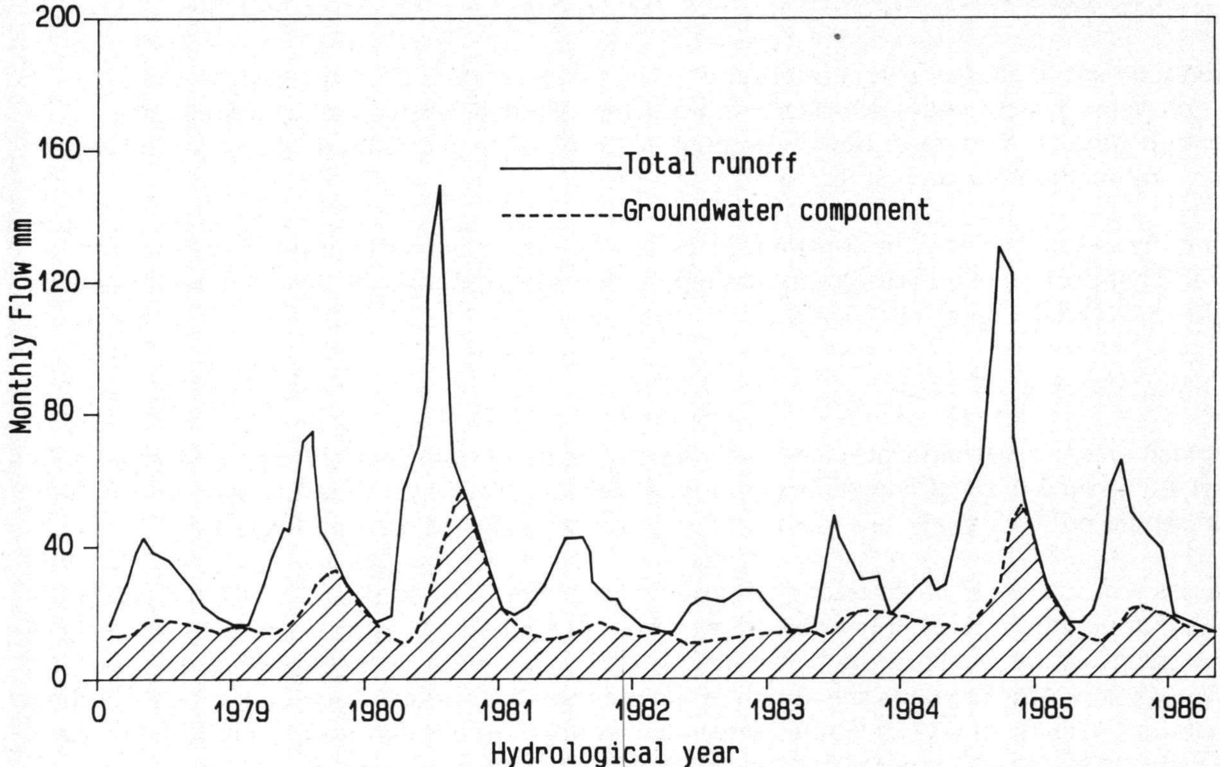

Figure 4
Hydrograph of Quaternary Catchment X31A, Sabie River

north of Clanwilliam and running southwards to Cape Agulhas and thence eastwards along the Cape Fold Belt, the cutoff limit for base flow is lower - a mean annual precipitation of about 400 mm. Figures 5 and 6 (see colour section) show base flow in terms of mean annual precipitation and total mean annual runoff.

That no measurable base flow occurs in those parts with lesser rainfall does not signify a lack of recharge as groundwater is not only discharged naturally as base flow but is also lost through evapotranspiration.

It should be noted that the lower the rainfall, the greater its variance. In the semi-arid to arid parts recharge is probably limited to periods of extraordinary heavy rainfall. Such periods may be short and may not necessarily be reflected by an above-average annual rainfall.

13. PROVISIONAL GROUNDWATER RECHARGE MAP (SHEET 2)

The map is an attempt at presenting a country-wide picture of groundwater recharge. Although recharge is expressed quantitatively, the map should be seen as depicting broad trends rather than laying claim to accurate regional recharge figures. It nevertheless gives a fair estimate of the wide range of values. The recharge map is based on the following:

- The base flow map which provides a regionalised, albeit somewhat underestimated, picture of recharge in the eastern and southern parts of South Africa.
- A comparison of base flow with recharge estimates within and just outside the base flow areas, yields a mean difference of about 30 mm/a for the underestimation of recharge by base flow.
- Base flow values were accorded the following recharge values:

Mean base flow (mm/a)	Mean recharge (mm/a)
0 (edge of area)	25
10	37.5
25	50
50	75
100	110
150	160
200	200

These figures have been used as a guide. They were not strictly adhered to everywhere.

