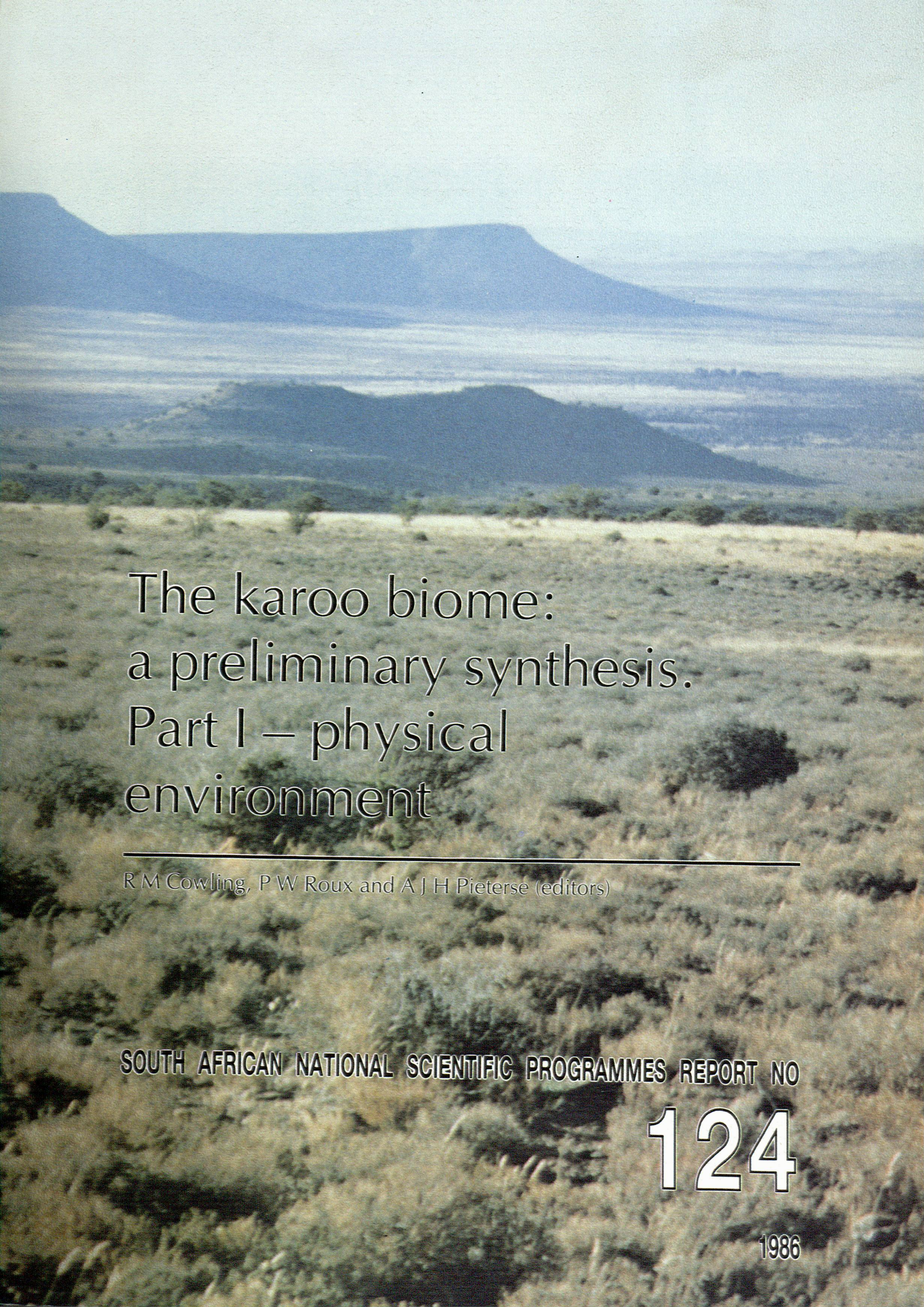

The karoo biome: a preliminary synthesis. Part I – physical environment

R M Cowling, P W Roux and A J H Pieterse (editors)

SOUTH AFRICAN NATIONAL SCIENTIFIC PROGRAMMES REPORT NO

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R M Cowling, P W Roux and A J H Pieterse (editors)

Report of the Committee for Terrestrial Ecosystems
National Programme for Ecosystem Research

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PREFACE

The karoo biome is the largest and most characteristically South African of our extremely diverse terrestrial ecosystems. The vast, seemingly monotonous plains of the Karoo are occupied by dwarf shrublands and arid grasslands that have changed considerably in special composition, but less in physiognomy, since the arrival of European settlers, their sheep, boreholes and barb-wire fences. It is these changes that have severely reduced the productivity, and threaten the future, of the once propserous small stock industry of this region.

The seriousness of veld deterioration in the Karoo has been reported on for over a century, but conventional approaches have failed to remedy the problem. During the past five years the National Programme for Ecosystem Research, one of numerous multidisciplinary programmes within CSIR's Foundation for Research Development, has addressed the need for developing a fundamental, and predictive, understanding of karoo ecosystems. Following an extended period of consultation and the review of available information and research activities, the Karoo Biome Project has been launched. Its objectives, approach and research programme is described in detail by Cowling (1986).

At an early stage in the planning of the project, a decision was taken to prepare a synthesis of available knowledge on the karoo environment. A wide range of workers were invited to prepare reviews on selected topics, ideally for inclusion in a single synthesis volume. Due to the extremely diverse levels of information on aspects of karoo ecology, the initial results were greatly varied in cover and depth. Furthermore, the combined length of the contributions made it impossible to bring them together under a single cover. As a consequence it is anticipated that the papers will be published in three volumes - physical environment, vegetation and flora, and zoology.

It should be noted that the term karoo biome used in this volume includes a wider range of systems than those understood within the original "karoo" of the Hottentot, meaning 'dry', 'arid' or 'hard soil'. The karoo biome furthermore differs slightly in geographic detail from the use of the term by geologists, botanists, zoologists and administrators, but in general the area treated in this synthesis differs little from the term's general usage in South Africa today.

ABSTRACT

This report, the first of three volumes, forms part of the Karoo Biome Project. One of the aims is to synthesize existing knowledge of the karoo biome and so provide a foundation for further research in areas where it is considered necessary. It is a multi-authored publication covering a wide range of topics. This first volume summarizes what is currently known on the physical environment of the biome; namely geology, soils, climate, hydrology, geohydrology and soil erosion. Other aspects of the karoo biome will be covered in the succeeding volumes.

SAMEVATTING

Hierdie verslag, die eerste van drie volumes, vorm deel van die Karoobioom-projek. Een van die doelstellings is om bestaande kennis van die karoo-bioom saam te vat en om sodoende 'n grondslag vir verdere navorsing te bied in gebiede waar dit as noodsaaklik beskou word. Hierdie publikasie wat deur verskeie outeurs geskryf is, dek 'n wye verskeidenheid van onderwerpe. Hierdie eerste volume som op wat tans bekend is oor die fisiese omgewing van die bioom met betrekking tot geologie, grondsoorte, klimaat, hidrologie, geohidrologie en gronderosie. Ander aspekte van die karoobioom sal in volgende volumes gedek word.

ACKNOWLEDGEMENTS

The preparation of the first volume of this synthesis has been delayed due to a variety of factor's, not least of which being several changes in editorial responsibilities. The long and tedious course, for both authors and editors, has been smoothed substantially by the assistance provided by Shirley Pierce, Lynette van Niekerk, Tisha Greyling, Margaret Orton and Marie Breitenbach. Furthermore, the early support of D P Opperman and continued support of B J Huntley is gratefully acknowledged.

TABLE OF CONTENTS

CHAPTER 1. GEOLOGY

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INTRODUCTION

The typical vegetation of the Karoo covers a large variety of rock types (Figure 1) which, because of their extent, provide various geomorphological characteristics to the area:

- Along the west coast there is a narrow coastal plain covered with Quaternary and Recent sands.
- To the extreme south and west isolated strips are found amongst the folded mountains, and are underlain by Nama, Table Mountain, Bokkeveld, Witteberg, Dwyka, Cretaceous and Cenozoic beds. These formations give rise to a low mountainous landscape with active incision by streams.
- South of the escarpment there is an undulating landscape underlain by Dwyka, Ecca and Beaufort beds. Geomorphologically the region represents a dissected area caused by the northward erosion of the escarpment.
- Above the escarpment there is a vast plateau which consists of Dwyka, Ecca and Beaufort beds. Incision by rivers has reached a mature stage.
- The north-western corner of the karoo vegetation region is represented by an inselberg landscape built by formations of the Namaqualand Complex. The development of this geomorphological area was caused by the progradation of valleys mainly by sand.

The most important part of the South African stratigraphy covered by karoo vegetation is indicated in Figure 2. A few stratigraphic units underlie such an insignificant area, that they will simply be referred to in the text. Because of the limited available space for the description of the stratigraphy, only a generalized review is provided, and readers are consequently referred to Haughton (1969) and Tankard et al (1982) for more particulars. The ages of the stratigraphic units vary from Early Precambrian (Archaean) to Recent, resulting in a full series from highly deformed formations to unconsolidated sediments. This period does not, however, represent a continuous process of deposition, but a number of large nonconformities can be distinguished (Figure 2). The duration of the nonconformities are not comparable in time with each other, while other smaller breaks in sedimentation in the Karoo Sequence are of such small magnitude that they are not indicated in the table.

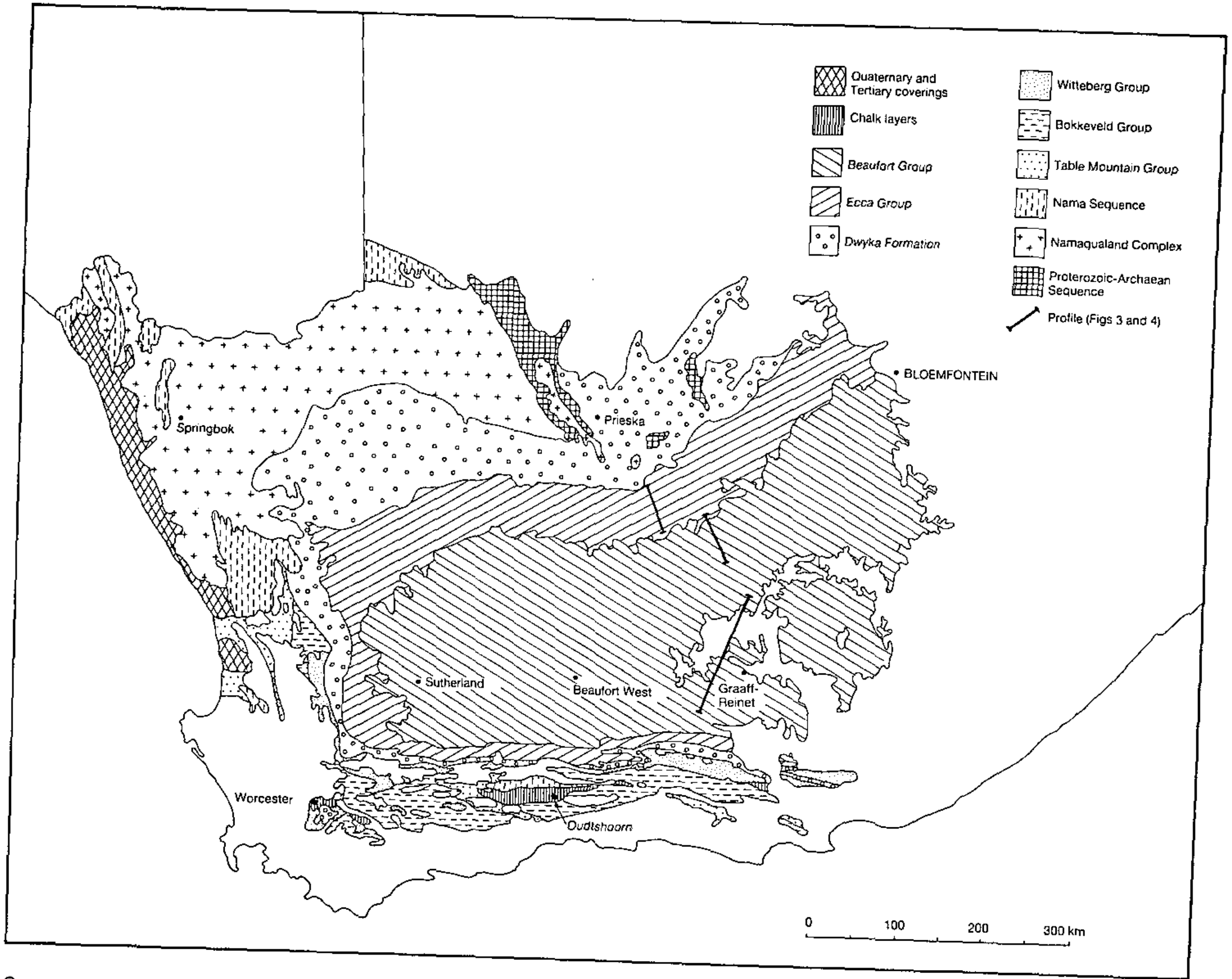

FIGURE 1. Generalized geological map of the karoo biome.

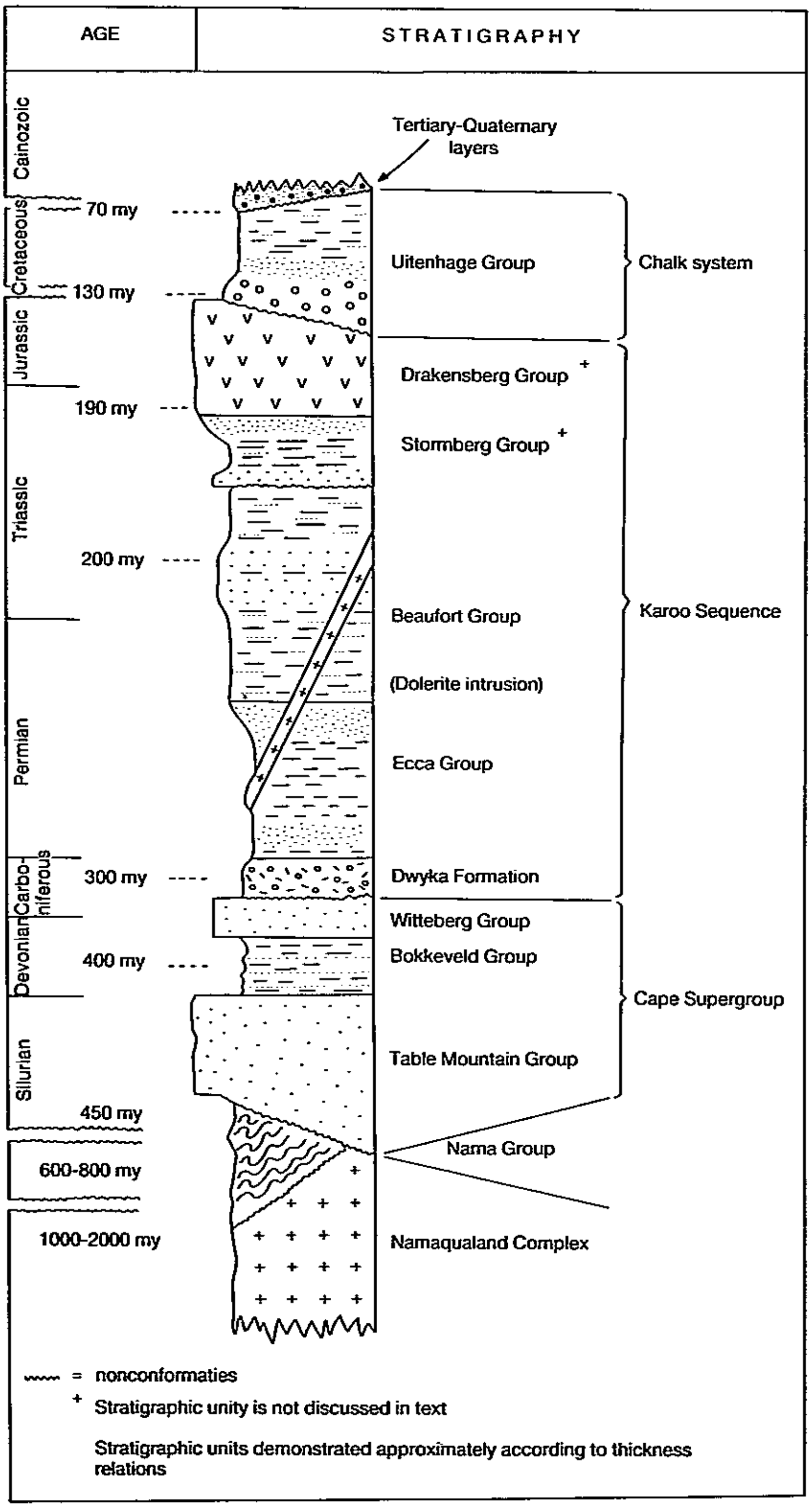

FIGURE 2. Important stratigraphic units covered by the karoo biome.

The geology plays a fairly indirect role in the distribution of the karoo vegetation. In some cases highly resistant beds (Table Mountain Sandstone in folded mountains and thick dolerite sills in the escarpment) build mountainous areas on which no karoo plants occur. In other cases the thick Cenozoic sediments in the Koa valley in Bushmanland probably influence the underground water and this in turn has an influence on the distribution of the karoo plant types in that area.

STRATIGRAPHY AND LITHOLOGY

Archaean Sequences

Beds belonging to these sedimentary formations occur in a limited area between Upington, Prieska and Kimberley (Figure 1), and usually form high-lying areas (Kaaien-Hills, Doringberg and T'Kuip-Hills). The beds consist of metalava of the Marydale Group; glassy quartzite of the Kaaien Group; andesitic lava, felspathic quartzite and conglomerate of the Ventersdorp Supergroup; and dolomite and banded iron-formation of the Griqualand West Sequence. Asbestos is found in the banded iron-formation in the vicinity of Prieska.

Basement rocks of the Namaqualand Complex

Sedimentary rocks belonging to this complex underlie karoo vegetation in parts of Bushmanland and Namaqualand (Figure 1). The Namaqualand Complex consists of a combination of metamorphic sedimentary rocks, which are the product of intense folding and shearing, and which belong to the green schist and granulite metamorphic facies. In the north-western Cape the complex forms the basement on which the younger stratigraphic sequences rest.

In the area the complex consists of metasedimentary and metavolcanic formations associated with a batholithic intrusion. This intrusion consists mainly of granitoids (granites and gneisses) which cover from 60 to 70% of the surface of the area. Remnants or outliers of the original stratigraphic succession are found amongst the granitoid bodies. The sequence, which possibly has a thickness of between 2 000 and 3 000 m, originally consisted of acid to intermediate lava, volcanoclastics, sandstone, siltstone, shale and banded iron-formation. During metamorphosis the rocks were changed mainly to quartzites, gneisses, schists, amphibolites and calc-silicate formations. The area is of economic importance because of the occurrences of copper, zinc, lead and silver in the metasedimentary beds and basic intrusions.

Nama Sequence

Scattered outcrops occur along the west coast from the Richtersveld to Piketberg, as well as north of Oudtshoorn. The beds vary from slightly deformed (Nama Group) to folded and highly deformed (Malmesbury Group). Rock types include sandstone, mudstone and limestone of the Nama Group; phyllite, greywacke and limestone of the Malmesbury Group; and quartzite, limestone, tillite and lava of the Gariep Complex.

Cape Supergroup

Table Mountain Group

Resistant Table Mountain beds covered by karoo vegetation form mountainous terrain in the environment of Vanrhynsdorp, near Ladismith and north-west of Port Elizabeth (Figure 1). The group which forms part of the Cape Folded Belt has a maximum thickness of 4 000 m and rests unconformably on the Nama and Malmesbury beds. It is overlain conformably by the Bokkeveld beds.

Stratigraphically the group can be divided into a western and eastern facies. The western Cape facies consists of a lower and an upper whitish-grey quartzitic sandstone unit, 1 500 m and 500 m thick respectively, within which small, dispersed vein-quartz pebbles occur. The two units are divided by a continuous shale layer with a thickness of up to 120 m. A thin tillite is sometimes present at the base of the shale. At the base of the western Cape facies conglomerate, reddish-purple sandstone and shale occur. Marine fossils and fossil trackways have been found in the beds.

The eastern Cape facies is much thinner and has a maximum thickness of approximately 2 500 m. It consists of two sandstone units, but the inter-bedded dark-coloured shale is very thin or absent. The top sandstone unit is also much more felspathic and shaly, and represents a transition to the Bokkeveld Group. The upper stratigraphic units of both facies overlap the bottom units northward, which points to sedimentation by a transgressing sea. Horizontal and cross-bedding are the most important sedimentary structures.

Bokkeveld Group

Beds of the Bokkeveld Group underlie long strips between the mountains in the west, south-west and south-east of the area (Figure 1). This phenomenon is the result of the Cape folding where the softer Bokkeveld beds were preserved in the synclines. The maximum thickness of the group is approximately 3 500 m in the south-east (Theron 1970), but the beds pinch out towards the north, which is partly the effect of sedimentation and partly due to erosion during the Carboniferous. The lower contact with the Table Mountain Group is taken at the first thick shale unit, while the upper contact with the Witteberg Group does not represent a clear boundary.

Stratigraphically, the group can be divided into an eastern and western facies (Theron 1970) with a facies overlap somewhere south of Beaufort West. The western Cape facies consists of five sandstone and six shale units, which succeed each other cyclically. Some of the units pinch out towards the east, so that the eastern Cape facies consists of four sandstone and five shale units. Further differences between the two facies are shown by the occurrence of red-coloured beds and the presence of more plant fossils in the eastern Cape. Each shale-sandstone couplet represents an upward-coarsening cycle.

As regards sedimentation, the lithostratigraphic units can be divided into three adjacent horizontal zones from the edge of the basin (Rust 1973). The proximal zone occurs in the far north-west and includes thin conglomerate lenses, grit, quartz arenite, silty micrite and red mottled siltstone. These beds are particularly micaceous and structures characteristic of very shallow water are present. The middle zone covers the largest outcrop area and consists of dark grey quartz and felspathic wackes and dark grey to black carbonaceous shale, mudstone and siltstone. In the upper lithological units in the eastern Cape facies, red mudstone and siltstone occur. Parallel bedding, cross-bedding, ripple marks and slump balls are the most important sedimentary structures. The distal zone on the southern margin of the area consists of dark shale and mudstone with minor siltstone. The north-south lithofacies changes comprise a gradual southward decrease in the thickness as well as maturity of the sandstones, and a corresponding increase in the thickness of the argillaceous units, with the result that virtually no more arenaceous beds are present south of Worcester.

Witteberg Group

Beds of the Witteberg Group underlie relatively small areas of the karoo vegetation region. Isolated outcrops occur in the south-west, while thin strips are present in the south-east of the area (Figure 1). As the Witteberg Group is also affected by the Cape folding, and consists of lithological zones of varying resistance against weathering, both mountainous and low lying regions are found. River valleys are often situated in the low lying areas where karoo vegetation is found. The sequence has a maximum thickness of approximately 2 600 m in the east. The lower contact of the group is transitional, but the upper contact with the Dwyka Formation is sharp.

Stratigraphically a western and south-eastern facies can be distinguished: sandstone is more prominent in the south and east, and more stratigraphic units can be distinguished there than in the west. The lithofacies overlap with each other approximately south of Touws River. The group consists of a cyclic sequence of sandstone and shale with a well-developed sandstone unit (Witpoort sandstone) which is up to 850 m thick, approximately in the middle of the group. The sequence is predominantly argillaceous both below and above the Witpoort sandstone.