- In the no-base flow area recharge contours are based on effective rainfall. Recharge estimates at the localities shown on the map and listed in Table 4 have been used as a guide but have not been adhered to strictly.
- In addition to the recharge values of Table 4, recharge has been calculated at the places A to H also shown on the map using the relationship between recharge and rainfall in excess of 15 mm per day according to the De Aar model of Vegter (1992). The validity of the calculated values rests on the assumption that the response of the soil zone does not differ materially from that at De Aar. Localities B to H are all situated in the North-western Cape; A (Alldays in the Northern Province) has been included for the sake of interest as a possible illustration of the effect of Bushveld vegetation on recharge. The results appear in Table 6.
- The calculated recharge for Alldays is definitely too high when compared with the 8.6 mm in the Dendron area (Table 4). The reason appears to be the difference in transpiration losses between shallow-rooted Karoo and deeper-rooted Bushveld vegetation. A study (Vegter 1993) of the effect of bush clearing on the farm Frankfort 69 KP in the Thabazimbi District suggests that a difference in mean annual recharge of cleared land and that under Arid Sweet Bushveld vegetation (Acocks 1953) is about 25 mm. In the draughting of the recharge map cognizance has been given to the distribution of Savannah.
- Martin (1961) and Foster et al. (1982) amongst others, have postulated that no recharge can be expected in arid to semi-arid areas with a thick sand cover such as in the Kalahari. Isotope studies of Verhagen (1990) on the other hand provide evidence of some recharge. Carlsson et al. (1994) state that based on the results of two approaches, i.e. the soil water balance method and the chloride mass balance method, recharge in the sand-covered

TABLE 6
CALCULATED RECHARGE - DE AAR MODEL (VEGTER 1992)

	Locality	Latitude degrees south	Longitude degrees east	Rainfall record period yrs	Mean annual rainfall mm/a	Recharge mm/a
A	Alldays	22.68	29.10	48	360	26.8
B	Pella	29.03	19.15	69	77	2.6
C	Kenhardt	29.35	21.15	32	135	5.9
D	Springbok	29.67	17.88	52	211	7.3
E	Brandvlei	30.47	20.48	37	118	4.4
F	Garies	30.57	17.98	57	142	2.9
G	Groot Toren	31.32	19.72	27	202	5.6
H	Williston	31.33	20.92	27	170	5.9

south-western half of Botswana has been assessed at less than 1 mm/a. Considering that values as low as 2.6 and 2.9 mm/a have been calculated on the basis of a thin soil cover for Pella and Garies respectively, it appears reasonable to map the West Coast sand belt north of the Olifants River mouth, the Koa Valley (western Bushmanland) and the western Kalahari as areas with less than 1 mm/a recharge. The mean annual effective rainfall is less than 150 mm/a and over a large portion of this area it is less than 100 mm/a. Under these conditions recharge is limited to the occasional event of abnormally high rainfall.

- Recharge has been contoured as follows: 1, 5, 10, 15, 25, 37.5, 50, 75, 110 mm/a. Areas with recharge in excess of 160 mm/a are too small to be contoured.

14. THE ROLE OF GROUNDWATER STORAGE

Groundwater in transit through aquifers and confining beds should be viewed as groundwater in storage. The volume of groundwater in storage and the storage capacity, i.e. the volume of saturated interstices and the combined volume of saturated and unsaturated interstices that are available for holding water respectively, determine whether a perennial supply equal to the long-term mean recharge is possible (assuming that there are no irrecoverable losses).

The volume in storage at any time should be adequate so that a supply rate equal to the long-term mean recharge rate can be maintained until the next recharge event, and if necessary beyond that event, should recharge on that occasion fall short of the mean. Likewise adequate storage space should be available at all times to accept all of the potentially possible recharge.If these two conditions are not fulfilled, the magnitude of a continuous supply is determined by the variable magnitude of recharge events, by the variable duration of the intervals between such events, and by the volume of groundwater in storage that can be abstracted between recharge events.

Springs that flow only for a short time after the rainy season are generally symptomatic of limited storage. With a high water-table the available space between the water-table and the surface may become replenished completely with the result that infiltration is halted and further rainfall is disposed of as runoff or evaporates. Under such conditions one has to distinguish between rainfall-dependent potential recharge and actual storage-dependent recharge.

A special case of storage-dependent recharge is that of so-called "dual porosity" formations such as Karoo sedimentary rocks. Permeable open fractures in these formations may fill up rapidly under favourable recharge conditions whilst the uptake of water from the open fractures into adjacent pores and micro-fractures is slow. The result is incomplete recharge of available storage space. Complete replenishment of the available space may only be realised during a prolonged period of rainfall. This may for instance have been the case in the Karoo during several abnormal high rainfall seasons in the mid-seventies. A corollary of dual porosity systems is that the same water level at different times does not necessarily mean equal storage volumes.

With the exception of intensely and extensively karstified dolomitic strata in the Southern Transvaal and some of the Neogene coastal deposits, the volume of groundwater contained in the country's hard rock formations is very limited. This is evident during droughts when numerous cases are reported of boreholes that are failing or have dried-up. Once rains have fallen the position is reversed. This holds particularly for hard rock areas with shallow groundwater levels in the drier parts of South Africa. There is also a possibility that compaction may close small fractures/interstices after they have been dewatered, and thus lead to a permanent reduction in storage capacity.

In hard-rock formations, storage capacity depends on the lateral and vertical extent of fracturing as well as the extent to which a zone of secondary porosity has been created by weathering processes. The volume of water in storage depends on the thicknesses of saturated fractured rock and of decomposed rock. The question is: Is it possible to map the varying storage conditions without extensive geophysical surveys, using only available borehole data?

15. STRIKE FREQUENCY ANALYSIS

15.1 PREMISE

Consider the water-bearing properties of earth material as typically encountered below the groundwater level in boreholes penetrating decomposable hard rocks such as granite, gabbro and shale. A typical situation in basalt is presented in Table 7.

A graph of the frequency with which water would be struck at different depths below the water level, in a number of holes penetrating sections consisting of both weathered and fresh basalt, may be expected to have the form of curve A in Figure 7. Should the formation of clay in fractures of the transitional zone between decomposed and fresh rock, largely inhibit the development of a well-defined zone of appreciable permeability, a strike frequency curve similar to B may be expected. Should the water level in the majority of holes be located below the upper decomposed zone, the upper low strike frequencies would be absent from the graph. With the water level in the majority of holes located within fresh rock, the only lower end of curve A would be apparent.