Lithologically the Witteberg Group consists of quartz and felspathic arenite, felspathic grit, thin conglomerate layers, siltstone, shale and diamictite. The Witpoort sandstone becomes more mature and conglomeratic towards the top. Well-developed cross-bedding is present in the sandstone. The shales are generally grey-coloured, although a red shale does occur along a specific horizon. The siltstones are micaceous. In the south-eastern facies a diamictite unit consisting of clasts of vein-quartz in a sandy to argillaceous matrix occurs. Ripple marks are abundant in the fine-grained beds. Some of the sandstone units become finer grained towards the south, while interdigitation of lithological units occurs especially in the upper part of the group.

Karoo Sequence

Dwyka Formation

The karoo region covers an east-west strip of Dwyka Formation in the south and an extensive area of Dwyka deposits in the north (Figure 1). The irregular distribution of the outcrops in the south can again be attributed to the Cape folding, with the result that Dwyka Formation usually occurs in narrow synclines. The northern Dwyka deposits on the other hand are undisturbed and bedding is horizontal, with the exception of compaction over an uneven floor. The formation reaches a maximum thickness of 750 m in the south, but thins out towards the north, where the thickness is controlled by the palaeotopography. The lower contact represents an erosion surface and is therefore sharp. In the south the upper contact is also sharp but in the north the contact with the Ecca Group is transitional.

Stratigraphically the Dwyka Formation can be divided into two lithofacies. The southern facies consists of a thick succession of massive diamictite with thin zones of bedded diamictite, rhythmite shale and mudstone with ice-rafted debris. The bedded sediments are, however, very subordinate in thickness to the massive formations. The diamictite consists of angular to subrounded clasts of predominantly gneiss, granite, quartzite, diorite and lava in a blue-grey argillaceous matrix. The clasts vary up to three metres in size. They do not show any regular distribution pattern, although clast-rich zones were found at some localities. Striated and facetted clasts are relatively scarce. The colour of the laminated interbedded shale is blue-grey to black, and the shale reaches a maximum thickness of three metres. Balls of carbonate-rich diamictite, with a diameter of up to 0,5 m, are dispersed in the succession.

In the northern facies, which has a maximum thickness of approximately 250 m, massive diamictite is subordinate to the bedded sediments. Green-grey bedded diamictite, boulder shale, conglomerate and conglomeratic sandstone occur intermittently with the massive diamictite, although the different types sometimes show a cyclic succession. At the top of the Dwyka Formation varve-like shale with occasional dropstones is found. Limestone beds and carbonate-rich nodules are often present in the boulder shale. The diamictite consists of sub-rounded to rounded clasts, of which some are striated and facetted, in a greenish argillaceous matrix. The boulder shale consists of scattered large rounded clasts in a dark grey to black bedded claystone. The clasts area between Kimberley and Vanwyksvlei the Dwyka Formation sometimes rests on striated pavements.

Ecca Group

The Ecca beds covered with karoo vegetation cover a small east-west strip in the south (Figure 1). The sequence is affected intensely by the Cape folding, with the result that the inclination of the beds varies from almost horizontal to vertical. In the north the Ecca beds underlie a very large area (Figure 1) and the soft rocks give rise to a flat landscape. These beds are undisturbed and horizontally disposed, except in cases where they are affected by dolerite intrusions. The sequence has a maximum thickness of up to 3 000 m in the south, but this decreases rapidly, to approximately 300 m towards the north. The lower contact with the Dwyka Formation varies from sharp to transitional. On the other hand the upper contact with the Beaufort Group is completely transitional and the position of contact has for years been a matter of dispute amongst South African geologists. There is a useful contact at the base of the fluvial sediments, although it is not always easy to map, and it also represents a diachronous plane.

Stratigraphically the southern outcrop area falls in the southern facies and the northern outcrops in the south-western and central facies (Figure 3). The southern facies, of which a typical sequence is represented north of Klaarstroom (Figure 3) can be divided into three lithological zones. The lower zone (Lower Ecca) begins with black carbonaceous shale and ends with quartz and lithic wackes at the top. The arenaceous beds which vary from medium-grained at the base to fine-grained at the top, and which are up to two metres thick, occur interbedded with dark grey shale. The sedimentary structures (predominantly sole marks, graded bedding and ripple cross-lamination) in the sandstone beds are closely related with the lithology (Bouma sequence). An excellent marker bed (White Band) which consists of pitch-black carbonaceous shale in fresh samples, but which weathers to white, is found near the base of the zone. The White Band is approximately 15 m thick and is particularly rich in fossils. The middle zone (Middle Ecca) consists of a thick succession of dark blue shale and mudstone. Locally arenaceous zones occur near the top of the unit. The upper zone (Upper Ecca) consists of an alternation of felspathic arenite, quartz and felspathic wackes, siltstone and mudstone, which occur in typical upward-coarsening cycles. Trough cross-bedding, ripple cross-lamination, graded bedding, ripple marks and slump structures are generally found in this zone.

The only difference between the south-western and the central facies in the northern outcrop area is the presence of more sandstone in the first, but for the purpose of this discussion they will be regarded as a single unit. The sequence can be divided into two lithological zones. The lowest zone (Lower Ecca) is argillaceous and begins with dark coloured micaceous shale. Approximately 60 m above the base a black carbonaceous shale which weathers to white (White Band) can once more be found. Here the maximum thickness of this marker bed is approximately six metres. The rest of the zone consists of homogenous blue-grey shale (Figure 3), although silty secretions consisting of rhythmites are present locally. The upper zone (Upper Ecca) consists of an alternation of felspathic arenite, felspathic wackes, siltstone and mudstone which once again occur in characteristic upward-coarsening cycles. In the west a larger number of cycles (mega-cycles) are found than in the east, and some cycles are already developed low down in the shale. Trough and ripple cross-bedding and slump structures are generally developed in this facies.

Beaufort Group

Beds of the Beaufort Group underlie the greater part of the karoo region and cover the central Karoo basin (Figure 1). Only the lower beds in the south are affected by the Cape folding and the formations are undisturbed over the greater part of the area. The Beaufort Group, however, has been intruded intensively by dolerites, which influenced both the structure and

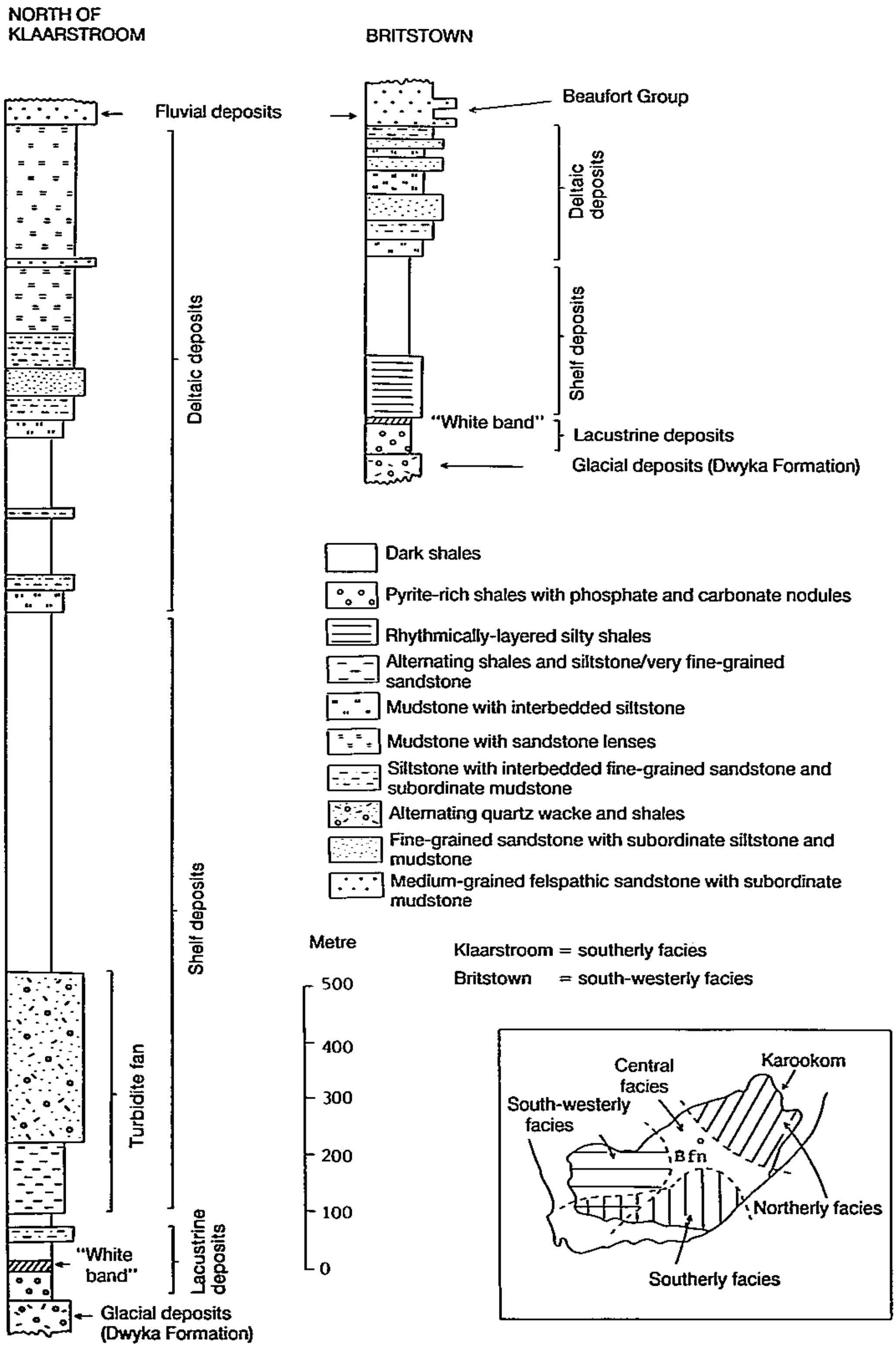

FIGURE 3. Stratigraphic sequence of the Ecca Group.

lithology of the beds. The upper contact of the group is not present in the area, although the eastern boundary of the Karoo virtually follows the contact with the Stormberg Group in certain parts. As a result a reliable maximum thickness for the sequence cannot be obtained in the south and west, and as a thinning of the beds towards the north occurs, it is difficult to give a reliable thickness of the group as a whole. In the south the lowest part of the Beaufort Group has a minimum thickness of approximately 3 000 m, while a corresponding value in the north is approximately 1 000 m. As already mentioned, the lower contact with the Ecca Group is transitional.

The Beaufort Group represents a monotonous alternation of argillaceous and arenaceous beds over the greater part of the area, and it is only in the environment of Middelburg and east of it that prominent arenaceous zones occur. The sedimentary basin can be divided into three lithofacies (Figure 4), but the differences are so subtle that they are not readily perceptible. The lithofacies is related more closely to the deposition of the sediments, and the amount of sandstone decreases towards the distal part of each facies. The largest part of the area is underlain by both the south-eastern and western facies, but they will be discussed together. A small part of the north-eastern facies occurs in the vicinity of Bloemfontein only (Figure 4).

The south-eastern and western facies consist of an alternation of fine- to medium-grained felspathic arenite and wackes, siltstone and mudstone. Greenish-grey mudstone is predominant in the lower part of the sequence, but reddish-purple mudstone is more abundant towards the top. In the mudstone, carbonate-rich nodules and lenses, which probably represent paleosols, often occur. The sandstones often have a mottled appearance and are mostly lenticular, although some stacked lenses give the impression of continuous beds of up to 10 m thick. Individual sandstone lenses, siltstone and mudstone are usually arranged in upward-fining cycles (several metres thick at the most), and are the result of the sedimentary processes. Clay-pellet conglomerate often occurs at the base of such cycles. Thin fine-grained sandstone beds which cover larger areas than the lenses are also interbedded in the massive mudstone. The whole sequence is inclined to adopt a large cyclic pattern of intermittent arenaceous and argillaceous zones (Visser and Dukas 1979). These mega-cycles are hundreds of metres thick and are probably the result of tectonism in the source area and the depository. The sandstones tend to become more medium-grained and abundant higher up in the sequence (Figure 4) and the Katberg sandstone which represents the highest stratigraphic unit in the area, builds prominent mountains in the vicinity of Middelburg. The sequence south of De Aar (Figure 4) represents a distal part of the western facies, and medium-grained sandstone therefore rarely occurs.

The northern facies consists of fine- to medium-grained felspathic arenite, siltstone, greenish grey mudstone and very minor lenses of felspathic grit. Pebbles of mainly vein-quartz and up to several centimetres in diameter, are found in the gritty beds. The lithologies are arranged in upward-fining cycles. Sedimentary structures are abundant in the Beaufort beds. Trough and ripple cross-bedding is often found; ripple marks, current lineation, erosional channels and desiccation cracks generally occur; while sole structures and clastic dykes occur less commonly. Some structures show characteristic associations in upward-fining cycles of the first order. Uranium is present in beds of the Beaufort Group.

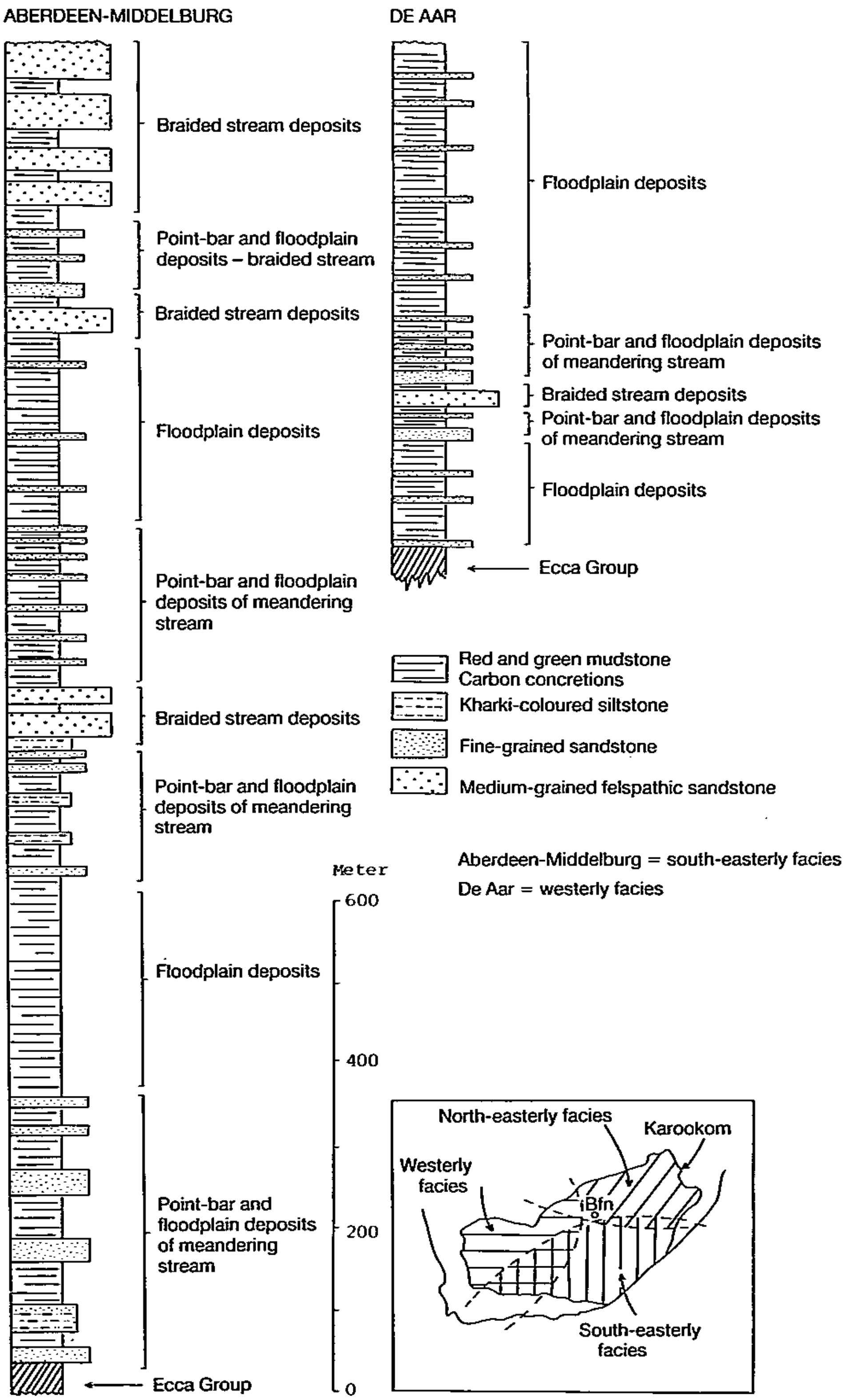

FIGURE 4. Stratigraphic sequence of the Beaufort Group.

Karoo dolerite

Dolerite intrusions of the same age as the lavas of the Drakensberg Group (Figure 2) occur scattered in beds of the Ecca and Beaufort Groups. The northern margin of the Cape Folded Belt determines the southern occurrence of dolerites, with the result that no dolerites are present in the southern outcrops of the Ecca Group. The dolerite intrusions give rise to a very uneven topography, because they are more resistant to weathering in the dry climate and show positive land forms. Mesas, hillocks and sharp ridges therefore occur generally.

The dolerites occur in the form of sills or dykes. The sills are concordant with the layering of the beds, vary in thickness from less than a metre to 300 m, and underlie areas up to 14 000 km^2 (Truswell 1977). The dykes cut across the bedding, vary in width to 10 m, and individual dykes have already been followed over distances of 85 km (Truswell 1977). All possible structural variations between dykes and sills do, however, exist, with the result that transgressive sills often occur. This causes very irregular dolerite structures, which stand out during erosion of the country rocks as ring-dykes, domes and basins.

The dolerite is a dark-coloured, fine to medium crystalline rock type, which consists primarily of plagioclase and pyroxene, with or without olivine. In composition it therefore varies from a picrite to a hyperite (McLaren and Visser 1975-76), and the difference in composition is often reflected by the weathering of the rock. The effect of the intrusions on the adjacent mudstone, siltstone and sandstone is firstly contact metamorphism and secondly, disturbance of the bedding. The mudstones in particular are baked to a hard rock (lidianite). The transgressive sills, especially where they are thick, caused an elevation and displacement of the beds, while some dykes led to slight folding of the country-rock.

Cretaceous beds

Beds of the Cretaceous System underlie the Karoo in the south-west (east of Worcester), south (Oudtshoorn) and in the south-east (part of the Uitenhage basin) (Figure 1). The beds rest unconformably on the older formations and have an angle of up to 45° to the interior. The sequences in the area under discussion have thicknesses of up to 1 900 m (Rust 1979).

Only the basal beds (conglomerate facies) of the Uitenhage Group crop out in the western corner of the basin, and beds show much the same characteristics as those at Oudtshoorn and Worcester. Therefore they will all be discussed together. The dominating rock type is conglomerate which consists of angular to rounded clasts with a diameter of up to two metres. The clasts are predominantly quartzitic in composition, but other lithological types representative of the basement are also found. The conglomerate, which has a distinctive red colour as a result of the presence of iron oxide, has its maximum development along the northern borders of the different areas. Southward and overlying the red conglomerate, a white-coloured conglomerate occurs. The clasts are much smaller, better rounded and the sorting of the rock is also better. The light-coloured conglomerate facies represent the distal facies of the red conglomerate. Towards the south the conglomerate grades to red mudstone and light-coloured sandstone with very minor carbonate lenses. Cross-bedding, ripple marks and slump structures occur in the fine-grained beds.

Tertiary to Quaternary sand, gravel and debris deposits

Although these deposits are not of sufficient extent to warrant inclusion in Figure 1, their presence has an effect on the distribution of the karoo biome. In the Cape Folded Belt, karoo plants are established along river valleys which cut through the mountains. Scattered gravel terraces, some of which have a thickness of 80 m, are found on the slopes of the valleys (Lenz 1957). The gravels, the basal parts of which are sometimes consolidated, consist of rounded boulders, pebbles and granules. Silica or ferricrete cements the gravels. Sandstone lenses are also found interbedded in the gravels (Lenz 1957).

In the Koa valley in Bushmanland a thick covering of red aeolian sand which sometimes overlies calcrete is found, but in deep gravels, sandstone and mudstone are found. The gravels vary from unconsolidated to well cemented. These depositions fill entire valleys, so that only the highest points of the surrounding landscape protrude as inselbergs. Boreholes of up to 200 m deep and more were drilled in the Tertiary to Quaternary valley aggradations without the basement being reached.

Vast sandy plains are found along the west coast. The thickness of the sand deposits depends on the underlying topography, and values of up to 100 m were found in bore-holes. The deposits consist mainly of windblown sands, with subordinate river and beach gravels and local claystone, which in some places are already cemented. Diamonds are exploited in the coastal deposits.

GEOLOGICAL HISTORY

Only a very concise summary of the origin of the beds which were discussed in the previous section will be given. New ideas and principles are incorporated in the summary, and gratitude is expressed to members of the Geology Department of the University of the Orange Free State for their assistance in this regard. Because of limited space, tests for the deductions could not always be given, but Truswell (1977) and Tankard et al (1982) give a more complete account of the geological history and interested readers are referred to these.

Precambrian sediment and metamorphosis

The Proterozoic Archaean sequences (age 2 000 to 3 000 million years) are deposited on a thin unstable crust. The lavas mostly flowed out on land, but the chemical precipitates (dolomite and banded iron-formation) and sands accumulated in shallow seas and littoral environment. Between 1 000 and 2 000 million years ago sedimentation with accompanying volcanism occurred over a large part of the north-west Cape and the southern part of Namibia. Deposition was possibly limited to a shallow sea and the shoreline environment, which possibly also included deltas. At times sedimentation was interrupted or preceded at places by the outflow of lava and the deposition of ash-fall tuffs. The depository was destroyed at the end of the period (approximately 1 000 million years) when large-scale deformation set in as a result of tectonic forces in the earth's crust. This resulted in temperature increases in the crust; some of the lower sedimentary units were melted, and various granitic bodies, which form part of a large batholith, intruded in depth into the beds. Deformation of the beds continued in places until after the intrusion of the batholith. Weathering since 1 000 million years ago, stripped thousands of metres of the Namaqualand Complex, with the result that at present only outliers of the original sedimentary sequences are found amongst the granitoid intrusions. Between 600 and 800 million years ago some of the eroded material was deposited in a north-south basin to form the Nama sequence. Depositional conditions varied from shallow to deep marine and at some stage glaciation occurred in the area. After deposition the beds were partly deformed and intruded by granite.

Cape-Karoo Basin

Although there is nonconformity between the Cape Supergroup and the Karoo Sequence, the basin development was a continuous process (Visser 1978) and therefore the two basins are discussed together. After the deposition of the sands of the Table Mountain Group on beaches during a marine transgression, the beds of the Bokkeveld Group were deposited as large deltas which prograded towards the south (Figure 5). The sedimentary material came from the north. The cyclic pattern in delta progradation was probably the result of tectonism which led to a number of transgressions and regressions in the basin (Theron 1970; Tankard and Barwis 1982). After the unstable conditions during the deposition of the Bokkeveld Group, greater stability set in, especially in the source areas. During local transgressions and regressions, sands and subordinate gravels were deposited on beaches and deltas, while clays and muds were deposited in a shallow marine environment, partly as prodelta beds (Figure 5).