C is the type of curve that may be expected in more or less uniformly fractured rock such as quartzite in which a distinct zone of weathering below groundwater level is lacking.

TABLE 7
HYDRAULIC CONDUCTIVITY, COEFFICIENT OF STORAGE AND PROBABILITY OF STRIKING WATER IN WEATHERED HARD ROCK (E.G. BASALT)

Depth below g/w level (m)	Nature of material	Hydraulic conductivity or permeability and likelihood of striking water	Coefficient of storage
0 to say 5	Completely decomposed basalt (saprolite) grading downwards into saprolite containing corestones; water held in pores	Low, owing to clayey weathering products; probability of striking water about zero; increases downwards with decreasing clay content	Relatively high - in the order of a few percent; water held in secondary pores in decomposed rock and in fractures
5 to a mean depth of 15	Saprolite consisting of angular interlocking basalt boulders; decomposition restricted to fractures; water held mainly in open fractures; some secondary pore space may be available along weathered fractures.	High as a result of a system of open inter-connected fractures; probability of striking water more than once high; decreases with depth	Less than one percent; generally in the order of 0.01 to 0.1 percent; storage mainly in fractures
Below 15	Fresh basalt, fewer open fractures; their number and aperture decreases downwards	Hydraulic conductivity and probability both low but variable	Lesser storage as fracture frequency decreases with depth

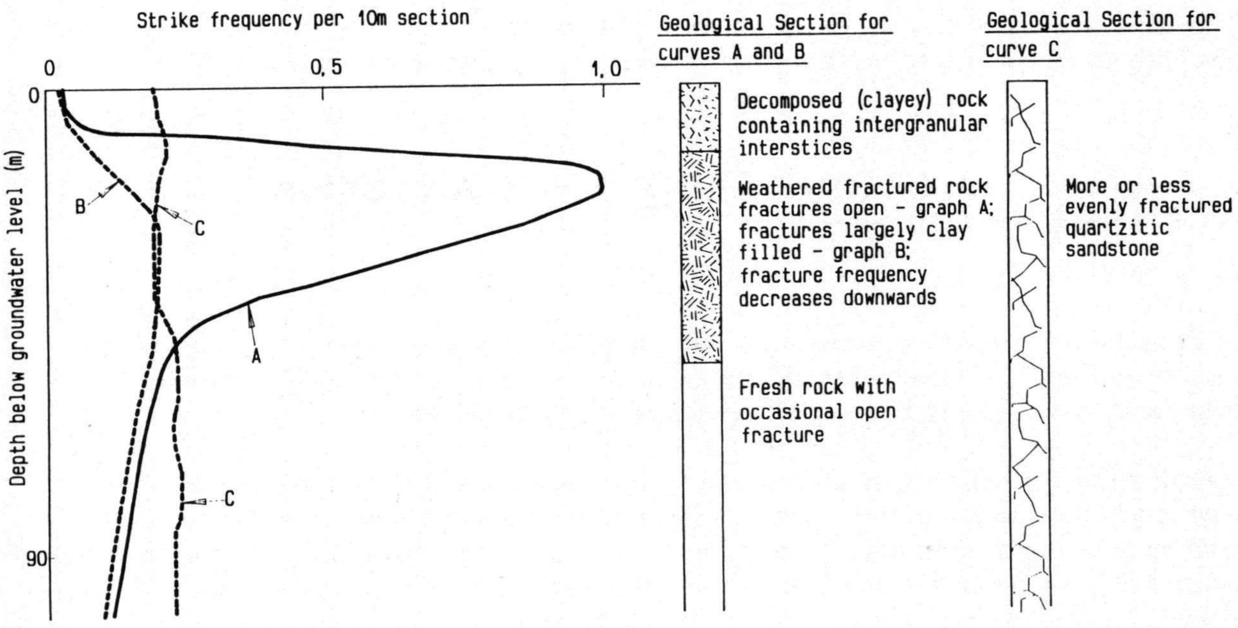

Figure 7
Postulated strike frequency graphs

It is postulated that the nature of the saturated zone in hard rock formations - whether groundwater is generally held in fractures only or in fractured as well as decomposed rock - may be deduced from strike frequency graphs. The proviso is strike data of an adequate and representative number of boreholes.

15.2 Analysis of Strike Data

The frequencies with which water was struck in boreholes at different depths below the groundwater level have been analysed statistically for 226 quasi-homogenous areas or polygons. These polygons resulted from superposing the exploitability on the lithostratigraphy map. Note that strike frequencies were calculated in terms of the number of holes which passed through particular 10 metre sections below the water level and not in terms of the total number of holes. The number of holes passing through a particular 10 m section decreases with increasing depth. Whereas the upper parts of frequency curves usually are smooth, lower ends tend to be jagged as a result of insufficient numbers of holes on which to base the statistics. The density of borehole data available for strike frequency analysis is shown in Figure 8 (see colour section).

15.3 Typical Strike Frequency Graphs

Figures 9 to 12 are typical strike frequency graphs. The initial increase in strike frequency in the case of Figures 9 and 10 is interpreted as an indication of the existence of saturated decomposed rock in a certain percentage of the holes.Whenever a strike frequency of zero directly below the water level is encountered, it would signify the presence of saturated decomposed material in all of the analysed holes. Strike frequencies of less than about 0.15 per 10 m at greater depths are found to be typical of fresh rock. In the case of Figure 11 saturation is restricted to fractured rock only.