The deposition of the Cape Supergroup was followed by a period of uplift and erosion, and afterwards possible flooding of the region in the south. At the same time the pole moved over the southern tip of Africa and an ice-cap formed over the Highveld area. In the south a floating ice sheet pushed far into the basin (Figure 5). In the north the debris was deposited on land by glaciers (northern facies of the Dwyka Formation) while glacial sediments were left behind by the ice sheet in the south (southern facies).

After the glaciation a large shallow lake formed where large volumes of melt water collected on the relatively flat glaciated landscape, and during the cool conditions with luxuriant vegetation, black clays and muds were deposited in the lake (inter alia White Band). Deformation of the distal part of the Cape Supergroup south of Africa had already started at this stage and mountain ranges formed in the far south (at present possibly part of Antarctica; then part of Gondwana) (Visser 1979). Material derived from the mountains, as well as from high-lying areas in the west and north-east, was deposited on large deltas which prograded in the lake to form the Ecca Group (Figure 5). The water in the lake was deeper in the south, and turbidite deposits formed on the southern delta fronts. Later the prograding deltas filled the entire basin and fluvial deposits (Beaufort

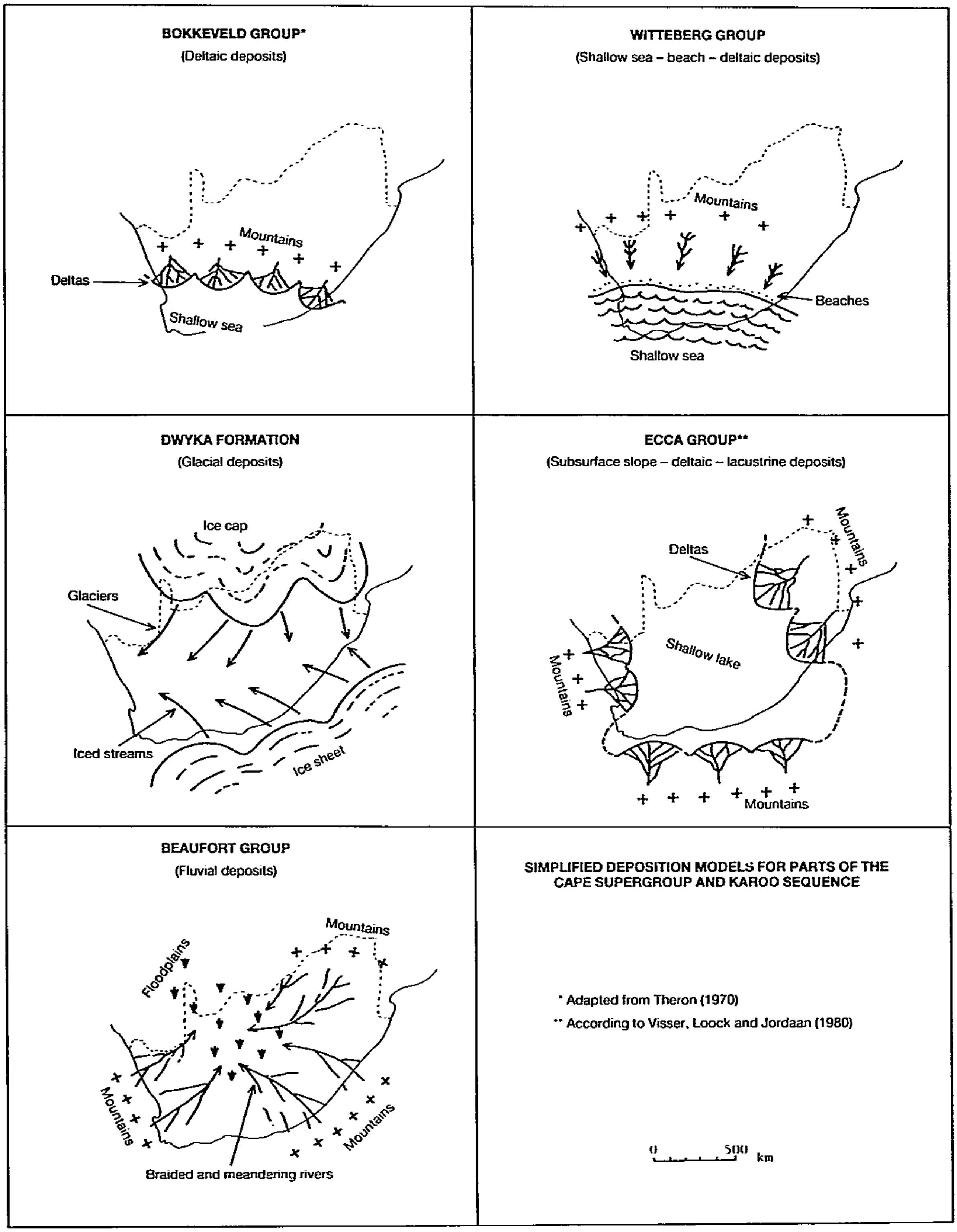

FIGURE 5. Simplified deposition models for parts of the Cape Supergroup and Karoo Sequence. Bokkeveld Group modified from Theron (1970) and Ecca Group according to Visser et al (1980).

Group) covered the deltaic beds. During deposition of the Beaufort Group the southern mountain ranges moved closer to the southern tip of Africa as a result of the folding, and braided streams drained the high areas. Coarse-grained debris was deposited along the slopes. Further in the depository, finer sediments were laid down by meandering streams on large floodplains (Figure 5). Elevation in the source areas, especially those in the south, was pulsating, with the result that zones of medium- and fine-grained beds alternate cyclically. After the deposition of the glacigene Dwyka Formation the climate became warmer, so that warm and arid conditions were prevalent during the deposition of the Beaufort beds. The deformation of the proto-basin of the Cape Supergroup reached its northern limit during the Triassic, and the lower part of the Karoo Sequence in the south was also folded.

Post-Karoo sedimentation

After the deposition of the Karoo Sequence a period of erosion followed. The drainage in the south of the country was probably still directed towards the north and in the valleys possibly the first Cretaceous beds were deposited. At this stage, break up of Gondwana started and shear tension developed in the crust along a zone now occupied by the coastal regions. This led to the formation of halfgrabens (intermontane basins), within which alluvial fans consisting of gravel and sand derived from the mountain slopes, were deposited. Playas within which mud and thin carbonate layers were deposited, developed towards the centre of the basins.

Sedimentation of the Cretaceous beds was followed by a long period of erosion. The drainage was now directed towards the south and with the elevation of the folded regions, possibly during the Early Tertiary, deep valleys were incised. During the Mio-Pliocene a rise in sea-level occurred and the transgression caused a rise in the base of erosion, which led to aggradation of the rivers (Lenz 1957). The river valleys were then filled with gravel and debris. A later drop in sea-level associated with the Pleistocene glaciation lowered the erosion base again and led to the incision of the gravel filled valleys, with the result that only terraces are left today. Later rises in sea-level, however, led to transgressions and coastal sands were deposited some distance inland. At present there is a regression and some of the low-lying areas are now filled with aeolian sand.

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CHAPTER 2. SOILS

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INTRODUCTION

The soils of the karoo region have not been studied and mapped in any detail before. The work of Van der Merwe (1962) is the only published work on the soils of the entire Karoo. The present description and map is the result of soil surveys carried out by the senior author and staff of the Soil and Irrigation Research Institute since 1973. Soil surveys in this area prior to 1973 were carried out to evaluate the suitability of land for irrigation development and were therefore restricted to areas near rivers.

This paper is a presentation of the soils of the Karoo in the form of a 1:1 000 000 scale map (Figure 1, see back cover) with a legend consisting of seventeen broad soil patterns (map units).

The soils of each of the seventeen map units are discussed in terms of: their classification; morphological, physical and chemical properties; distribution and natural fertility status; genesis; and the uses to which they are put. Profile descriptions and analytical data for seven soils selected to represent the dominant soils of the karoo region are given in Tables 1 and 2. The norms used in the discussion of natural fertility status are given in Table 3. The soils have been classified using the binomial system (MacVicar et al 1977). This publication also contains an explanation of the technical terms used.

Descriptions of the environmental factors which have contributed to soil formation in the karoo region (parent material, climate, relief, vegetation and time) are contained in other chapters of this volume.

A section dealing with soil erosion in this region is included here.

The information on soils contained in the text, accompanying diagrams and soil map, may contribute to regional and agricultural planning, environmental and conservation studies and to assessing the relationship between substrata and vegetation communities; it may also be of value in geomorphological, palaeoecological and archaeological research.

DESCRIPTION OF THE SOILS OF THE MAP UNITS

The survey was carried out by mapping pedosystems (Land Type Survey Staff 1984). A pedosystem is land with uniform terrain form and soil pattern. By excluding terrain form boundaries between similar soil patterns, a map at 1:250 000 scale showing the distribution of soil patterns was produced.

+This paper is based inter alia on data collected by the senior author towards the fulfillment of the PhD degree in the University of Stellenbosch.

TABLE 1. Morphological properties of seven selected soils of the karoo (see Figure 1)

Profile No + Lat/Long	Classification*	Hor	Depth (mm)	Colour**	Texture	Structure	Cutans	Consistence	Lime***	Transition
1	Fernwood Langebaan	A	0 - 250	10YR6/4	Medium sand	Single grain	None	Loose	Common	Diffuse
29°17'/16°54'	Typic Xeropsamments	C	250 - 1 400	10YR7/4	Medium sand	Single grain	None	Loose	Common	Gradual
		C	1 400 - 1 600	10YR7/2	Loamy medium sand	Massive	None	Soft	Abundant	-
2	Huton nyala	A	0 - 100	5YR4/4	Coarse sand	Single grain	None	Loose	Few	Gradual
28°59'/17°45'	Typic Durorthids	B	100 - 250	2.5YR4/6	Medium sand	Single grain	None	Loose	None	Abrupt
		db	250 - 350	2.5YR4/6	Coarse sand	Massive	Few clay & lime	Extr. hard	Few	-
3	Hutton gaudam	A	0 - 150	2.5YR4/8	Coarse sand	Single grain	None	Loose	None	Diffuse
29°12'/18°38'	Typic Ustipsamments	B	150 - 500	2.5YR4/8	Medium sand	Single grain	None	Loose	None	Diffuse
		B	500 - 1 200	2.5YR4/8	Medium sand	Single grain	None	Loose	None	-
4	Arcadia eenzaam	A	0 - 30	2.5YR3/4	Clay	Strong angular blocky	Common brown clay	Slightly hard	None	Clear
31°23'/19°09	Typic Chromusterts	A	30 - 600	2.5YR3/6	Clay	Strong subang. blocky	Common brown clay	Hard	Few	Abrupt
		C	600 - 700	10YR3/3	Sandy clay loam	Medium platy	None	Soft	Abundant	-
5	Oakleaf mutale	A	0 - 30	10YR4/3.	Clay	Weak fine platy	Few grey clay	Hard	Common	Clear
30°00'/21°06'	Lithic Haplustalfs	B	30 - 150	10YR4/3	Clay	Weak angular blocky	Common grey clay	Slightly hard	Common	Clear
		B/C	150 - 300	10YR4/3	Clay	Weak subang. blocky	Common grey clay	Slightly hard	Common	-
6	Glenrosa kanonkop	A	0 - 60	10YR4/3	Loamy fine sand	Massive-platy	None	Soft	None	Clear
32°38'/24°12'	Lithic Haplustalfs	B	60 - 250	5YR4/6	Sandy clay loam	Weak subang. blocky	Common brown clay	Hard	None	-
7	Sterkspruit swaerskloof	A	0 - 70	7.5YR4/4	Fine sandy loam	Mod. fine platy	None	Hard	None	Abrupt
31°17'/24°34'	Typic Natrargids	B	70 - 300	5YR4/6	Clay	Strong med. blocky	Common brown clay	Very hard	None	-

* Classification : (a) S A Binomial System (MacVicar et al 1977)
(b) Soil Taxnomy (Soil Survey Staff 1975)

** Munsell Colour notation for moist soil

*** Relative amounts as determined by field observation and with dilute HCl
[% $CaCo_3$ by volume : few = 10; common = 10-50; abundant = 50]

TABLE 2. Some analytical data of the soils described in Table 1 (see Figure 1)

Profile No	1			2			3			4			5			6		7	
Horizon	A	C	C	A	B	db	A	B	B	A	A	C	A	B	B/C	A	B	A	B
Depth (mm)	0-250	250-1 400	1 400-1 600	0-100	100-250	250-350	0-150	150-500	500-1 200	0-30	30-600	600-700	0-30	30-150	150-300	0-60	60-250	0-70	70-300
Particle size distribution%*																			
C Sand (2,0-0,5 mm)	13,2	7,1	10,7	19,9	17,6	17,3	32,9	13,3	11,6	1,4	2,9	24,6	2,0	2,6	1,6	12,3	11,5	0,4	0,3
M Sand (0,5-0,2 mm)	57,7	57,9	46,4	26,9	26,5	29,9	58,7	59,5	60,5	4,2	3,3	16,6	2,5	2,0	2,1	20,9	12,8	9,6	6,4
F Sand (0,2-0,02 mm)	25,1	29,9	23,2	43,3	48,4	40,5	8,2	26,6	26,6	12,4	13,6	20,6	18,7	12,4	12,2	51,5	44,1	56,3	30,8
Silt (0,02-0,002 mm)	3,0	2,6	14,4	6,7	5,8	10,8	0,1	0,1	0,1	23,5	16,3	12,0	19,3	18,1	17,1	5,8	6,6	16,9	8,3
Clay (0,002 mm)	1,9	3,4	6,8	5,2	4,3	10,2	2,1	2,2	1,9	54,7	63,2	26,8	59,4	65,0	66,8	9,1	24,8	15,7	53,0
Extractable cations me kg^{-1} oven dry soil**																			
Na	2	22	109	2	2	20	1	1	4	26	46	24	50	116	162	1	1	10	76
K	2	2	4	6	5	4	2	2	3	8	4	2	8	6	5	5	2	5	2
Ca	5	60	132	34	16	29	7	5	39	211	223	140	135	107	127	51	96	16	40
Mg	4	3	11	12	15	26	6	5	8	139	134	54	28	21	21	8	20	22	56
TEB	13	87	256	54	38	79	16	13	54	384	407	220	221	250	315	65	119	53	174
CEC	10	17	17	44	31	63	13	13	13	335	377	138	183	202	210	60	119	100	253
C%***	0,1	0,1	0,1	0,2	0,1	0,0	0,0	0,0	0,0	0,3	0,2	0,2	0,3	0,3	0,3	0,3	0,3	0,4	0,3
R(ohms)	600	30	24	1400	2000	740	2300	3600	6800	340	230	300	100	58	28	1000	120	420	120
pH (H_2O)	8,9	3,2	8,3	8,8	8,9	8,9	8,2	8,2	8,3	7,9	8,0	9,1	8,5	8,5	8,4	8,3	8,0	6,6	8,3
pH ($CaCl_2$)	8,3	3,1	8,3	8,1	7,9	7,7	6,7	7,0	7,0	6,8	7,2	7,7	7,9	8,0	8,1	7,2	7,1	6,5	7,7
Micronutrients mg kg^{-1}***																			
Mn	1,2	33,5	42,1	0,60	1,10	0,30	547,0	284,0	1,2	ND	ND	ND	334,9	287,8	247,6	90,4	114,2	ND	ND
Cu	0,03	0,03	0,03	0,72	0,33	1,14	0,06	0,15	0,18	ND	ND	ND	1,01	1,11	1,10	0,52	0,73	ND	ND
Za	0,66	0,16	0,57	0,96	0,33	0,33	0,21	0,27	0,15	ND	ND	ND	1,32	1,15	0,96	0,41	0,06	ND	ND
B	1,28	2,71	1,66	0,86	0,50	0,75	0,12	0,11	0,12	ND	ND	ND	3,39	3,39	1,68	0,74	0,64	ND	ND
P status mg kg^{-1}****	127,3	167,4	14,5	87,1	21,7	28,0	3,8	3,9	3,8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

* Pipette method (Day 1965) ND - Not determined

** Modified LICI method (peech 1965)

*** Beyers and Coetzer 91971)

**** ISFEI method (Hunter 1975)

TABLE 3. Norms used for evaluating natural fertility status of A horizons*

Element	mg kg^{-1}				Method	Norm data references
	Low	Medium	High	Very High		
P	0-8	8-16	16-100	100	ISFEI (Hunter 1975)	Van der Merwe (1980)
K	0-20	20-80	80-300	300	Modified LiCl (Peech 1965)	A J van der Merwe (Soil and Irrigation Research Institute, personal communication)
Mn	0-1	1-5	6-300	300	(NH_4)2 EDTA (Beyers and Coetzer 1971)	C P de L Beyers (Winter Rainfall Region, personal communication)
Cu	0-0,3	0,3-0,6	0,6-5,0	5		
B	0-0,2	0,2-0,5	0,5-3,0	3		
Zn	0-0,3	0,3-0,6	0,6-3,0	3		

*The norms used are based on the accepted requirements for most agronomic crops for these plant nutrients. No data are available on the nutrient requirements of the natural vegetation of the Karoo but they are expected to be lower than those of agronomic crops. Data on natural fertility status of different soils of the Karoo used in the text are based on analyses from 322 soil profiles.

A 1:1 000 000 scale soils map was then produced by reduction and rationalization of soil boundaries. The delineated areas were then classified into seventeen broad soil patterns in a manner similar to that described by Land Type Survey Staff (1984). Each symbol given on Figure 1 and described in more detail below therefore denotes land over which the soil pattern displays a marked degree of uniformity.

In Tables 1 and 2, morphological and chemical data are given for seven selected soil profiles. Their positions are indicated in Figure 2. The five regions shown in this figure are a convenient basis for describing the distribution and properties of the soils of the karoo region because they reflect major geological, geomorphological and pedological subdivisions. They also correspond well with geomorphological delineations made by Wellington (1955) and King (1967). The five regions are: Region 1 - West Coast and Namaqualand, Region 2 - Upper Karoo, Region 3 - Escarpment, Region 4 - Great Karoo, Region 5 - Little Karoo.

Figure 3 shows the distribution of topsoil (A horizon) texture classes in the karoo region. Texture is of importance in karoo soils especially with regard to the capacity of the soil to hold water and withstand erosion.

Soils with the highest A horizon clay content occur in areas where diagnostic vertic horizons (unit J, Figure 1: Region 3, Figure 2) are dominant. Very sandy soils (less than six per cent clay) occur along the West Coast (Region 1, Figure 2), in inland areas where dunes are present (Region 2) and in the mountain ranges to the south where Table Mountain Sandsone (TMS) is the parent material (Region 5).

The organic carbon content of 322 topsoils analysed, ranges from 4,1% C (The A 11 horizon of a Bonheim soil sampled on the Hantam mountain near Calvinia in Region 3) to zero (many topsoils in map unit B in Regions 1 and 2) with a mean of 0,38% C. There is a decrease in carbon content with depth in all profiles analysed.

The relationship between soils, landscape and geology is shown schematically in Figure 4 for the area between the coast (Region 1) and the Escarpment (Region 3) near Calvinia. Figure 5 shows soil-landscape relationships for the area between the Kamies mountain, south of Springbok (Region 1), and Commissioner's Salt Pan, west of Brandvlei (Region 2).

RED AND YELLOW, APEDAL TO WEAKLY STRUCTURED, FREELY DRAINED SOILS (MAP UNITS A, B, C AND D)

Classification

This class refers to yellow and red soils of varying thickness, without water tables and belonging to one or more of the following soil forms: Hutton, Clovelly and Oakleaf (reddish coloured series). To fall in this class, one or more of these soils must occupy at least 40% of the land. Unit A (red and yellow dystrophic and/or mesotrophic soils) indicates land where moderately leached soils are dominant. In unit B red high base status soils dominate with yellow soils (Clovelly) covering less than 10% of the area. Land with red and yellow high base status soils, where red and yellow soils each cover more than 10% of the area, is denoted by the

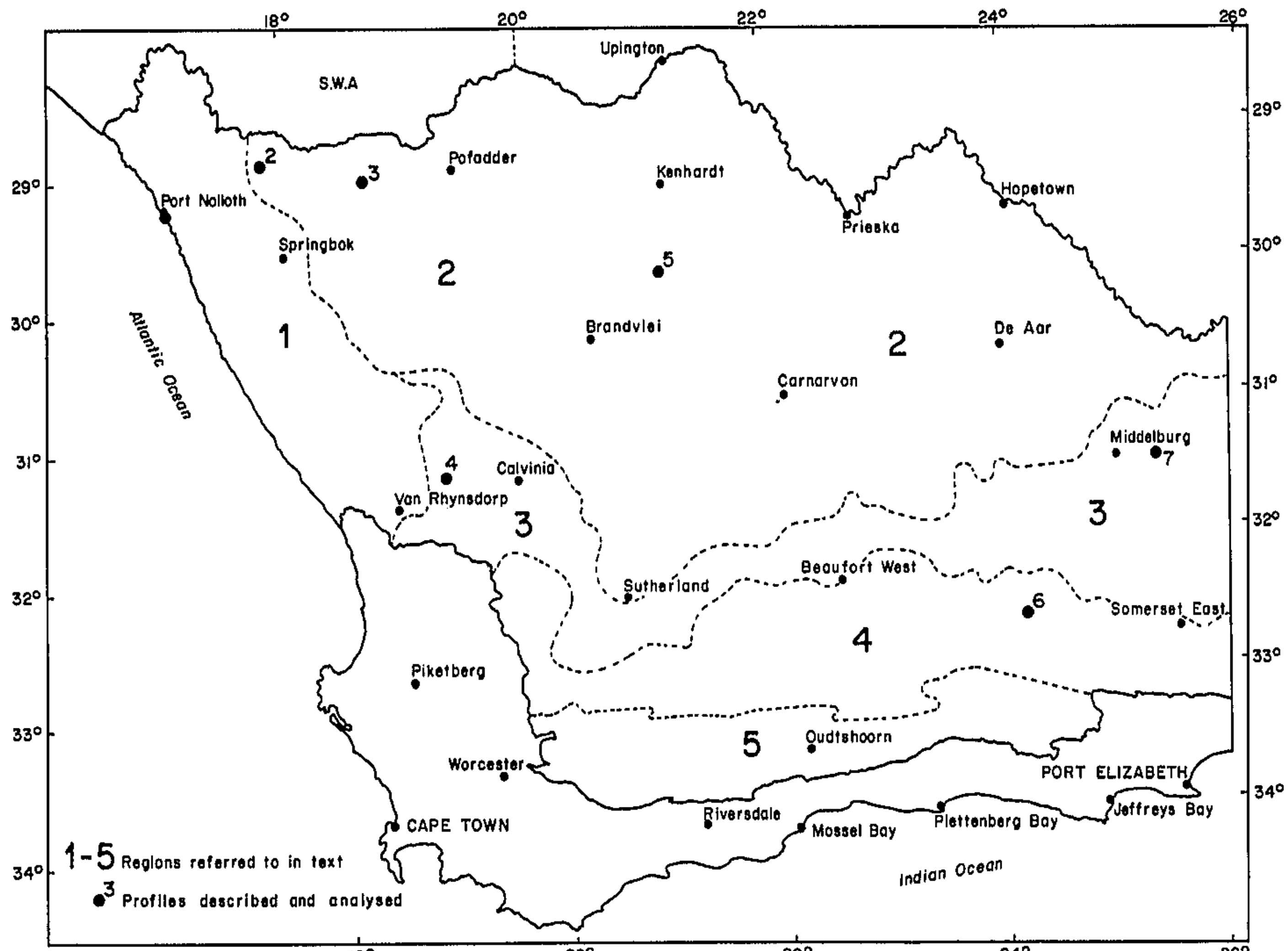

FIGURE 2. Part of South Africa, showing the five regions of the Karoo and the profile positions referred to in the text.