Folded competent Table Mountain quartzitic sandstones do not decompose and there appears to be little near-groundwater-level enhancement of fracturing as can be seen in Figure 13 (see colour section). On the other hand, in spite of the low strike frequency, open fractures exist to depths of 100 m and most likely deeper.

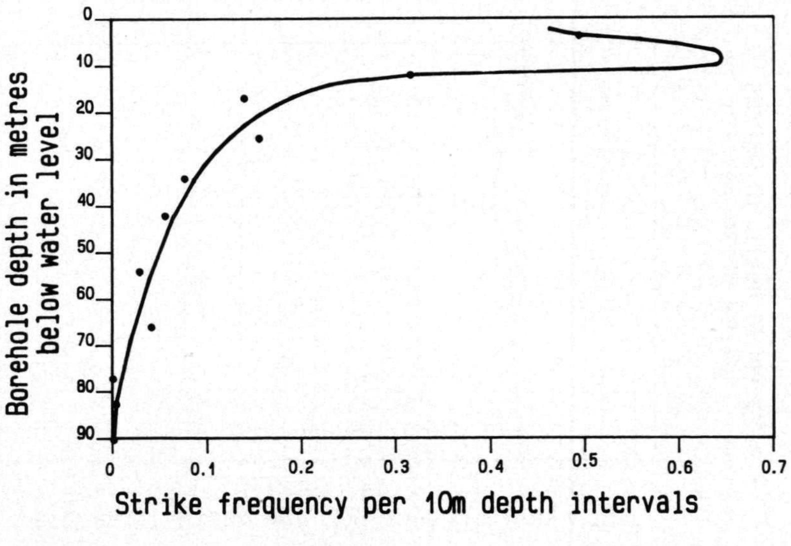

Figure 9
Strike frequency graph Granite Gneiss, NW of Pietersburg.

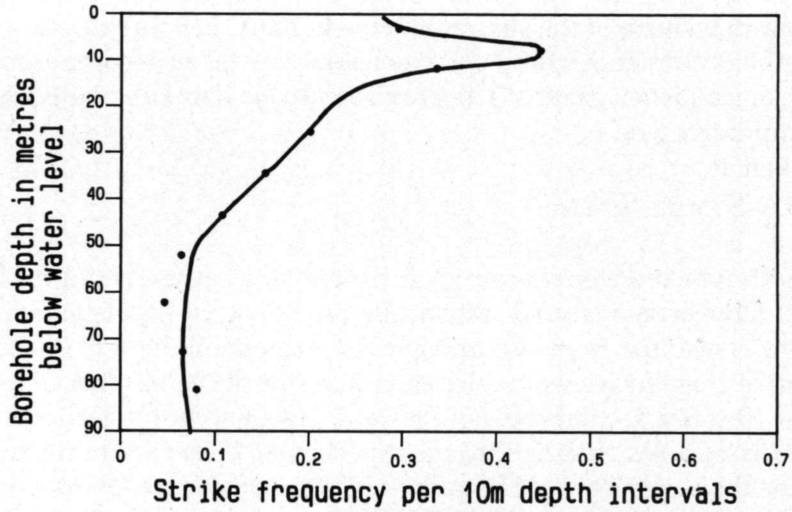

Figure 10
Strike frequency graph Karoo sedimentary rocks (one of lithostratigraphic unit Trmc polygons).

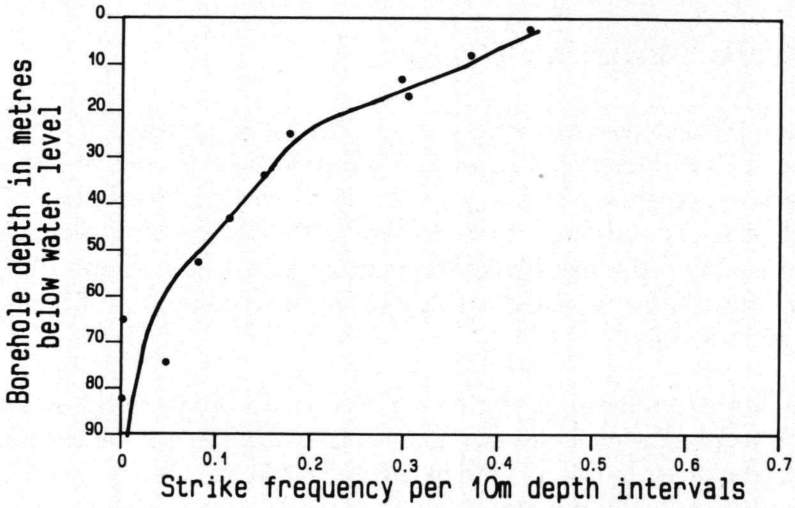

Figure 11
Strike frequency graph Granite Gneiss, Dendron.

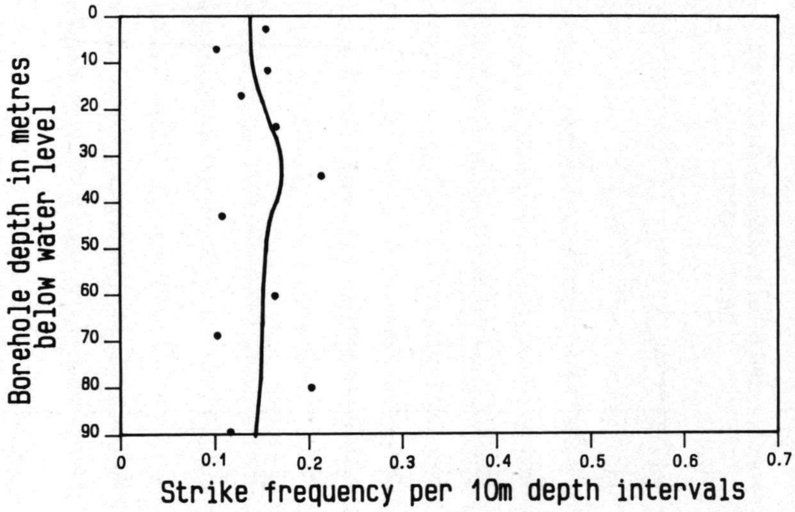

Figure 12
Strike frequency graph Table Mountain Group.

Except for the quartzitic sandstones of the Table Mountain Group, the mean thickness of that part of the saturated zone which contains the bulk of the readily accessible and exploitable groundwater, may be taken as about half the depth to where strike frequencies typical of fresh rock make their appearance on the frequency graph. In the case of Figures 9, 10 and 11 these depths may be taken as 30, 50 and 40 m and the corresponding mean thicknesses as 15, 25 and 20 m.

16. DEPICTING STORAGE QUALITATIVE

With the exception of the folded quartzitic sandstones of the Table Mountain Group, the bulk of readily accessible groundwater is stored in the upper fractured and weathered zone of hard-rock formations. The saturated thickness of this zone is variable but seldom exceeds a mean of 25 m. The volume of groundwater stored depends not only on the thickness of the saturated zone but also on whether the water is contained in fractures only or in secondary intergranular openings in decomposed/disintegrated rock as well. It should be noted that, regardless of fracture density, the storage coefficient of fractured rock is at least one order smaller than that of porous decomposed/disintegrated rock.

In the previous chapter it was shown that these aspects i.e. the mean thickness of the main water-bearing zone and whether the zone is composed of fractured rock only or also comprises some decomposed rock, may be deduced from the strike frequency graphs that have been compiled for the 226 quasi-homogeneous areas into which the country has been subdivided.

It was found possible to classify the deduced groundwater storage conditions in the polygons according to the scheme set out in Table 8. By comparison the storage coefficient of semi- and unconsolidated deposits which have a primary porosity, is of the order of 0.1. The lithology classification is basic: a distinction is made between areas consisting principally of sedimentary and those mainly comprising igneous and crystalline metamorphic rocks. Separate provision however has been made for the Malmani and Campbell Rand dolomite.

It should be noted that as strike frequency analysis involves successful boreholes only, a particular storage condition does not apply to an area (polygon) as a whole. Consequently, areal distribution of storage conditions is further subdivided according to one of the following three drilling success ranges:

Less than 40 per cent
40 - 60 per cent
More than 60 per cent (See Table 2).

17. GROUNDWATER QUALITY
(CO-AUTHOR M. SIMONIC)

The data file used for this section contains in excess of 52 000 analyses. After location and ionic balance checks and aggregating and averaging analyses from the same sampling point, a coverage of 35 752 point values was available for processing and map compilation (see Figure 13 in colour section). Analyses of ionic balances not conforming to an accuracy of 5% in the case

TABLE 8
A QUALITATIVE CLASSIFICATION OF HARD ROCK STORAGE

Main storage component of saturated zone	Qualitative indication of mean storage coefficient (order of)	Mean thickness of water-bearing zone
Fractured sedimentary hard rock; open fractures extend to depths of 100 m and more below the water level	< 0.001	25-50
Fractured sedimentary hard rock within the zone of weathering	< 0.001	< 10
		10 - 15
		15 -25
Fractured igneouş/crystalline metamorphic rocks within the zone of weathering	< 0.001	<10
		10 - 15
		15 - 25
Combination of fractured and decomposed to partially decomposed sedimentary hard rock	0.001 -0.01	< 10
		10 - 15
		15 - 25
Combination of fractured and decomposed to partly decomposed igneous/crystalline metamorphic rock	0.01	< 10
		10 - 15
		15 - 25
Fractured dolomite and minor limestone; chert. Dissolution features not prominent	< 0.01	10 - 15
Intensely karstified dolomite and minor limestone; chert.	> 0.01	15 - 25

TABLE 9
MAPPING RANGES OF TOTAL DISSOLVED SOLIDS

Lower geometric standard deviation value mg/ℓ	Upper geometric standard deviation value mg/ℓ
< 300	< 500
	500 - 1 000
< 500	1 000 - 1 500
	1 500 - 2 000
	> 2 000
500 - 1 000	500 - 1 500
	1 500 - 2 000
	2 000 - 3 500
	> 3 500
1 000 - 1 500	> 3 500
> 1 500	> 4 000

of total dissolved solids (TDS) contents of less than 1 000 mg/ℓ, and an accuracy of 10% for over 1 000 mg/ℓ, were discarded.

As mentioned above, the country was divided on the basis of lithostratigraphy and exploitability into 226 quasi-homogeneous polygons. It was found that the TDS distribution in the polygons did not conform to a normal distribution. (See Figure 14). For this reason the values were transformed into log values in order to determine the geometric mean and variance for each polygon. The upper and lower values of the geometric standard deviation were calculated from the geometric variance. In a small number of cases the number of analyses were inadequate for proper statistical analysis. TDS was mapped according to the scheme set out in Table 9. Eleven different categories are indicated by colours and shades.