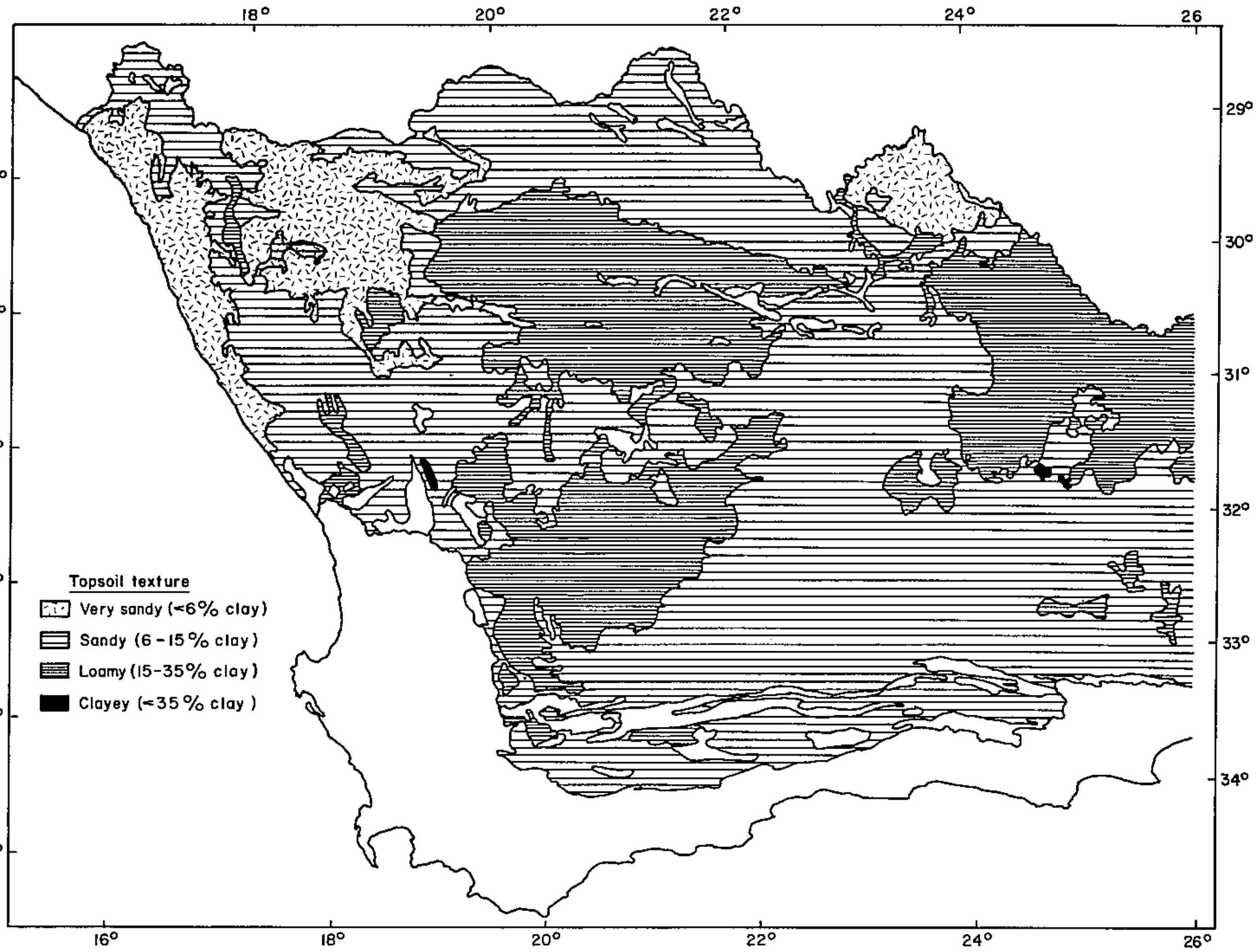

FIGURE 3. Topsoil (A horizon) texture classes.

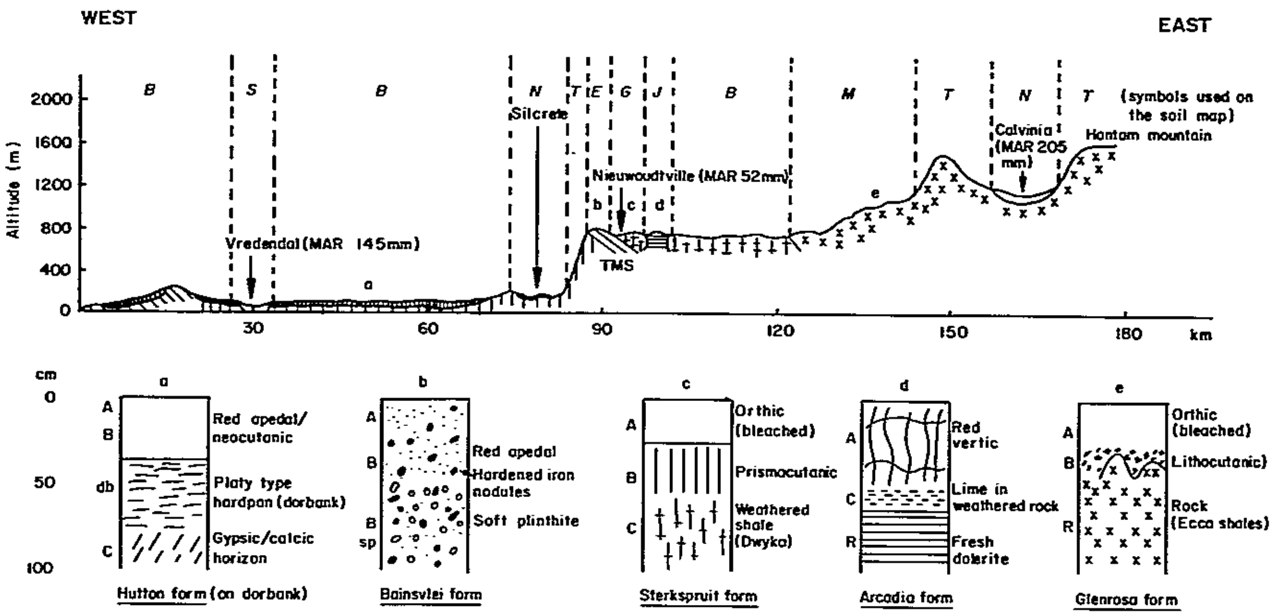

FIGURE 4. Schematic cross-section from the coast (at Strandfontein) to Calvinia showing the soils and substrata associated with this landscape.

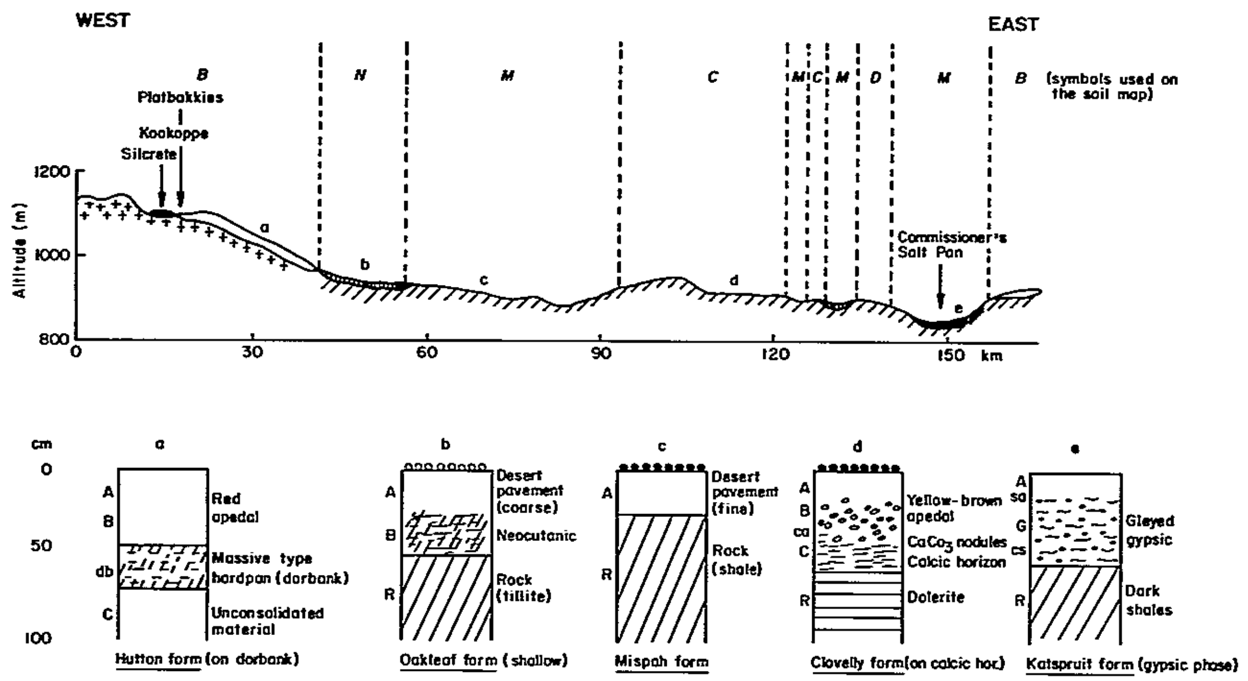

FIGURE 5. Schematic cross-section from Platbakkies (west) to Commissioner's Salt Pan (east) in Bushmanland showing the soils and substrata associated with this landscape.

symbol C. In unit D, yellow high base status soils dominate with red soils covering less than 10% of the area.

Distribution

Soils of unit A are limited to small areas in Regions 3 and 5 and because of their limited occurrence, are not discussed further. Soils of unit B occur in all five regions but are particularly common in Regions 1 and 2 where granite and dolorite are their main parent materials. In the other regions they are found chiefly developed in pedisediments. Soils of unit C occur mainly in Regions 1 and 2. In Region 1 they occur near the coast as a transition zone from the yellow soils (unit D at the coast) to the reddish soils of unit B further inland. In Region 2 they are prominent in the area underlain by Dwyka tillite.

Soils of unit D only occur in Regions 1 and 2. In Region 1 they occur in areas more or less parallel to the coastline immediately inland from the grey regic sands of unit P; in Region 2 they are associated with dolerite in the area surrounding Carnarvon.

Morphological, physical and chemical properties

Map unit B

Morphologically, four dominant soil types may be recognized, namely:

B1: Deep uniform coarse textured (sand) soils with minimal profile development. The uniform reddish colour is due to the coating of iron oxides around siliceous sand grains. These soils are associated with dune areas in Regions 1 and 2 (see profile 3, Tables 1 and 2).

B2: Shallow (less than 400 mm) usually coarse textured (sand to loamy sand) soils overlying a reddish coloured hardpan (duripan, locally known as "dorbank") (see profile 2, Tables 1 and 2). These soils occur mainly in Regions 1, 2 and 5 on flat-lying "drowned" landscapes such as the Annis Plain, an area some 30 km to the east of Alexander Bay in Region 1 near the village of Khubus (Figure 6). They are also associated with deep, reddish coloured pedisediments (called "deflation residue" by De Villiers and Söhnge 1959). Dorbanks are very common in the western and southern arid to semi-arid parts of South Africa as well as in the south of South West Africa/Namibia (Ellis and Schloms 1982). These soils generally have high to very high pH values (pH_{H_2O} 8,0) in the horizons above the dorbank.

B3: Shallow (less than 400 mm) usually coarse textured (sand to sandy loam) soil overlying hardpan calcrete or a calcareous horizon. These soils mainly occur in Region 2 and are prominent in the Kalahari sand area eg Prieska-Hopetown and in the interdune areas in the granite landscape of the Springbok-Pofadder-Kenhardt area. The most common calcrete is that defined as hardpan calcrete by Netterberg (1980). Although sometimes higher than pH 8,4, topsoil reaction is usually in the range of pH 7,0-8,4.

B4: Soils of varying depth, usually medium textured (sandy loams to sandy-clay loams) overlying rock (mostly dolerite) or which have developed in pedisediment or alluvium. These soils mainly occur in Regions 2, 3 and 4. In Region 5 they are associated with the Cretaceous Enon Conglomerates.

Map unit D

Morphologically two main soil types may be recognized in map unit D.

D1: Moderately deep uniform coarse textured (sand) soils occurring in Region 1. Usually underlying the yellowish sand is a more clayey neocutanic horizon characterized by high exchangeable sodium percentage (ESP) values (often higher than 25), low resistance values (less than 120 ohms) and high to very high pH_{H_2O} values (6,5-9,5).

D2: Shallow to moderately deep, calcareous, medium textured (sandy clay loam) soils, mainly occurring in Region 2 and which are mostly associated with dolerite. Calcrete and calcareous horizons are associted with these soils.

Map unit C

Soils in Region 1 are calcareous, deep, uniform, coarse textured (sand) with minimal profile development. Soils in Region 2 are usually medium textured (sandy loam to sandy-clay loam) and calcareous throughout the profile. They are usually associated with Dwyka tillite and their surface is covered by a prominent layer of stones (desert pavement).

Natural fertility status

Map unit B

B1: (vide supra): A horizons are generally low in most plant nutrients but consistently low in copper and zinc.

B2: A horizons are generally rich in most plant nutrients and potassium seems to be consistently high to very high.

B3: P status is generally medium for most A horizons but low values have been reported for certain sandy topsoils in Region 2. In Region 1 most A horizons have high to very high P status. K-status seems to be consistently high to very high for most A horizons. Of the micro-nutrients only copper and zinc appear to be medium to low.

B4: These are generally rich in most plant nutrients.

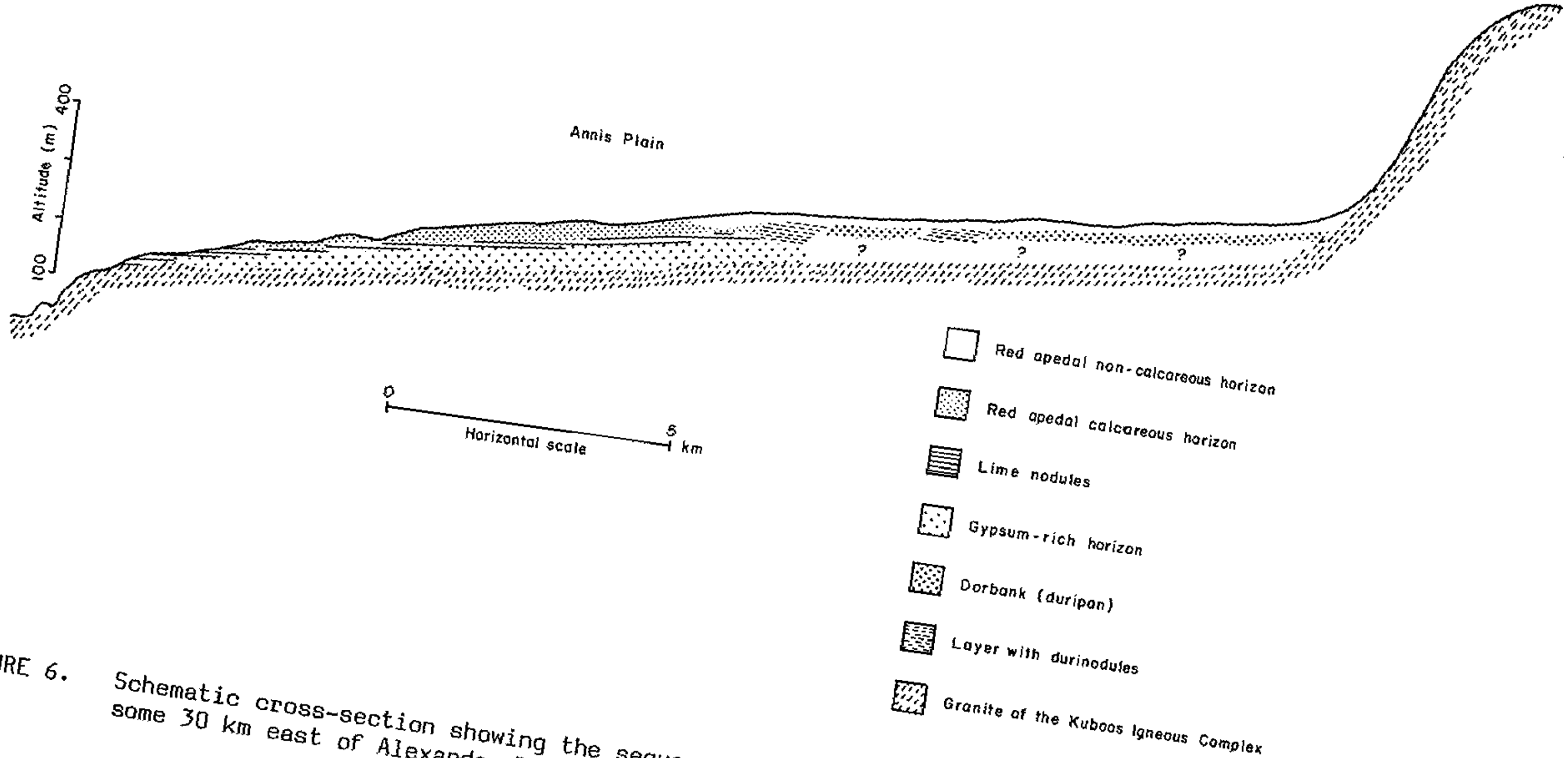

FIGURE 6. Schematic cross-section showing the sequence of soils that occur on the Annis Plain, an area some 30 km east of Alexander Bay (after Ellis 1980).

Map unit C

The sands in Region 1 appear to be high to very high in all plant nutrients except zinc. Low zinc values have been reported for some A horizons. The soils associated with Dwyka tillite in Region 2 appear to be rich in plant nutrients.

Map unit D

D1: All plant nutrients except zinc appear to be high or very high in the A horizons of these soils. Low zinc values have been reported for some A horizons.

D2: These are generally rich in most plant nutrients.

Land use

Map unit B

B1 and B3 soils are used for extensive grazing only. B2 soils are used mainly for extensive grazing, although in the Vredendal area they carry irrigated vineyards after physical break-up of the dorbank layer. B4 soils are mainly used for grazing. Some are used for cultivation under irrigation in the vicinity of rivers.

Map units C and D

All soils mentioned under these map units are used exclusively for extensive grazing.

Genesis

The soils have formed in aeolian material, pedisediments, alluvium or developed in situ from granite, dolerite and Dwyka tillite. The main soil forming processes have been weathering under conditions of high base saturation and some clay eluviation, especially in areas with a mean annual precipitation (MAP) in excess of 300 mm. Under the more arid (MAP less than 300 mm) coditions, gypsum and other more soluble salts released from weathering have accumulated in the lower part of the profile.

PLINTHIC AND DUPLEX SOILS (MAP UNIT E)

Classification

This class includes soils that have or have had water tables (as indicated by the presence of plinthite, gleyed material or ferricrete). More than 20% of the area is covered by soils of one or more of Bainsvlei, Avalon Longlands, Westleigh, Glencoe and Wasbank forms or Klipfontein series (Mispah form). Hydromorphic duplex soils (Kroonstad and occasionally Estcourt form) also occupy more than 20% of the area.

Distribution

Soils of this class only occur in Region 3 on the western fringe of the gently sloping plateau at Nieuwoudtville (Figures 1 and 3).

Morphological, physical and chemical properties

On certain higher lying parts, ferricrete outcrops occur, for example on the farms Lokenburg and Brakputs. The soil profile overlying the two metres deep ferricrete is the dystrophic Hutton series, while the ferricrete itself is a nodular to vesicular material overlying pale coloured weathered sandstone saprolite. Other plinthic soils (Bainsvlei, Avalon and Glencoe forms) found in this landscape are also moderately to highly leached) (dystrophic to mesotrophic) with textures ranging from coarse sandy loam to sandy-clay loam in the B horizon. The duplex soils found in association with the plinthic soils are characterized by a coarse sand abruptly overlying a gleyed clay at about 1 000 mm depth. The plinthic soils have pH less than 6,0 in all horizons.

Natural fertility status

Little is known about the natural fertility status, but it is expected to be low with regard to most plant nutrients.

Land use

The soils are used mainly for pastures and the production of wheat during winter.

Genesis

Although duplex soils also occur, the occurrence of low base status red and yellow, highly weathered plinthic soils under a mean annual rainfall of 350 mm, concentrated in the winter, indicates an old land surface and possibly paleosols. The presence of plinthite is no doubt due to the presence of flat-lying sandstones and quartzites. The ferricrete cappings are certainly relict features but the soft plinthic soils which occur in the lower parts of the landscape appear to be in phase with present-day soil forming processes.

DUPLEX SOILS (MAP UNITS F, G AND H)

Classification

This class (units F and G) refers to soils in which the clay percentage of the B horizon is at least twice that of the A horizon, with A/B horizon boundaries clear to abrupt. Soils with duplex character cover at least 40% of the area. In unit F, duplex soils with red B horizons dominate while non-red B horizons are dominant in soils of unit G. In unit H 10% or more of the land, in addition to the duplex soils present, is also occupied by one or more of the following: Shortlands, Bonheim, Inhoek or May forms.

Distribution

Map units F and G

These soils occur in all five regions but are especially prominent in the higher rainfall areas (MAP greater than 300 mm) of the Karoo such as along the Escarpment (Region 3) and in eastern parts of the Upper Karoo (Region 2) and Great Karoo (Region 4). The parent materials are mainly Karoo System shales or shale-derived pedisediments. The terrain is usually level to near-level.

Map unit H

The soils occur only as isolated patches in parts of Region 3 associated with dolerite.

Morphological, physical and chemical properties

Map units F and G

The distinguishing characteristics of these soils are a massive to platy structured, coarse to medium textured (loamy sand to loam) relatively pale coloured A horizon overlying a moderately to strongly structured B horizon. In some places the pale horizon has been sufficiently hydromorphically reduced for an E horizon to be identified above the structured B horizon. Available data indicate that the B horizons of these soils have relatively high exchangeable sodium (ESP greater than 15) or magnesium percentages and it is expected that the dominant clay-mineral present would be of the 2:1 type (see profile 7, Tables 1 and 2).

Map unit H

The duplex soils in this class have similar properties to those in map units F and G above. The additional soils show a well structured (usually dark coloured) A horizon.

Natural fertility status

Map units F and G

Little information is available on the P status of A horizons but available data show high to very high amounts of potassium, copper and boron but low zinc values.

Map unit H

Little information is available but it is expected to be rich in most plant nutrients in soils with well structured A horizons.

Land use

The soils are used for extensive grazing.

Genesis

The duplex soils tend to develop on level or near-level terrain under a mean annual precipitation in excess of 300 mm on sodium rich Karoo System shales or shale-derived pedisediments. These conditions favour high ESP values, chemical dispersion of soil clays, and pronounced lateral and vertical translocation (eluviation) of clay and formation of structured B horizons. Swelling and shrinking of the partially sodium-saturated clays following wetting and drying, contribute to the development of the strong structure of the B horizon. The reddish coloured duplex soils of map unit F appear to have developed in parent materials slightly richer in dolerite weathering products. The formation of the structured A horizons in map unit H referred to above is discussed together with the genesis of soils of map unit J below.