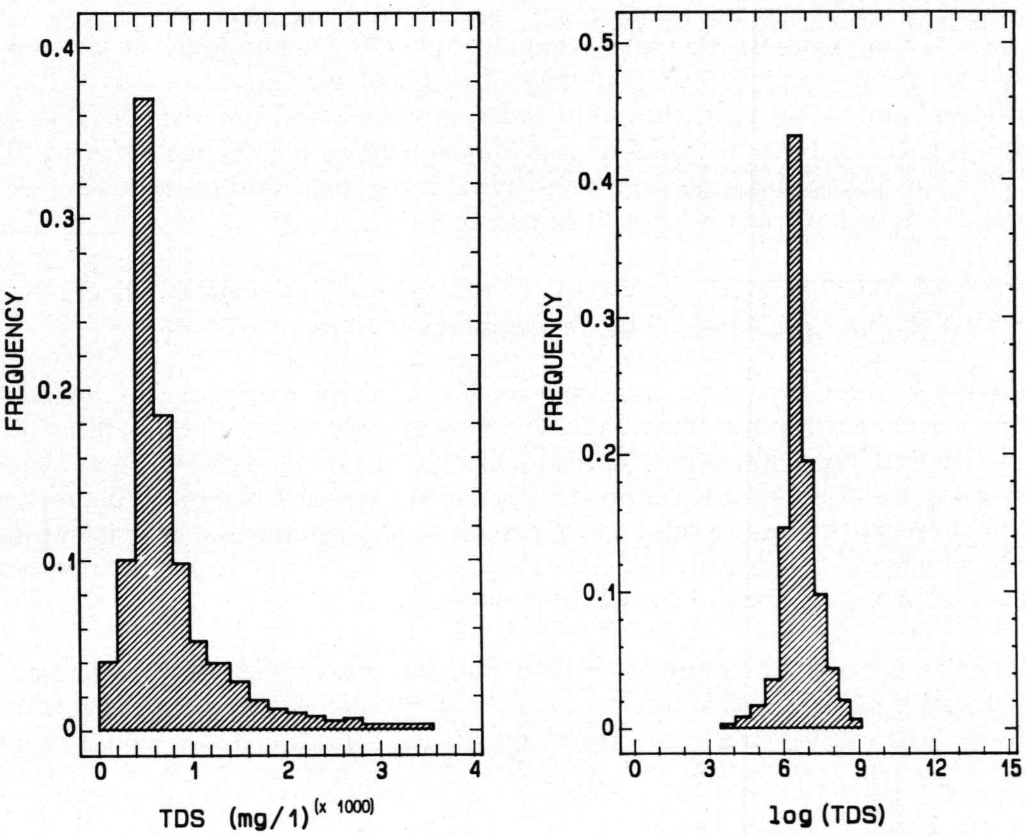

Figure 14
Distribution of total dissolved solids in groundwater samples from Karoo Supergroup rocks.

The TDS limit for drinking water recommended in Specification 241-1984 of the South African Bureau of Standards, expressed in terms of electrical conductivity (EC), is 70 mS/m. Depending on the dissolved constituents, this is equivalent to a TDS concentration of between 350 and 550 mg/ℓ. The maximum allowable limit is given in the Specification as 300 mS/m which is roughly equivalent to a TDS content of 2 000 mg/ℓ. According to guidelines of the World Health Organisation, TDS concentrations of less than 1 000 mg/ℓ are generally acceptable (Department of Water Affairs 1986). However, it is not so much the TDS level as the concentration of specific ions that is detrimental to health, which determines the suitability.

The ideal of mapping according to the recommended, the generally acceptable and the maximum allowable limits of 70 mS/m, 1 000 mg/ℓ and 300 mS/m cannot be realised with the available data and the map scale. The areal variability of TDS is too great and requires a considerably denser network of sampling points. By using *inter alia*, cutoff points of 500, 1 000 and 2 000 mg/ℓ in the mapping scheme, cognisance has been given to the specified limits.

Of the constituents detrimental to health, the most commonly occurring, but not necessarily the most detrimental, have been singled out, namely nitrate and fluoride. Polygons in which more than 20 per cent of the analysed samples contains nitrate and fluoride in excess of the prescribed limits, are indicated by two sets of hachuring. The limits are 10 mg/ℓ as N for nitrate and 1.5 mg/ℓ for fluoride as F.

It seems significant that the incidence of more than 20 per cent of analyses with nitrate in excess of 10 mg/ℓ, is within two fairly well-defined and all but merging areas:

- In the Transvaal a more or less triangular region bounded by the Limpopo River in the northwest, a longitude of about 30 degrees and a latitude of 25.5 degrees.
- In the northern Cape the area stretches south-eastwards from the Namibian and Botswana borders and is enclosed by a line running from Onseepkans on the Orange River past Pofadder to Williston and then northeastwards past Britstown and Trompsburg to Kroonstad from where it swings northwards towards Mmabatho.

These two areas are underlain by a large variety of lithologies of widely different ages. No case can be made for a relationship between lithology and the occurrence of nitrate.

Effective rainfall over these two areas varies between 50 mm in the west and 500 mm in the east. Except for certain parts of the Transvaal, as for instance the Springbok Flats, little or no agriculture is practised, especially not in the arid west. The fact that the greater-than-20-per cent areas are fairly well-defined and confined to the north-western sector of the country, seems to discount the presence of nitrate as an exclusive man-made phenomenon. Why is nitrate apparently not a regional scale problem in other parts of the country? Which conditions enhance the production and leaching of nitrate from the soil?