SOILS WITH RED VERTIC AND RED STRUCTURED DIAGNOSTIC HORIZONS (MAP UNIT J)

Classification

This class refers to land with high base status soils in which strongly structured swelling clay-soils cover more than half of the area. Dominant soil forms are Arcadia and Shortlands.

Distribution

These soils occupy very small areas in Region 3 with a relatively high precipitation (MAP about 350 mm) and where dolerite is the parent material. The main occurrence is about two kilometres east of Nieuwoudtville (Figure 3).

Morphological, physical and chemical properties

These soils are strongly structured with more than 45% clay in the A or B horizon. Plasticity index values are in the range 25-35. The soils with vertic horizons show prominent vertical cracks in the dry state while the surface is typically self-mulching. The soils are all base-saturated with Ca and Mg the dominant cations on the exchange complex (see profile 4, Tables 1 and 2). Soil reaction is neutral to alkaline, while lime (either as soft powder or a slightly hard calcrete layer) is usually found in the C horizon.

Natural fertility status

Data available on the natural fertility status of these soils are limited but they are expected to be rich in most plant nutrients.

Land use

In the Nieuwoudtville area these soils are used for dryland cultivated pastures, wheat production and extensive grazing.

Genesis

The mean annual rainfall (concentrated in winter) of approximately 350 mm seems to have been able to produce smectitic red clays from dolerite.

SHALLOW SOILS OF PEDOLOGICALLY YOUNG LANDSCAPES (MAP UNITS K, L, M AND N)

Classification

This class refers to land of pedologically young landscapes typified by rock, shallow upland soils and shallow recent alluvial deposits. In units K, L and M, Glenrosa and Mispah forms dominate although Cartref form does also occur in unit K. Unit N represents weakly structured soils (mainly Oakleaf form) developed in pedisediments overlying hard rock at shallow depth (less than 1 000 mm). Presence of lime has been used in map units K, L and M as an indication of degree of leaching to which these landscapes have been subjected. In unit K, lime is rare or absent in the entire landscape, in L, lime occurs only in soils of low-lying positions (valley-bottoms) while in unit M, lime is formed in upland and bottomland positions.

Distribution

Soils in this grouping (units K, L M and N) are by far the most widespread of all the soils in the karoo region and occur in all five regions. However, they are particularly prominent in Regions 2, 4 and 5. Although parent material plays a part, the distribution of lime in the landscape broadly reflects the extent to which these young landscapes have been leached and hence is also a reflection of rainfall. There is no lime in the higher rainfall (MAP greater than 300 mm) TMS mountains in the south. Soils rich in lime are associated with the low rainfall (MAP less than 200 mm) and karoo sediments of Regions 2 and 4. Shallow soils of the Oakleaf form, developed in transported material (unit N), occupy large areas of Regions 2 and 4. These are generally associated with low-lying, flat pediment slopes, smaller pans or playas and the extensive pans or "vloers" such as Verneukpan, north-east of Brandvlei.

Morphological, physical and chemical properties

Soils are usually shallow (less than 300 mm to hard rock or calcrete) with A horizons ranging in texture from sand to loamy sand (unit K) to sandy loam and sandy-clay loam in units L and M. Lime may be absent (unit K and L) or present (unit M) in the solum or underlying rock.

In the Brandvlei-Carnarvon area (Region 2) soils are characterized by an abundance of $CaCO_3$ in both the solum and underlying parent rock. Calcans and palygorskans are common on peds in the lower part of profiles and in the underlying rock or saprolite. The total lime content in soils of unit M gradually decreases from Brandveli (west) to De Aar (east) in Region 2 as rainfall increases (see profiles 5 and 6, Tables 1 and 2).

Natural fertility status

In general, the A horizons of soils of units L, M and N are rich in most plant nutrients, but very high values for zinc and boron have been recorded in soils (unit N) of depression areas (see profile 5, Table 2). Little is known about the natural fertility status of A horizons for soils of unit K but due to their quartzite and sandstone origins, they are expected to have a medium to low plant nutrient status.

Land use

This land is used for extensive grazing.

Genesis

Soils of unit K, L and M are found in young landscapes where the dominant landscape process is one of erosion. Soil forming processes are rock weathering, the formation of orthic topsoil horizons and, commonly, some clay illuviation, giving rise to lithocutanic horizons. In unit N the dominant landscape process is one of deposition, giving rise to shallow transported material overlying rock. Because of the slow rate of soil formation under these arid conditions (MAP less than 300 mm), very little soil formation has taken place in the deposits of unit N; some clay illuviation has taken place as well as a reorganization of the material in the position of a B horizon, obliterating any depositional stratifications that may originally have been present.

GREY REGIC SANDS (MAP UNITS P AND R)

Classification

This class indicates areas where deep grey sands are dominant. In unit P, soils of the Fernwood form cover 80% or more of the area while in unit R, Fernwood soils cover 20-80% of the area. Soils found in association with Fernwood in unit R include Vilafontes, Clovelly and, occasionally, Kroonstad and Pinedene forms.

Distribution

These soils are formed in aeolian deposits along the West Coast in Region 1. Soils of unit P occur as a discontinuous, narrow strip along the coastline. Soils of unit R are limited to small depression areas inland and adjacent to unit P.

Morphological, physical and chemical properties

Soils of unit P are generally deep, usually calcareous throughout with little or no horizon differentiation (see profile 1, Tables 1 and 2). In unit R, it is common to find Vilafontes soil form where a more clayey horizon occurs in the subsoil. These clayey horizons are generally characterized by high ESP values (greater than 25), low resistance values (lower than 120 ohms) and neutral to very high water pH (6,5-9,5) values.

Natural fertility status

Map units P and R

Copper and zinc status seems to be consistently low in all horizons while, surprisingly, it appears that P status is always high to very high in the A horizon. Other plant nutrients seem to be high.

Land use

Soils of unit P are seldom used for any farming activity, while those of unit R are used for extensive grazing.

Genesis

In unit P, the soils are developed in beach-derived aeolian sands, the calcareous fraction consisting largely of fragments of seashells and other marine skeletons. Soil formation is minimal. The genesis of soils of unit R is not yet fully understood. However, it seems that periodic flooding of red sands has caused reduction and removal of iron oxide coatings, removal of carbonates and clay illuviation.

DEEP UNCONSOLIDATED DEPOSITS (MAP UNIT S)

Classification

At least 60% of the area consists of young, deep, unconsolidated deposits which are not grey regic sands. Soils are usually stratified and weakly structured and occur mainly on alluvial river terraces. Common soil forms are Oakleaf and Dundee.

Distribution

These are deep (greater than 1 000 mm) soils on unconsolidated deposits along river terraces, mainly in Regions 2, 4 and 5. Examples of such soils are those found along the Sak River (near Brandvlei-Region 2), the Orange River, especially between Upington and Kakamas (Region 2) and the Olifants River in Region 5 near Oudtshoorn.

Morphological, physical and chemical properties

These non-red, stratified to weakly structured alluvial soils have A horizon textures ranging from sandy loam to sandy-clay loam, with a slight increase in clay content with depth in the non-stratified members. They are usually calcareous in the subsoil but often they are calcareous throughout (eg along the Sak River).

Land use

Where irrigation water is available (eg Upington, Oudtshoorn or Vredendal), these soils have a high potential for a range of crops. Many rivers in the Karoo are for the most part dry and only contain water after rainstorms. In many places (eg along the Sak and Tanqua Rivers) large basins, several hectares in extent, are constructed in the alluvial terraces to receive floodwaters which are then used to grow crops such as wheat. This is known as the "saaidam" method of irrigation.

Genesis

Because of the slow rate of soil formation under these arid conditions, little soil formation takes place other than some clay illuvation and lime precipitation in the subsoil.

OTHER SOILS (MAP UNIT T)

This class indicates soils of mountainous areas, difficult to accommodate in any one of the above-mentioned map units because of the variability in soil pattern and the fact that large areas are covered by exposed country, rock, stones and boulders. Because access is difficult, comparatively little information has been collected. However, it is known that soils belonging to almost all soil forms with orthic, melanic and occasionally, vertic diagnostic horizons occur in this unit. For example, a Houwhoek profile (podzol) was found near the summit of the Swartberg mountain pass between Oudtshoorn and Beaufort West.

Morphological, physical and chemical properties and natural fertility status will vary considerably. These soils can only be used for extensive grazing.

SOIL EROSION IN THE KAROO

Sheet, gully and rill erosion are known to be especially prominent in the eastern parts of the Karoo, especially in the area east of De Aar (Region 2) and Middelburg (Region 3). These areas are dominated by duplex soils with leached A horizons of units F and G. Water infiltration is poor and B horizons are in a dispersed condition in these soils.

The low infiltration rates are probably due to duplex profile morphology (units F and G), a low "free" iron content in the topsoil (Ellis and Lambrechts 1983) and relatively high ESP values. These properties, together with the action of falling raindrops, cause dispersion and a breakdown of soil aggregates at the surface which lead to sealing (Shainberg and Letey 1984).

Wind erosion is especially severe in areas where coarse textured (less than six per cent clay) A horizons occur, for example along the west coast (Region 1) or the inland dune areas (Region 2). The distribution of soils with coarse textured A horizons in the karoo region is shown in Figure 3.

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CHAPTER 3. CLIMATE

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INTRODUCTION

The climate of the karoo biome is determined mainly by:

- degree of latitude
- distance from the sea
- height and topography.

In terms of latitude, the area falls under the influence of the subtropical high pressure belt, with its characteristic dry, upper air. On account of distance from the sea, the moderating maritimal influence of the ocean is lacking. Height and topography have a great influence, especially on the temperature and rainfall regime.

For the rainfall analysis, data from 81 stations were used, as well as from the relatively long records of regional rainfall (Weerburo 1972). Data from only 40 stations were available for the analysis of temperature and evapotranspiration.

A brief description of the pattern of the most important climatic factors is given below.

RAINFALL

General

Average annual rainfall decreases westwards from approximately 500 mm in the east to less than 100 mm over the north-western areas (Figure 1). Over the high-lying parts in the south-west, south and south-east, annual rainfall of up to 600 mm occurs.

Similarly, the number of rainy days per year shows a decrease from east to west. The average number of days per year with a rainfall of 10 mm or more, ranges for example from approximately 18 in the east to less than five in the west.

With the exception of the south-western parts, the major part of the area receives mainly summer rain. In Figure 2, rainfall in the summer season (October-March) is expressed as a percentage of the mean annual rainfall.

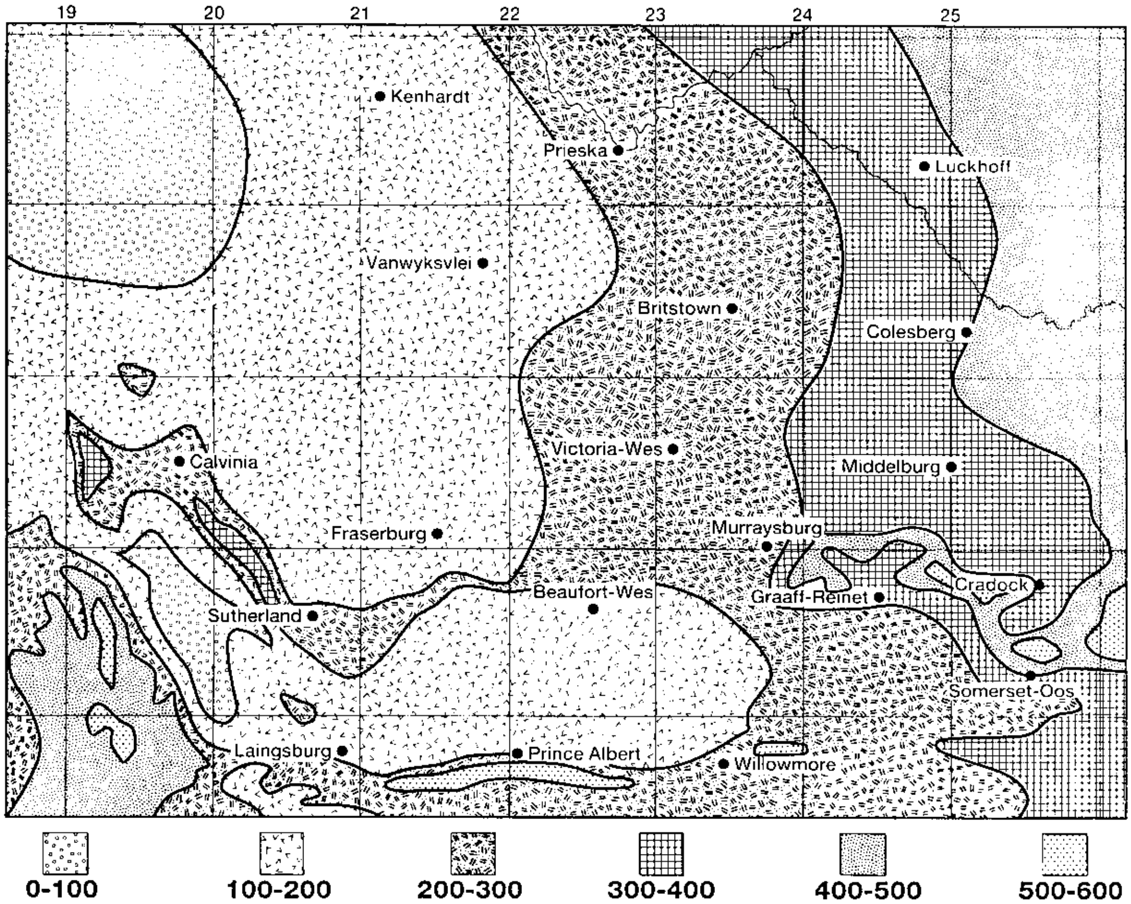

FIGURE 1. Isohyets of mean annual rainfall (mm) for the karoo biome.

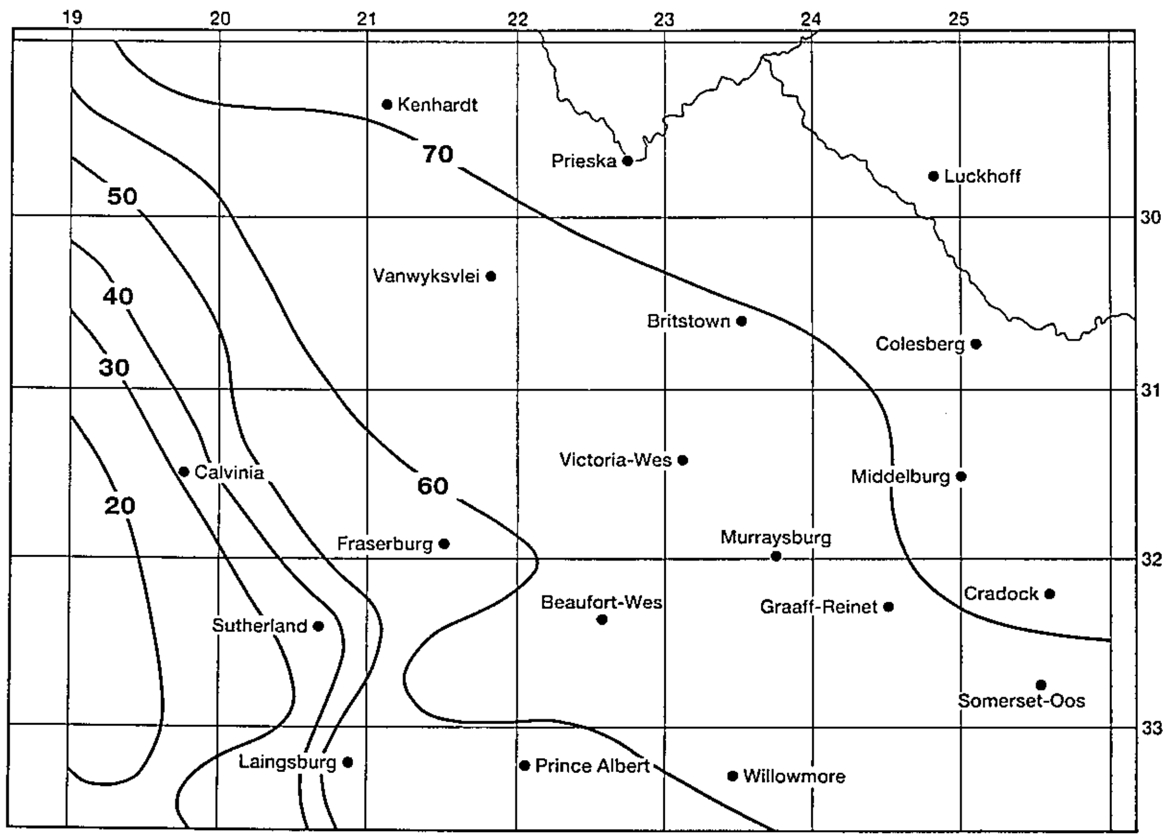

FIGURE 2. Geographic distribution of summer (October-March) rainfall as a percentage of mean annual rainfall.

Further analysis of the seasonal variation shows there is more rain in autumn than in spring. The difference between autumn and spring rain, when expressed as a percentage of the average annual rainfall, varies from five per cent in the south-east and south-west to just over 25% in the north (Figure 3).

The reliability of the rainfall diminishes rapidly from south to north. Figure 4 shows the percentage frequency of years of rainfall greater than or equal to 85% of the average. According to the Figure, the frequency decreases from more than 70% in the south-east and south-west to less than 50% in the north.

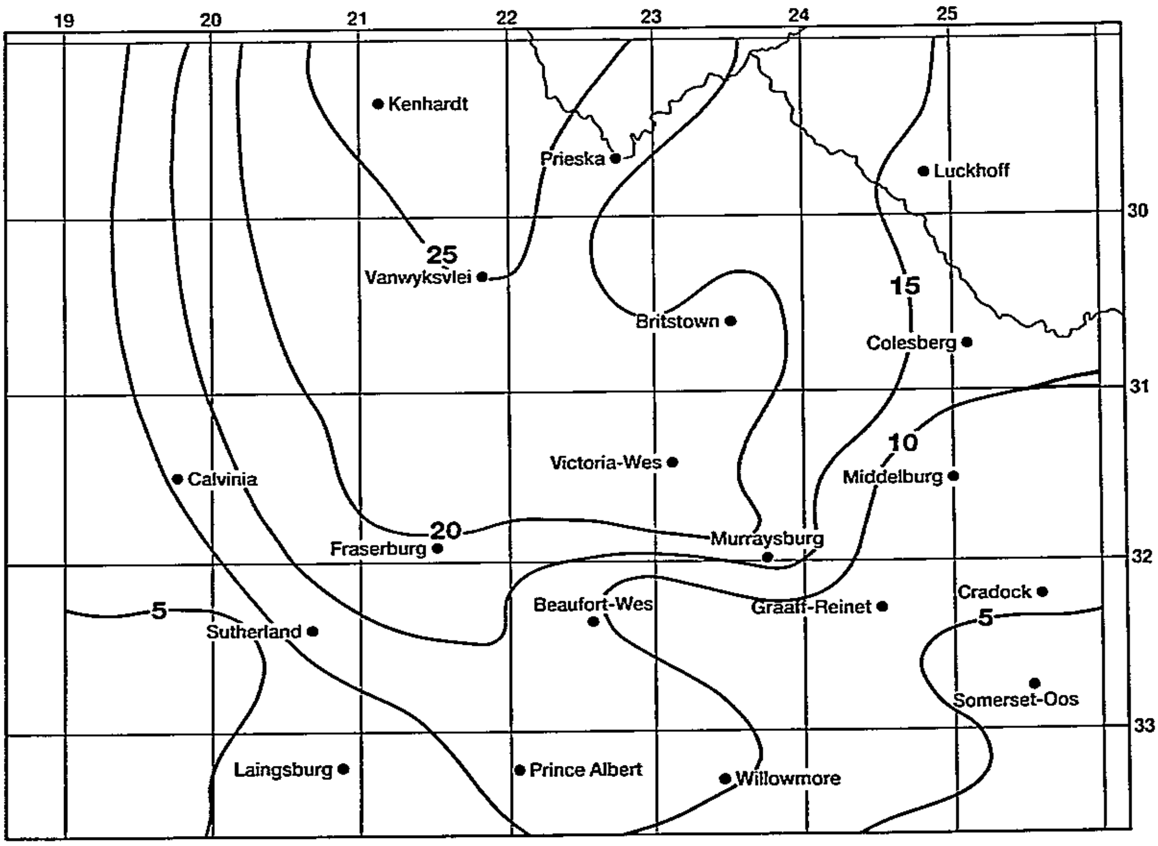

FIGURE 3. Geographic distribution of excess of autumn over spring rain, expressed as a percentage of mean annual rainfall.

Drought occurrence

The frequency of droughts is given in Table 1. The criterion used for defining a drought is a 12-month rainfall total below 60% of the average annual rainfall. The rainfall regions are based on the Weather Bureau's classification of homogeneous rainfall regions as indicated in Figure 5.

A month preceded by 12 months during which the total rainfall is below 60% of the average, should in fact be characterized by poor grazing conditions. It is clear from the Table how often severe droughts occur, especially in Region 10 (see also Roux 1980).

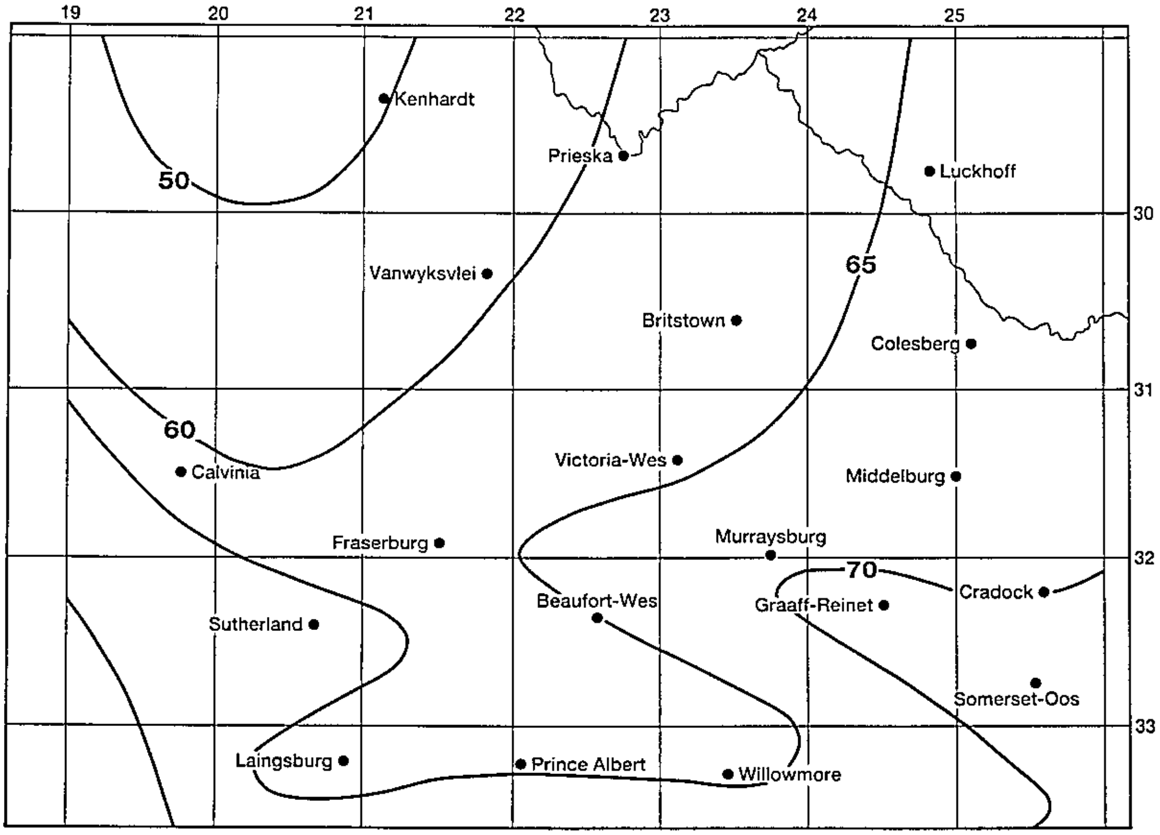

FIGURE 4. Geographic distribution of the reliability of annual rainfall. Reliability is expressed as the percentage of years with rainfall greater than or equal to 85% of the mean annual rainfall.

TABLE 1. Frequency of occurrence of consecutive months which are preceded by 12 months with a rainfall total of 60% of the mean annual rainfall (from Weerburo 1960)

Rainfall region	Number of consecutive months														Percentage of drought months
	1	2	3	4	5	6	7	8	9	10	11	12	19	20	
2	1	4			1			2		1	1	1			8,74
5	2	1			2	1		1	1						6,31
6	2			2	2					1					4,03
9	9	4				1							1		5,51
10	5	3		3					1		2	1		1	11,96
11	4	3				1	1				1			1	7,37
12	4			1	1										1,59
13	5	2			1				1	1	1			1	8,57
15	6	2		4						1					5,14

The rainfall of the karoo biome is therefore subject to extended periods during which there occur regular decreases and increases in five-year running averages. These circumstances hold special implications for the carrying capacity dynamics of the veld.

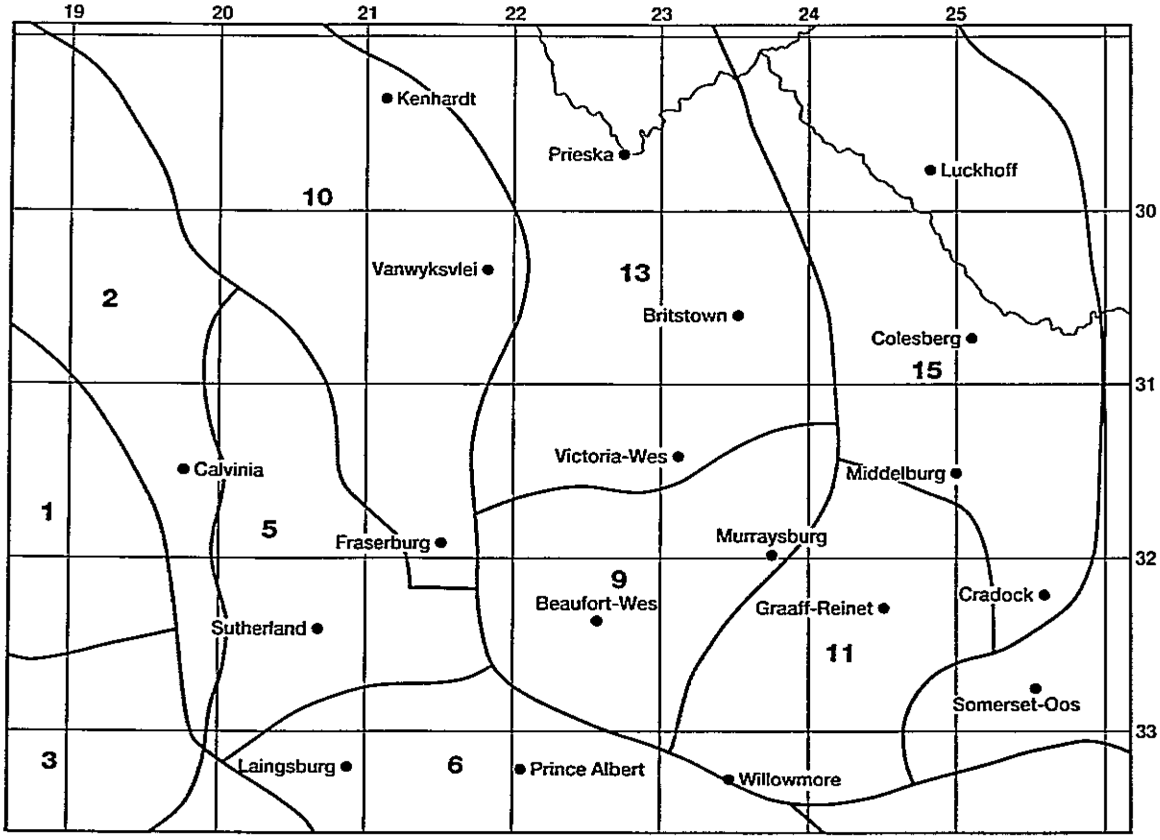

FIGURE 5. Rainfall regions according to Weerburo 1960.

South African rainfall data, have in the past few years enjoyed considerable attention and various publications in this connection have recently appeared. Amongst others are those of Tyson and Dyer (1975, 1978), Louw (1980) and Van Rooy (1980).

Rainfall data on a regional basis for the period 1878-1958 and 1921-1975 appear in Weerburo (1960) and Van Rooy (1980) respectively. The Weather Bureau's classification of rainfall regions for the former period is shown in Figure 5 and for the latter period, in Figure 6.

In order to investigate the occurrence of possible cycles in the rainfall of the karoo region, five-year running averages of the above-mentioned rainfall data, (which covers the greatest proportion of the karoo region), were analysed and are given in Figure 7. Curve A is based on data for areas 9, 10, 13 and 15 for the period 1886-1958 (from Figure 5); while curve B applies to areas 36, 52, 68, 69, 81, 70, 55, 54, 31, 38, 19, 15, 53, 40 and 41 for the period 1921-1975 (from Figure 6). The difference between the two curves can be ascribed to the difference in size of the two areas and an improved distribution of rainfall stations for the second period.

From the analyses (see also Louw 1980) it is apparent that there were approximate midpoints of dry and wet periods as follows:

- Wet: 1892, 1909, 1919, 1940, 1957, 1973
- Dry: 1904, 1914, 1929, 1947, 1966.

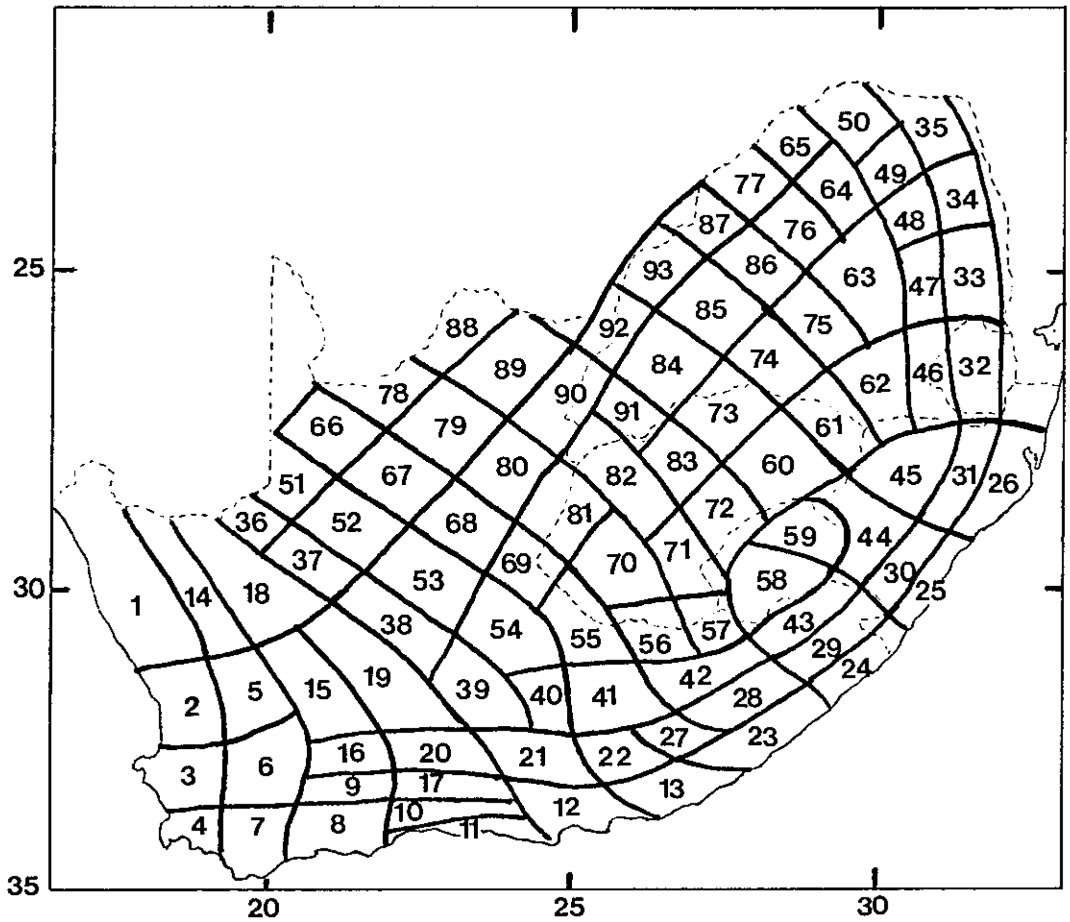

FIGURE 6. Rainfall regions according to Weerburo 1960.

It is clear that there are signs of a 15-20 -year oscillation from about the twenties, but this was preceded by oscillations with shorter periods. The 15-20 -year oscillation lends support to the quasi 20-year oscillation determined for the summer rainfall region by Tyson et al (1975).

The question now arises whether these findings can in any way be used to predict future rainfall occurrences.

In view of the fact that there is no certainty that the most recent cyclical pattern will continue, it must be concluded that it would be extremely daring to use the relatively short rainfall records available for predictive models. For further opinions, the works of Louw (1980) and Markham (1980) may be consulted.

Pittock (1978) states the following:

> "Climatic data series are notoriously unstable in their statistical properties, ie they tend not to be statistically "well behaved". It behoves us therefore to move with great caution from a true description of a past or given data set to a generalization about all such data sets, such as would be useful for prediction."

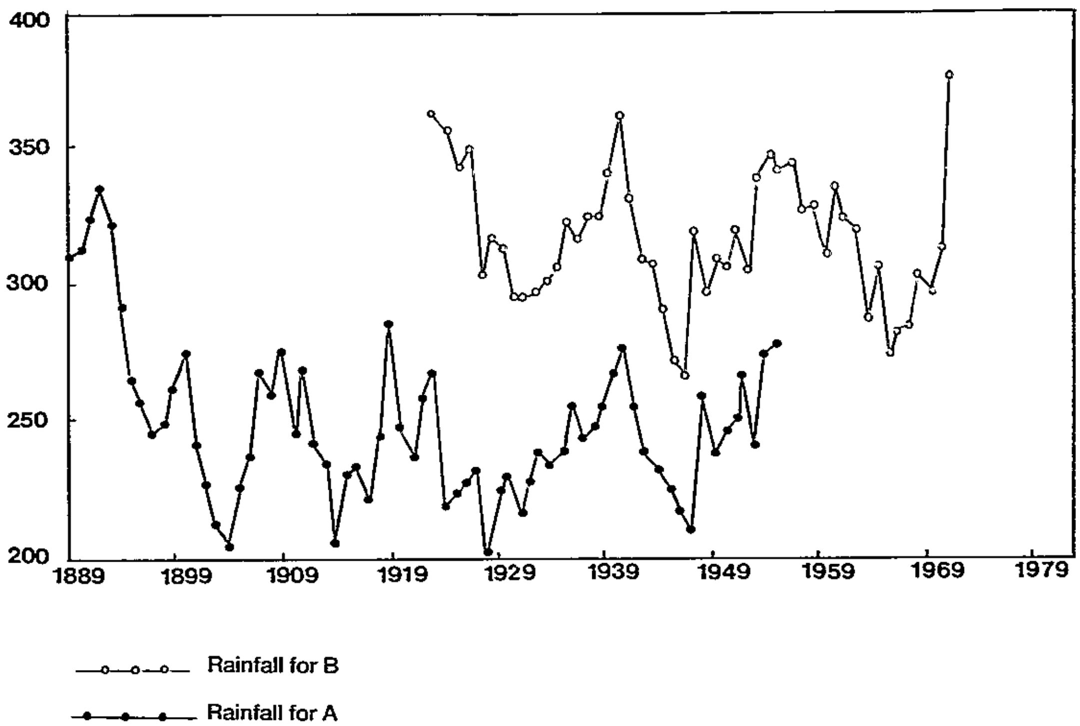

FIGURE 7. Pattern of five-year running average rainfall for the karoo biome. Curve A indicates values for the regions 9, 10, 13, 15 (see Figure 5) and Curve B indicates values for the regions 15, 19, 31, 36, 38, 40, 41, 52, 53, 54, 55, 68, 69, 70, 81 (see Figure 6).

AIR TEMPERATURE

One of the most outstanding characteristics of the temperature regime of the region is the large temperature fluctuation both daily and seasonal. A range of 25°C between day and night is not unusual.

The isotherms of the average annual temperature (Figure 8) follow more or less the contours with a minimum belt of below 15°C which extends from Sutherland in an east-north-easterly direction. Furthermore there is a rapid increase in a northerly direction. This tendency is also conspicuous on other temperature maps (Figures 9 to 11) which are self-explanatory. Of note is the high frequency of days with a maximum temperature above 30°C in the north (Figure 10) and the high occurrence of days with a minimum below 0°C in the cold belt over the central parts (Figure 11).

The start and end point of frost and the duration of the potential frost period has important ecological implications. Kotze (1980) calculated the probability of the occurrence of different temperatures for a number of stations. According to him, there is an 80% probability that temperatures of 0°C will not occur before or after the dates indicated in Table 2.

According to the Table, the potential frost period varies from as long as 183 days in the high-lying parts at Sutherland to only 53 days at Kenhardt.

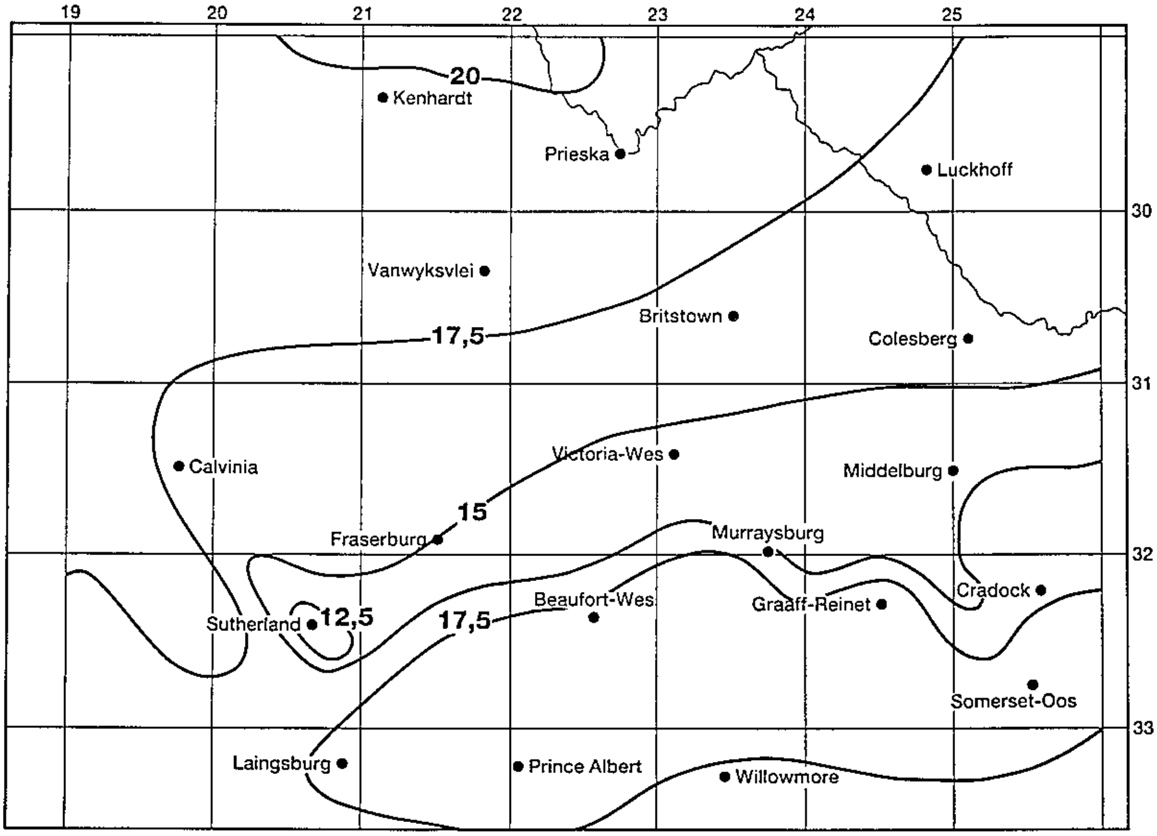

FIGURE 8. Isotherms for mean annual temperature in the karoo biome.

TABLE 2. Apparent start and end points of frost in the karoo biome

	Start	End	Duration of frost period
Sutherland	23 April	22 October	183 days
Kenhardt	17 June	8 August	53 "
Willowmore	25 May	28 August	97 "
Van Wyksvlei	7 June	18 August	73 "
Fauresmith	13 May	12 September	123 "
Victoria West	7 May	25 September	142 "
Middelburg	2 May	5 October	158 "

WATER ECONOMY

The annual potential evapotranspiration for a short period, calculated by Louw and Kruger (1968) by means of the Penman-formula, is given in Figure 12. There is a rapid increase northwards from 1 600 mm in the south to 2 200 mm in the north.

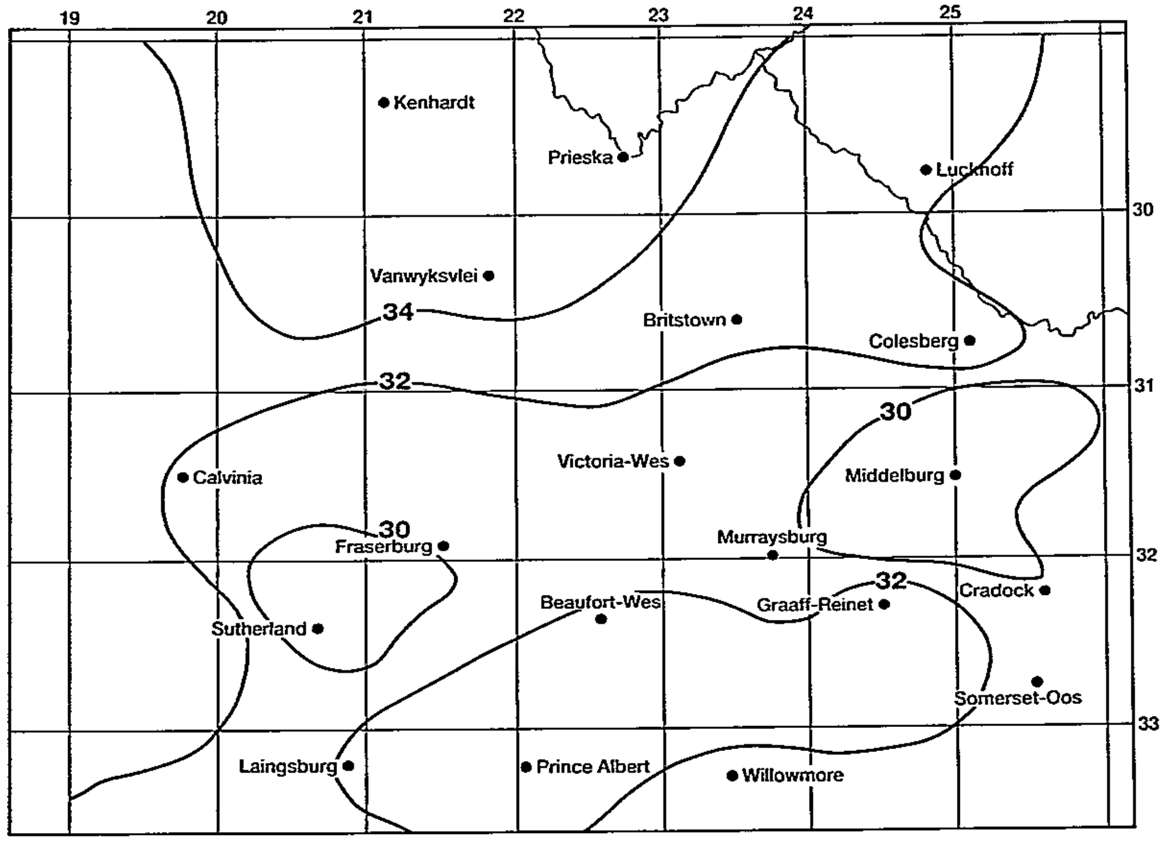

FIGURE 9. Isotherms of mean daily maximum temperature (January).

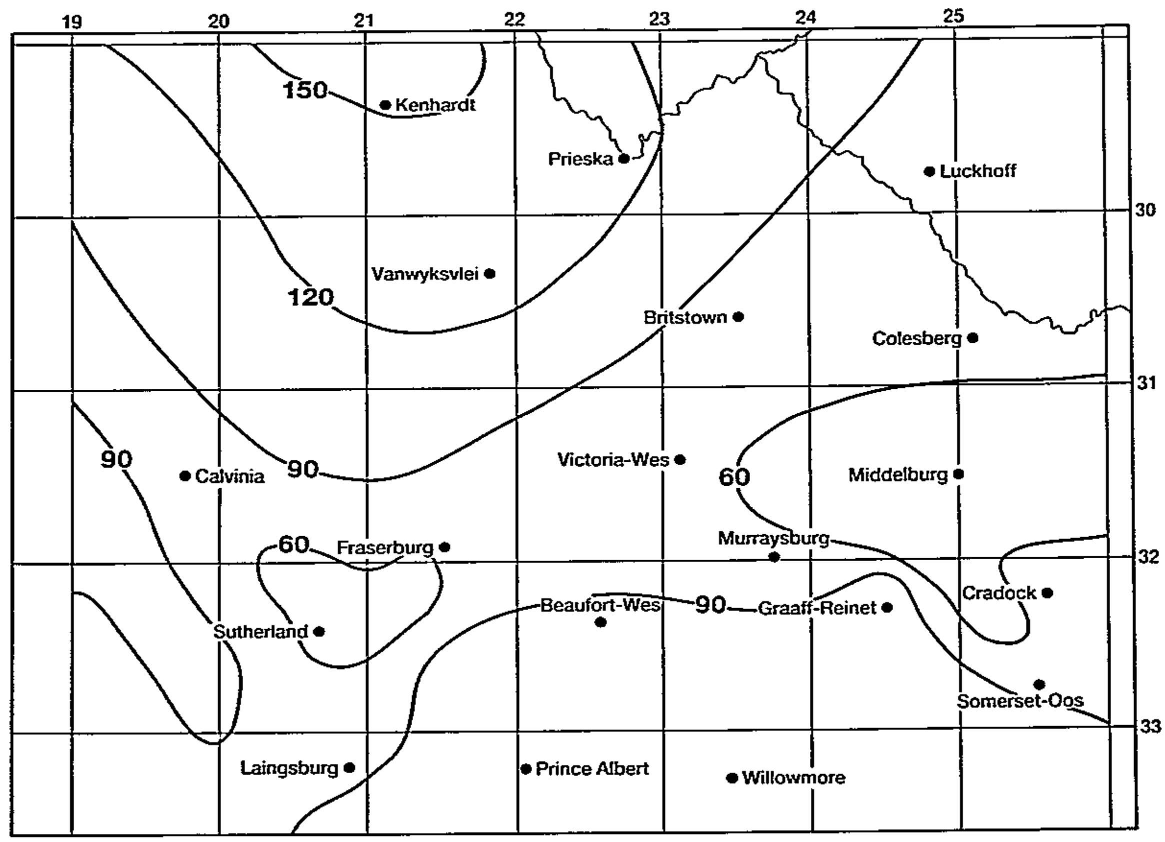

FIGURE 10. Mean annual frequency of days with maximum temperature above 30°C.