Lawrence (1983) has speculated that in the arid parts of inland Australia nitrate is derived from nitrogen-fixing native plants such as Acacias and *Atriplex vesicaria*. Because the unsaturated zone is highly aerated and has minimal organic content, denitrification losses would be minimal.

According to Acocks' map, *Veld Types of South Africa* (1953), the major part of these two areas is occupied by Savannah vegetation i.e. Kalahari Thornveld and Shrub Bushveld, Turf Thornveld, Arid Sweet Bushveld, Mixed Bushveld, and Northern Mopaniveld. In the south the Savannah-type vegetation changes to certain Karoo/Karroid types. By analogy to the Australian situation the question arises whether at least some of the excessive nitrate concentrations in groundwater could not be ascribed to native nitrogen-fixing vegetation. The extent to which nitrogen-fixing plants are part of the mentioned veld types would need to be established. (See also Tredoux 1993).

The more common occurrence of higher fluoride values can be largely correlated with lithostratigraphic units that consist of or include acid intrusive and extrusive igneous rocks such as the Lebowa granite and the Rooiberg rhyolites.

18. HYDROCHEMICAL TYPES
(CO-AUTHOR M. SIMONIC)

Bond (1946) produced a water map of South Africa as part of a geochemical groundwater survey. He distinguished five groups:
- Strongly mineralised chloride-sulphate waters
- Slightly saline chloride waters
- Temporary hard (carbonate) waters
- Soda-carbonate waters
- Pure waters.

This division was made in order to discuss principally the suitability of groundwater for the generation of electricity and for industrial use. Bond's classification combines in a sense ionic composition and dissolved solids concentration. He had about 450 analyses at his disposal. Except for very broad similarities such as an increase in TDS and deterioration in quality from east to west, there is no point in trying to compare his map with either the TDS map discussed in the previous chapter and the map of hydrochemical types which is the subject of this chapter. Not only are ionic composition and TDS presented separately, but finer subdivisions have been made.

Water may be classified in terms of the dominant anions and cations. For this purpose the fourfold division of the quadrilateral Piper diagram (Hem 1992) is used. The dominant anions and cations in the four fields are as follows (see legend Sheet 2):

Field	Anions	Cations
A	Ca + Mg	CO_3 + HCO_3
B	Na + K	CO_3 + HCO_3
C	Ca + Mg	Cl + SO_4
D	Na + K	Cl + SO_4

Dominance means that the sum of the relevant two anions and the sum of the relevant two cations, in each case expressed in terms of milli-equivalents, range between 50 and 100 per cent of the total anion and cation composition in milli-equivalents.

An area may be characterised in terms of the proportion of analyses that plot in the different four fields. The following classification was found to cover all of the possibilities (20 classes):

I. Single-field dominance
This means that only one field contains more than 40 per cent of the analyses of any particular area. The balance of the analyses is divided between the other three fields in such a way that no other field is presented by more than 30 per cent of the samples. Two categories are distinguished:

More than 60% of the analyses lie in one field
Between 40 and 60% of the analyses lie in one field

This results in 8 classes of single field dominance.

II. Two-field dominance
In this case each of two fields contains more than 30 per cent of the analyses of any particular area. Again two categories are distinguished for each of the six possible combinations:

Two fields each contains more than 40% of the analyses
Two fields each contains between 30 and 40% of the analyses.
This results in 12 classes of two-field dominance.

With the exception of the coastal areas which are characterised by sodium-potassium chloride-sulphate water owing to cyclic salts from the ocean, there is broadly speaking a gradation from bicarbonate-carbonate water in the eastern higher rainfall parts to chloride-sulphate water in the semi-arid to arid western areas.

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APPENDIX I

METHODOLOGY OF DETERMINING BASE FLOW
(CONTRIBUTED BY W.V. PITMAN)

One of the products of the Water Resources 1990 project is a time series of monthly flows for each of the approximately 2 000 Quaternary catchments into which the study area (South Africa, Lesotho and Swaziland) is divided. Each time series covers a seventy year period (1920 to 1989 hydrological years). To divide the monthly flows into surface and groundwater components a simple procedure first developed by Herold (1980) was proposed.

Prior to its adoption, a test run was made with Herold's model using flows measured at the Department of Water Affairs and Forestry's gauge No X3H001 on the Sabie River. The results of the model were verified using the standard technique of base flow separation on a semi-log plot of the daily hydrograph (method No 1) and a linear interpolation between lowest monthly flows in each dry season (method No 3). The results obtained are shown in Table 10.

The model yields about 10 per cent more groundwater flow than the traditional method No 1. The latter was however applied conservatively. It is interesting to note that more than 40 per cent of the total runoff is derived from groundwater (semi-log plot and Herold's model).

Herold's procedure of separating the monthly flows into surface and groundwater components is given below:

Let Q_i = total flow during month i
QG_i = groundwater contribution
QS_i = surface runoff
i.e. $Q_i = QG_i + QS_i$

The assumption is made that all flow below a certain value called GGMAX is groundwater flow, hence:

$QS_i = Q_i - GGMAX$ (for $Q_i > QGMAX$)
or $QS_i = 0$ (for $Q_i \leq QGMAX$)
and hence $QG_i = Q_i - QS_i$

The value of GGMAX is adjusted each month according to the surface runoff during the preceding month and is assumed to decay with time, hence

$$GGMAX_i = DECAY.GGMAX_{i-1} + PG.QS_{i-1} /100$$

where the subscripts i and i-1 refer to the current and preceding month.