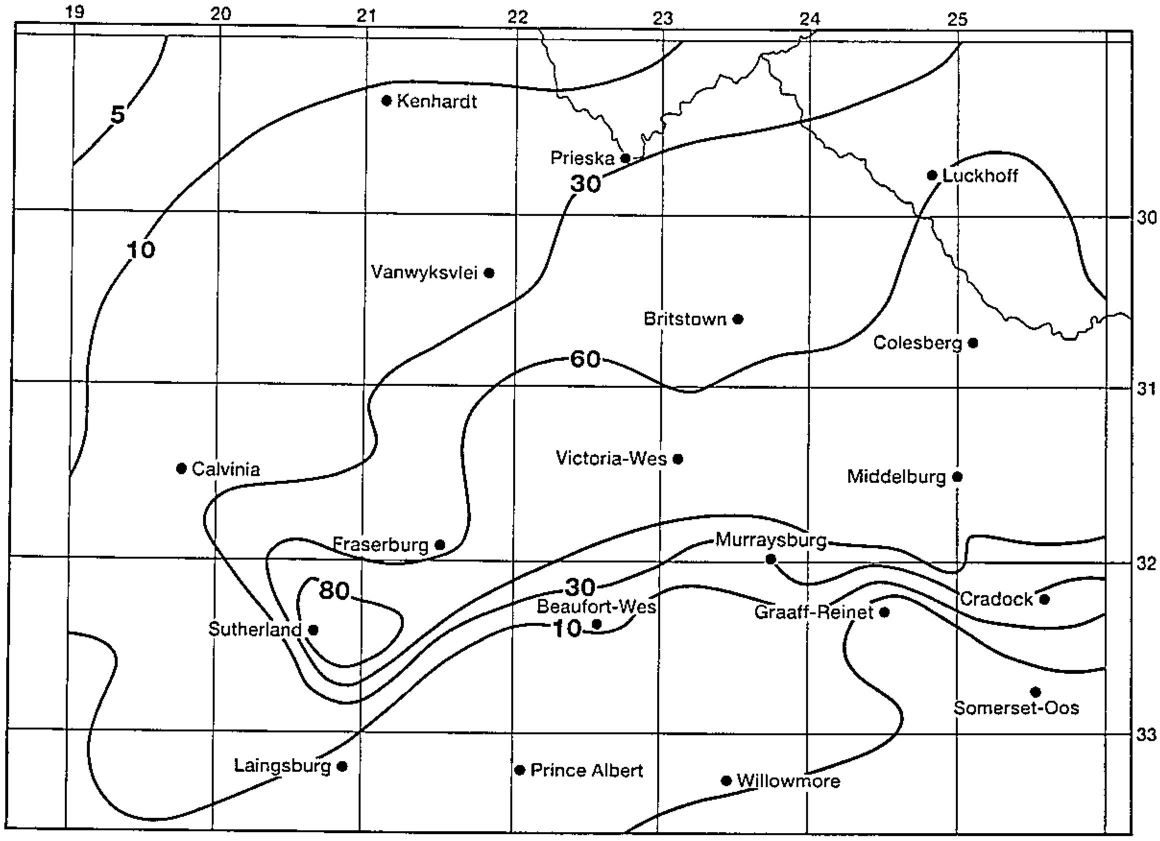

FIGURE 11. Mean annual frequency of days with minimum temperature below 0°C.

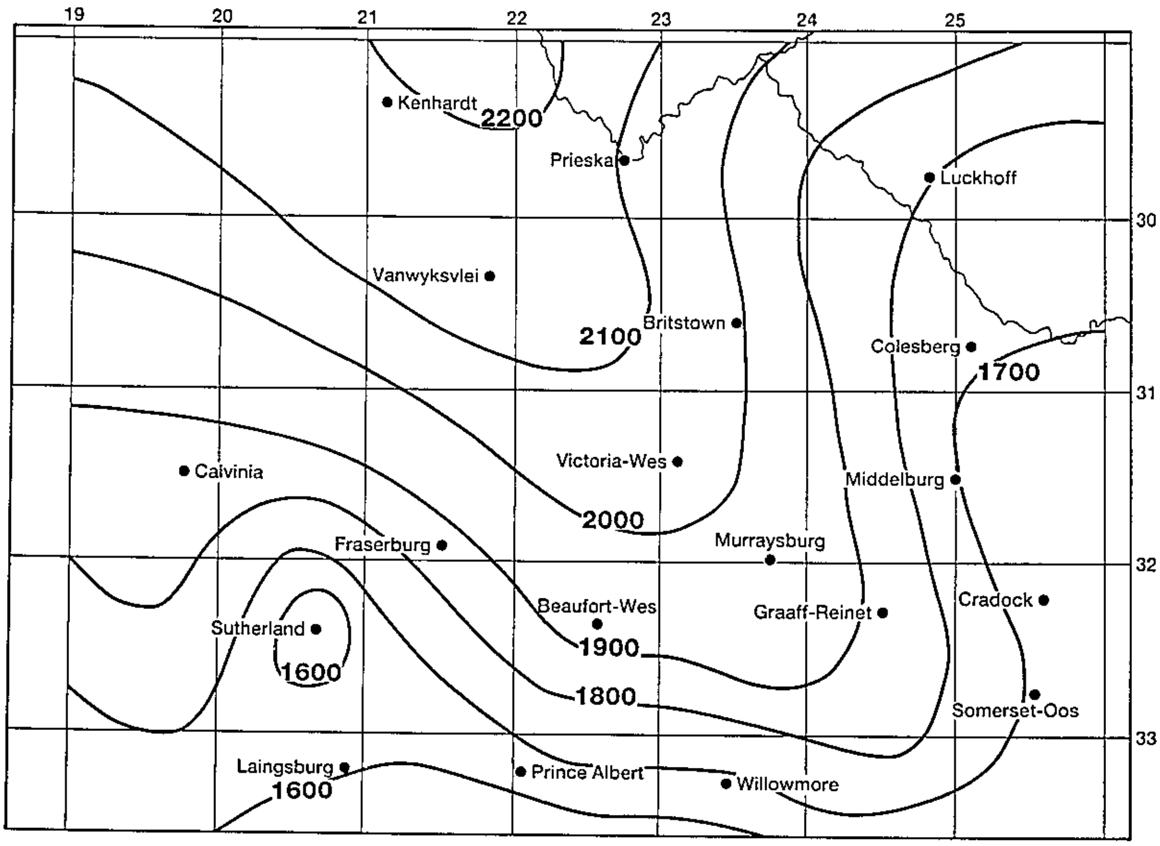

FIGURE 12. Distribution of annual total water consumption (potential evapotranspiration) as determined by the Penman method for short periods (Penman 1948).

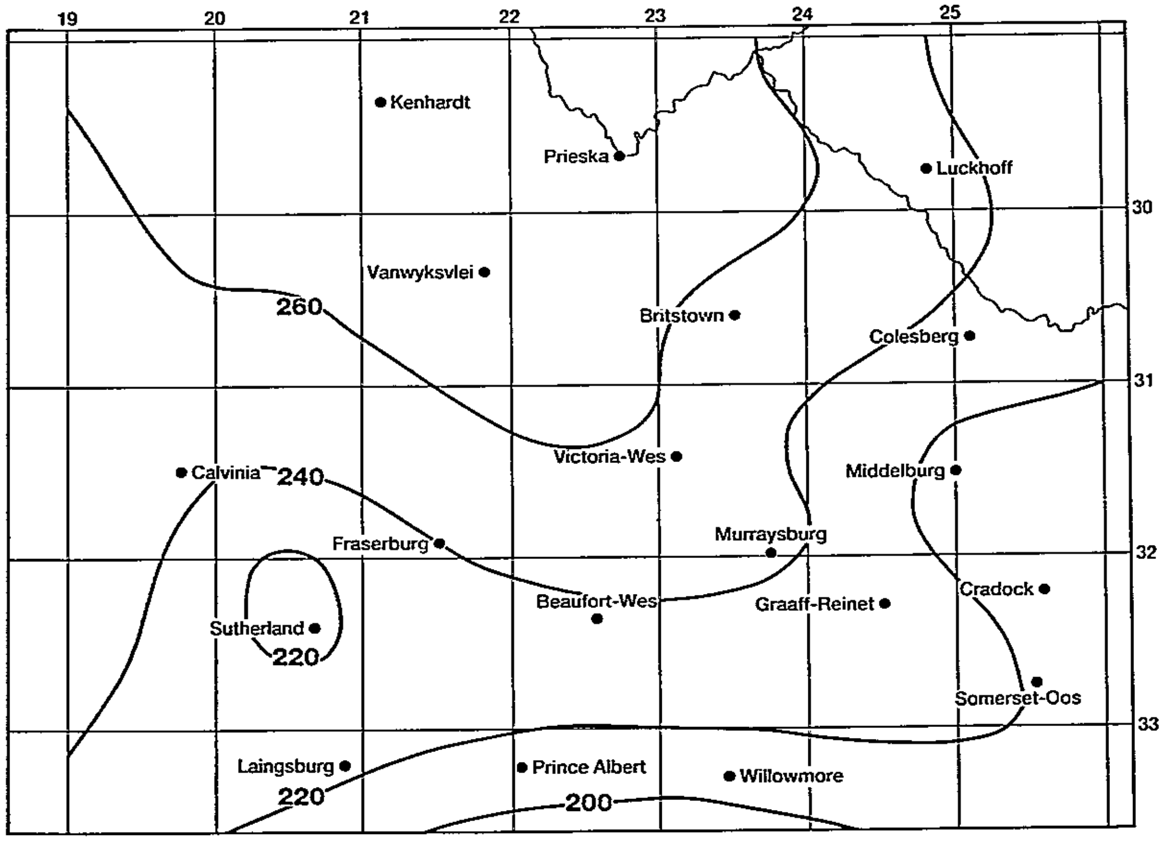

FIGURE 13a. Potential evapotranspiration for December.

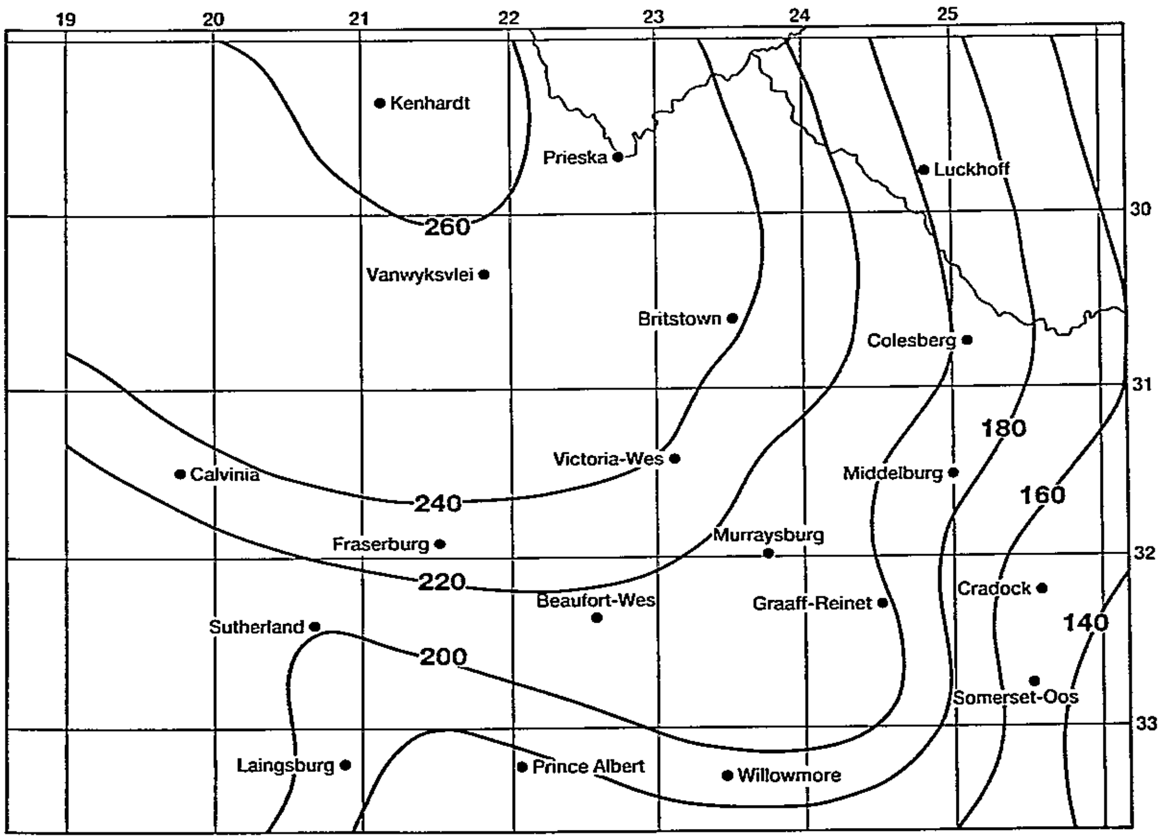

FIGURE 13b. Geographic distribution of rainfall deficit during December (potential evapotranspiration minus rainfall).

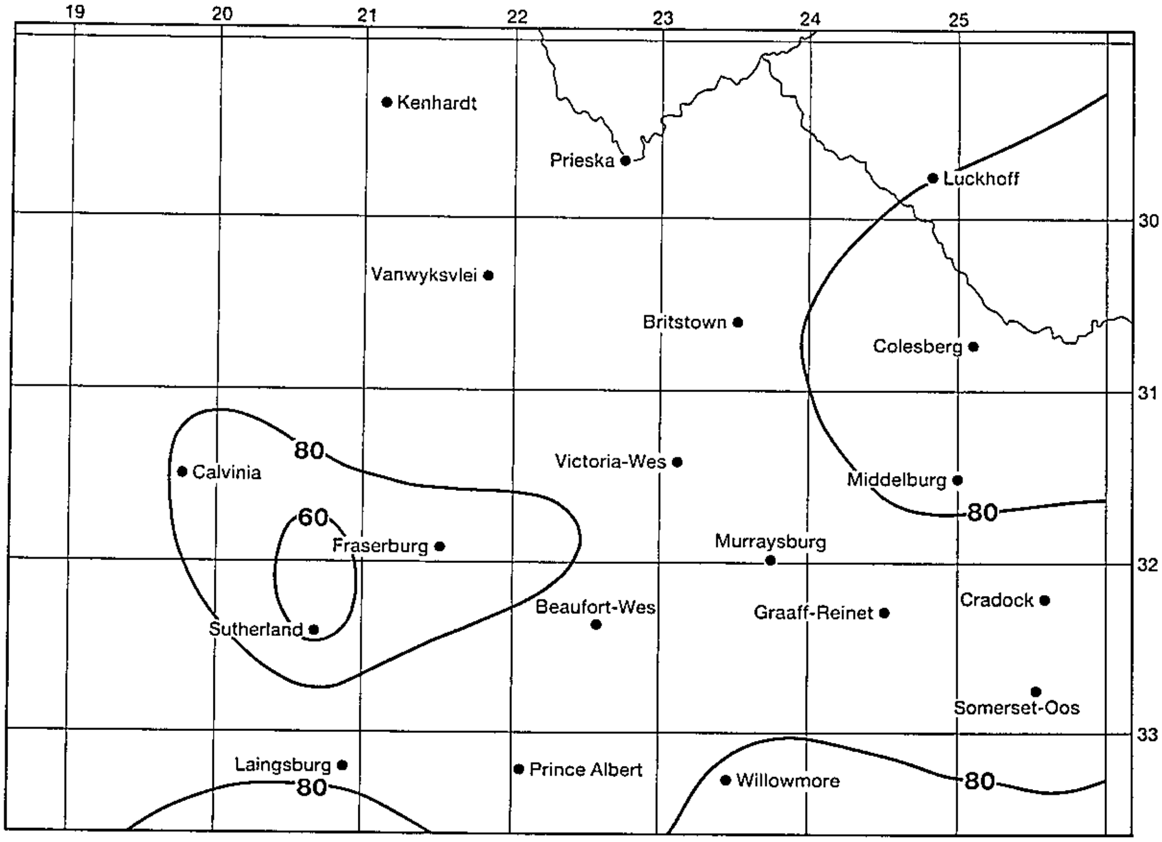

FIGURE 14a. Potential evapotranspiration for June.

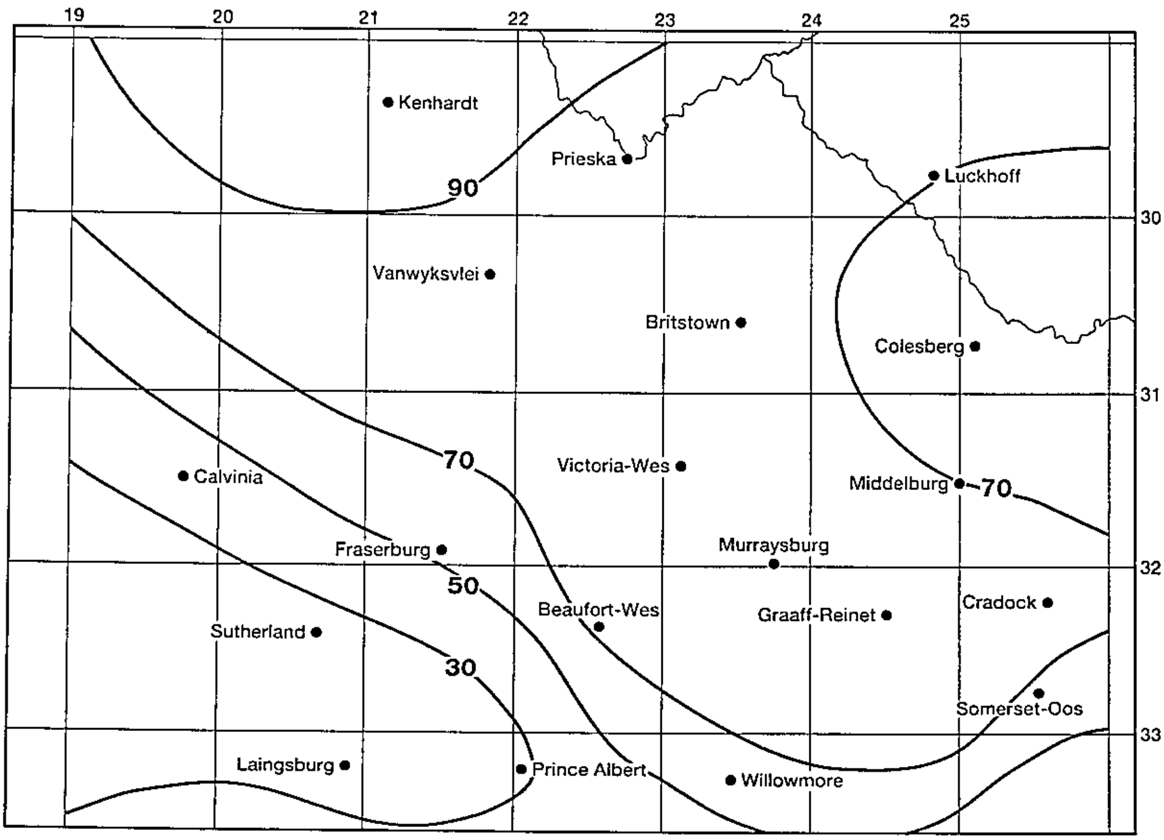

FIGURE 14b. Geographic distribution of rainfall deficit during June (potential evapotranspiration minus rainfall).

In order to estimate rainfall deficit, the potential evapotranspiration and the differences between average rainfall on the potential evapotranspiration for the months December and June are included in Figure 13 (a and b) and Figure 14 (a and b) respectively. As expected, the deficit is greater in the summer than in winter while the rapid increase from south to north is generally conspicuous. Furthermore these data give an indication of irrigation requirements in the karoo region.

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CHAPTER 4. HYDROLOGY

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INTRODUCTION

In a country like South Africa where more than half the land surface experiences a climate ranging from semi-arid to arid, water must be regarded as one of the most valuable natural resources. Soon after the year 2 000, demand for high-quality potable water will have increased to the point where, in certain areas of the country, maximum utilization of surface water resources will have been reached (Alexander 1973).

As the whole karoo biome falls inside the semi-arid to arid zone of South Africa (Table 1; Venter et al this volume), it represents one of the regions where an absolute limit to the total economically exploitable surface water resources can be foreseen. Furthermore, the typical characteristics of semi-arid regions, such as the large spatial and temporal variability of rainfall, high temperatures, shallow erodable upland soils, sparse vegetation and large channel losses, dictate a rather tenuous hydrological equilibrium in karoo catchments. Globally, semi-arid regions are characterized by small runoff proportions from rainfall. The runoff component of the hydrological cycle in semi-arid basins is dominated by processes such as infiltration, surface and subsurface detention and evapotranspiration. Consequently, the response of the karoo catchments to rainfall is likely to be very sensitive to changes induced by land use and management (Roux and Opperman this volume). This hydrological sensitivity underlies the fragile and delicately balanced nature of all semi-arid ecosystems and may manifest itself in changes in runoff quality, as well as quantity. Trends or sharp changes in sediment concentration and yield, mineral quality and nutrient levels, as well as the volumes of karoo streamflows may all represent signals of changes in the biome.

This chapter sets out to quantify for the karoo biome the characteristics of annual and monthly streamflows, the statistics of droughts and floods, the typical character of the mineral quality of streamflows and the long-term sediment yields. Finally, a synthesis of available information on the effects of land use on streamflow, mineralization and sediment yield is attempted. For the purposes of this hydrological synthesis the karoo biome is defined as comprising all the Acocks' veld types in the range 26 to 43 (Acocks 1975), as shown in Figure 1.