DECAY = Groundwater decay factor ($0 < DECAY < 1$)
PG = Groundwater growth factor (%)

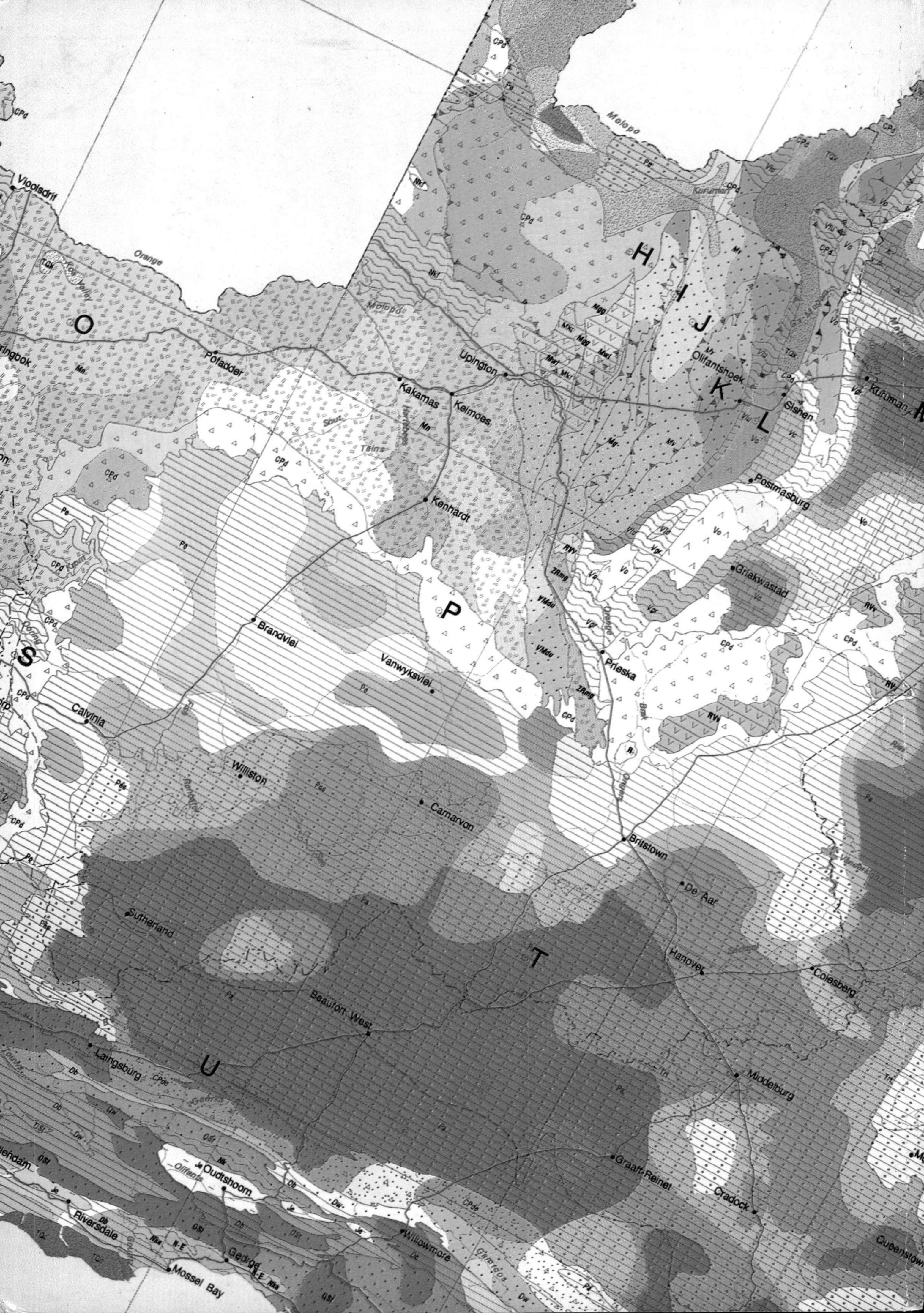
An added constraint is that GGMAX may not fall below a specified value, QGMAX.

TABLE 10
VERIFICATION OF HEROLD'S METHOD OF BASE FLOW DETERMINATION

Period	Total runoff 10^6 m^3	Mean annual runoff mm/a	Groundwater Component of Runoff					
			Method No. 1 Semi-log plot		Method No. 2 Herold's model		Method No. 3 Linear Interpolation	
			mm/a	% of total	mm/a	% of total	mm/a	% of total
10/72 to 9/78	520	493	208	42	222	45	167	34
10/79 to 9/86	386.5	306	141	45	156	51	129	42
Periods combined	906.5	398	172	43	172	47	147	37

Calibration of this model is achieved by selecting appropriate values of DECAY, PG and QGMAX so that a realistic division between surface runoff and groundwater is obtained. Calibration is facilitated by graphical output of the total and groundwater hydrographs to the computer screen (Figure 4 Chapter 12).

As the effort involved in carrying out this procedure on each of the approximately 2 000 time series would be enormous, Quaternary catchments were grouped on the basis of similar hydrological characteristics and a small sample per group selected for analysis. By plotting the mean annual groundwater runoff against the mean annual precipitation for each sample, it was possible to obtain a linear relationship between these two variables for each group. In this way the mean annual groundwater runoff of each Quaternary catchment was estimated.



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Carnarvon
Britstown
De Aar
Sutherland
Hanover
Colesberg
Beaufort West
Laingsburg
Middelburg
Graaff-Reinet
Oudtshoorn
Riversdale
Cradock
Willowmore
George
Mossel Bay