STREAMFLOW MONITORING

Surface drainage patterns

Figure 1 depicts the main drainage regions (as defined by the Department of Environment Affairs - DEA) of which significant proportions form part of the karoo biome. The Report of the Commission of Enquiry into Water

TABLE 1. Precipitation and runoff information for major drainage regions relevant to this study (after Commission of Enquiry into Water Matters 1970)

Drainage region no	Catchment or region	MAR* (mm)	MAP** (mm)	MAR/MAP (%)	MAR as % of total South African MAR
D:430	Orange between Bethulie and Vaal confluence	5,83	363	1,61	0,38
D:440-480	Lower Orange	0,65	225	0,29	0,40
E:520-540	Doorn and Sout	9,81	188	5,22	0,88
F:600	Western coastal region (Namaqualand)	2,46	130	1,89	0,14
H:800	Breede	131,35	651	20,18	3,95
J:900	Gouritz	14,88	249	5,98	1,31
L:1100	Gamtoos	16,43	277	5,93	1,11
N:1300	Sundays	14,07	340	4,14	0,38
Q:1500	Great-Fish	19,16	423	4,53	1,13
Total	RSA and Lesotho:	40,46	483	8,38	100,00

* MAR - Mean annual runoff
** MAP - Mean annual precipitation

Summer rainfall regions - D430, D440-480, E:520-540, N:1300, Q:1500.
Winter rainfall regions - F:600, H:800.
All-year rainfall regions - J:900, L:1100.
Summer - October-March
Winter - April-September

Matters (1970) contains mean annual runoff (MAR) and mean annual precipitation (MAP) information for all the principal drainage regions of South Africa, and Table 1 shows those values relevant to this study.

From this Table it is clear that the drainage regions containing the karoo biome produce only 9,9% of the total MAR of South Africa and Lesotho, in spite of constituting 44,8% of the total surface area. This runoff figure is much inflated by the inclusion of higher rainfall, non-karoo areas especially in the Breede and Great-Fish River catchments, and the karoo biome itself probably produces less than 6,5% of the total South African

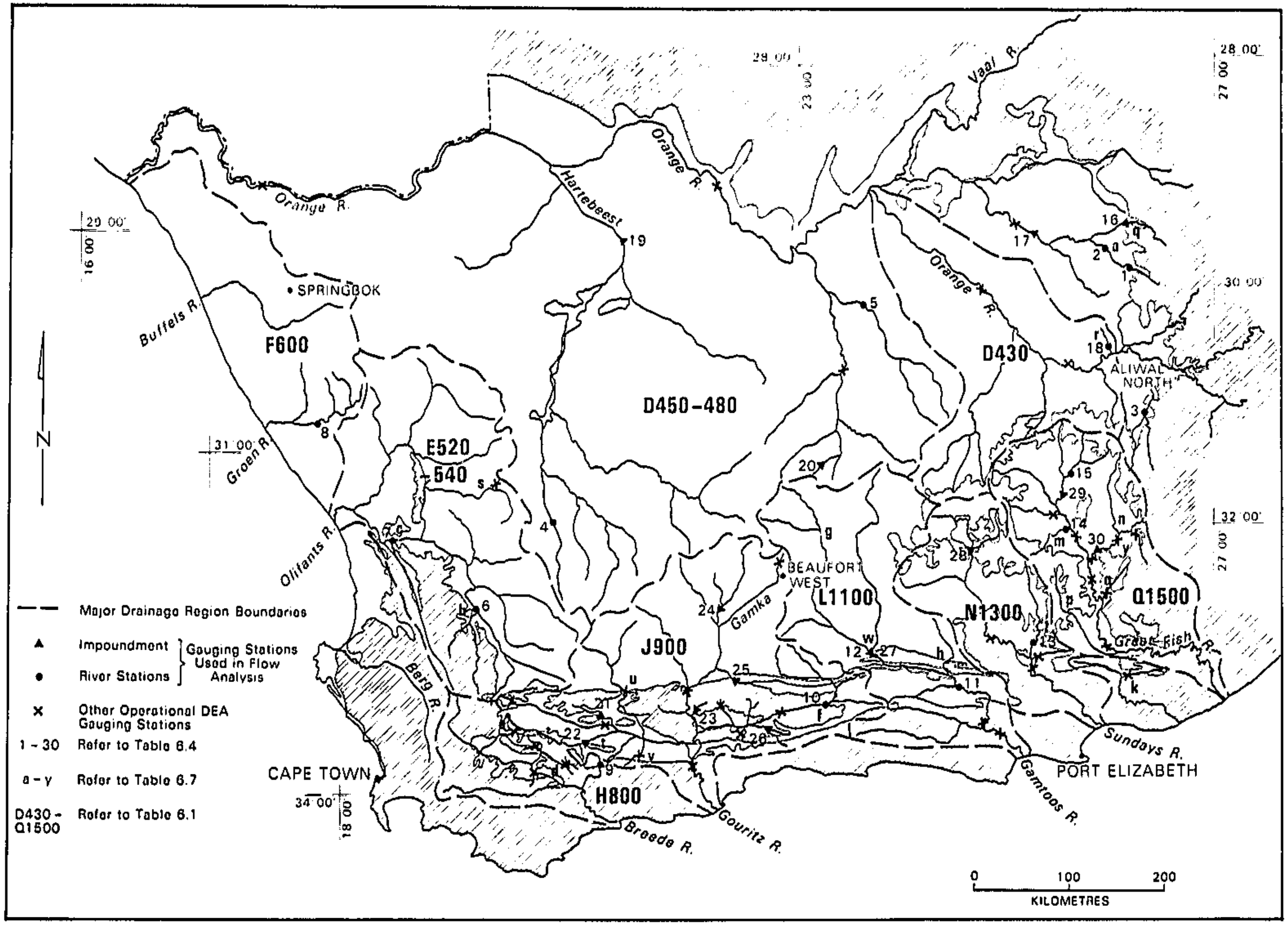

FIGURE 1. The karoo biome (unshaded area) as defined for the hydrological synthesis, showing the principal drainage regions, locations of operational streamflow gauging stations, locations of stations selected for the analysis of streamflows and locations of water quality stations used in this study (DEA - Department of Environmental Affairs).

MAR. A hydrologically important feature of the overall drainage system is the flatness of both the channel gradients and the general physiography of the bigger tributaries of the lower Orange, such as the Sak, Hartebeest and Ongers. This is a cause of the existence of numerous pans and vleis in these regions which contribute to the already large evaporative losses in these catchments.

Streamflow monitoring network

Monitoring of streamflow in the karoo regions falls exclusively under the aegis of the DEA and is usually done by either regularly (or continuously) recording the depth of flow over a weir or by calculating inflow into impoundments on a monthly basis from dam storage and operation records. Figure 1 depicts the location of all river gauging stations in the karoo biome which are classified as "reliable" by the DEA (South Africa 1976), while Table 2 contains information on the number, length and quality of records available at all karoo stations which are currently operational, or have a record length greater than 15 years. In addition, Table 2 presents other information on reservoir inflow records.

TABLE 2. Summary of flow gauging stations currently in operation or with record length longer than 15 years*

Gauging station type	No	Quality of record**	Mean record length (yr)	Range of record lengths (yr)	Range of catchment areas (km)
River	35	Reliable up to max meas cap	22	4-70	14-43 451
River	50	Unreliable	27	8-63	40-40 426
Reservoir	30	Variable due to effects of reservoir sedimentation	37	4-65	18-72 300

** Excluding stations on the Orange River.
* As defined by the DEA (South Africa 1976).

For proper hydrological analysis the flow gauging situation is actually worse than is apparent from Table 2, as many of the 35 reliable river station records have long periods of missing data, or do not reflect diversions at or upstream of them, or are in regulated sections of rivers. Furthermore, 22 of the operational stations have records shorter than 15 years, of which 12 are shorter than 10 years. Reservoir records usually have fewer missing data periods, but their accuracy is totally dependent on the provision made for the effect of reservoir sedimentation in the water balance calculations, while their hydrological usefulness is determined by whether they are largely unaffected by upstream diversions, irrigation or reservoirs. Six of the reservoir records are shorter than 15 years, of which four are shorter than 10 years.

The density of operational streamflow gauging stations in the karoo biome with at least 15 years of data is at present one station per 22 500 km^2. This compares well with the arid zone of Australia of one 15-year station per 350 000 km^2 (French and Roberts 1975), but contrasts poorly with the more humid parts of South Africa (Natal: one 15-year station per 1 100 km^2) and Australia (one 15-year station per 3 200 km^2 (French and Roberts 1975). The World Meteorological Organization (1971) recommends a gauge density for semi-arid areas of one station per 5 000-20 000 km^2.

CHARACTERISTICS OF STREAMFLOWS

Published analyses of streamflows

The study of the surface water resources of South Africa by Midgley and Pitman (1969) and their recent revision of this work (HRU 1981), is to date the only work that provides detailed data on the spatial variation of MAR and low-flow sequences in the karoo region. There have been few South African studies on rural land-use effects on steamflows (see section on Sediment), the most prominent of which, by Braune and Wessels (1980), included 18 karoo catchments in an 82 catchment analysis. The other land-use studies, however, provide little information on monthly or annual streamflow statistics. For engineering design purposes, data on karoo catchment yields and low-flow return periods are available in Midgley and Pitman (1969) and the HRU (1981) water resources survey, and for flood design there are manuals on design flood determination for South Africa (HRU 1972), probability analysis of South African annual flood peak series (Adamson 1978), small catchment design floods (Schulze and Arnold 1979), runhydrograph analysis (Hiemstra and Francis 1979), and a report on extreme South African flood peaks (Kovàcs 1980).

Considering the absence of published studies specifically on karoo streamflows, Görgens and Hughes (1982) executed a statistical analysis of published streamflow data for karoo catchments in terms of monthly and annual flow volumes, low-flows and flood peaks. To this end, a data set of 30 station records, as shown in Table 3 and Figure 1, was compiled. To achieve reasonable spatial distribution, length and quality of record had to be compromised in a few cases. However, no station was subject to major upstream interference. The following four sections review the results of this study and integrate them with the findings of other researchers.

Annual streamflow characteristics

Frequency distributions for some of the more common statistical properties of annual streamflows are depicted in Figure 2. In Table 4 these properties are compared with those indicated by McMahon's (1979) global study of arid zone stream-flows (72 catchments on six continents - 17 being from South Africa's semi-arid to arid zones), and with statistics extracted from Braune and Wessels (1980). The karoo statistics are notabley "worse" than the global arid zone averages, but compare remarkably well with the overall arid Australian picture.

TABLE 3. Streamflow records analysed (Görgens and Hughes 1982)

Station code	River or dam name	Location in Fig 1	Main runoff season	Area of catchment (km^2)	Length of record (yrs)	Missing mths	Dominant Acocks' veld types*	MAR** (mm)
RIVER GAUGING STATIONS								
C5M08	Riet	1	S	593	29	7	36,50,49	27,35
C5M12	Riet	2	S	2 372	34	8	36,50,49	24,09
D1M01	Stormberg	3	S	2 397	57	8	36,48,50,60	17,57
D5M03	Fish	4	W	1 463	33	0	28,29,43	12,68
D6M02	Brak	5	S	6 440	16	4	35,27,36	5,82
E2M02	Doorn	6	W	6 903	47	3	31,28,69	44,71
E2M03	Doorn	7	W	24 044	44	37	31,28,69	14,89
F5M01	Swartdoring	8	W	2 349	14	7	33	0,55
H7M04	Huis	9	W	28	19	0	26,43	157,90
J3M04	Olifants	10	S	4 305	47	0	26,25,43,70	4,34
L7M02	Groot	11	S	25 587	19	0	30,26,31,25	3,65
L3M01	Groot	12	S	20 368	23	6	30,26,31	4,48
N3M01	Voël	13	S	1 598	19	0	24,25,37,38	24,30
Q3M01	Pauls	14	S	859	22	4	37,42,60	17,49
Q1M06	Teebus	15	S	1 571	20	0	36	7,40
RESERVOIRS								
C5R01	Kaffer	16	S	922	47	4	36,50,49	19,63
C5R02	Kalkfontein	17	S	10 300	32	0	36	13,91
D3R01	Bethulie	18	S	255	41	0	36	17,01
D5R01	Rooiberg	19	S	72 300	30	0	29,32	0,76
D6R01	Victoria West	20	S	280	46	3	27	4,50
J1R01	Prins	21	All	757	52	0	26,70	4,60
J1R02	Ballair	22	All	558	50	0	26,43	4,12
J2R01	Calitzdorp	23	All	170	51	0	25	39,41
J2R02	Leeugamka	24	S	2 090	50	12	26,42	14,15
J2R03	Oukloof	25	All	141	40	0	26	24,64
J2R01	Kammanassie	26	All	1 500	48	15	25,43,70	26,40
L3R01	Beervlei	27	S	20 365	22	6	30,26,31	2,91
N1R01	Van Ryneveldspas	28	S	3 680	42	0	25,37,38,60	7,70
Q1R01	Grassridge	29	S	4 370	46	0	36	7,85
Q4R01	Lake Arthur	30	S	4 500	30	0	36,37,60	18,82

* From Acocks (1970)
** MAR - Mean annual runoff

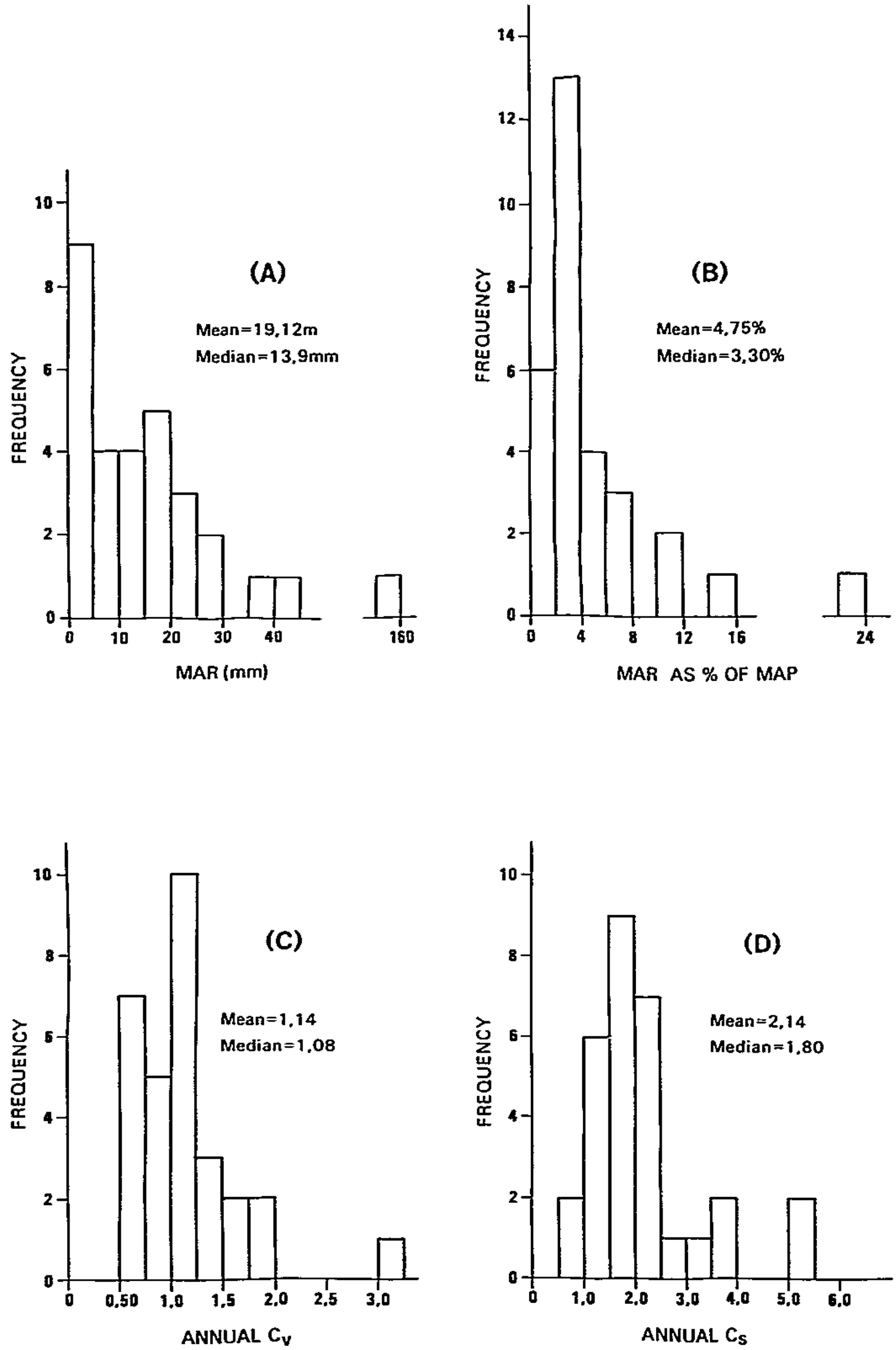

FIGURE 2. Frequency diagrams of various annual streamflow characteristics:
(a) Mean annual runoff - MAR (mm)
(b) MAR as % of mean annual precipitation (*MAP)
(c) Coefficient of variation of annual streamflow - C_V
(d) Skewness coefficient of annual streamfow - C_S (Görgens and Hughes 1982).

Examining the annual precipitation-runoff relations for the karoo biome, it is noted that except for one case, the MAR's do not exceed 50 mm. Average values for both the karoo MAR and the MAR/MAP ratio are less than half that of the country as a whole (Table 1) and an order of magnitude smaller than those for humid catchments (Table 4).

Görgens and Hughes (1982) stressed the problem of annual runoff variability in the Karoo. As an extreme, in one year the runoff at Rooiberg Dam was one-and-a-half times the total runoff experienced in the previous 29 years. The average maximum annual runoff of 527% of the MAR and minimum of six per cent MAR of the Karoo can be compared with equivalent figures of 186% and 56% for the humid Tugela River catchment; 355% and 24% for the subhumid Vaal River catchment and 367% and 41% for the semi-arid to subhumid Crocodile/Marico system (Alexander 1973).

In the above context, the coefficient of variability, C_v, is an apt statistic to consider. Table 4 reveals that the Karoo average C_v of 1,14 is slightly more than the global average of 0,99, but about double that of humid South Africa. It is of interest to note that the average C_v of annual rainfall totals of 0,30 reported by Braune and Wessels (1980) for 18 karoo catchments, is only 1,5 times the average of 0,20 for their 28 humid catchments, and only 25% of the karoo streamflow C_v - suggesting that rainfall variability is not the major cause of the high runoff C_v's.

TABLE 4. A comparison of details of a global study of arid zone annual streamflow characteristics (McMahon 1979), South African humid zone characteristics (Braune and Wessels 1980) and the karoo biome study. (Görgens and Hughes 1982)

	McMahon: Global total	McMahon: Arid Australia	McMahon: Arid South Africa	Braune and Wessels: Humid South Africa*	Karoo biome
No of catchments	72	16	17	28	30
Ave record length (yr)	29	40	20	30	35
Range of record lengths (yr)	11-89	14-89	11-38	20-69	14-55
Range of catchment areas (km^2)	33-1 840 000	440-570 000	34-23 000	9-7 081	28-72 300
Average MAR (mm)**	30	21	32	348	19
Average MAR/MAP(%)***	-	-	-	30,20	4,75
Average annual C_v****	0,99	1,27	1,14	0,57	1,14
Average annual C_s****	1,80	2,20	2,00	-	2,14

* Only catchments with MAP's less than 750mm were selected from Braune and Wessels (1980).

** MAR - Mean annual runoff

*** MAP - Mean annual precipitation

**** See Figure 2 for explanations of C_v and C_s

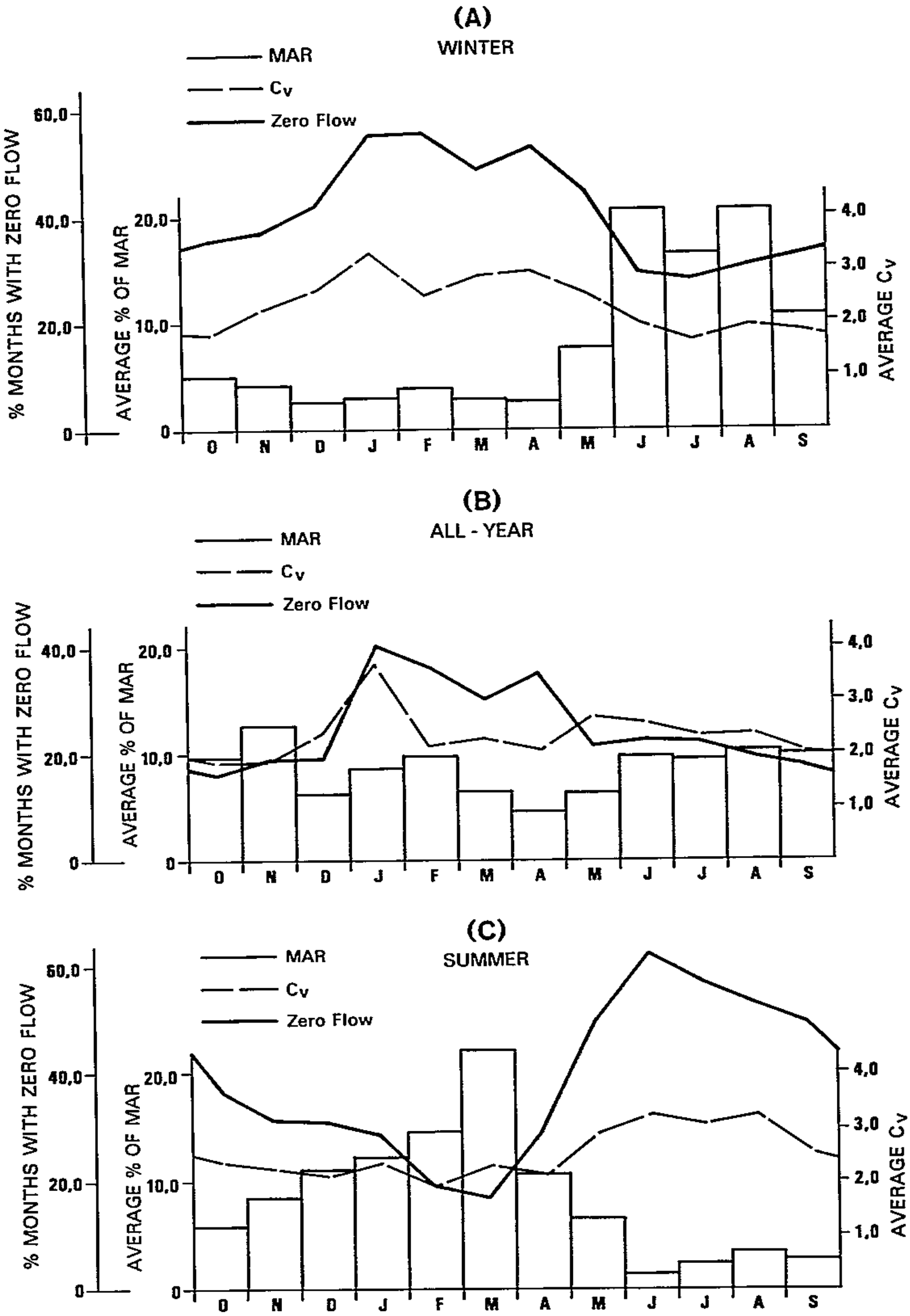

FIGURE 3. Average monthly distribution of MAR, C_V by month and zero flow month total for:
(a) winter (5 catchments)
(b) all year (5 catchments) and
(c) summer (20 catchments) runoff regimes (Görgens and Hughes 1982).

A further measure of the variability of runoff is the "gross yield" which can be obtained with this runoff, ie the rate at which water can be provided without shortages from a specific storage, based on a very long historic flow record. Using a hypothetical storage of one MAR, Braune and Wessels (1980) calculated the average gross yields for 18 karoo rivers as 42,6% MAR, while the average for their humid catchments is 67,5% MAR. The range of gross yields is 27,2-67,4% MAR and 34,3-95,0% MAR for karoo and humid catchments respectively. When looking at net yields, evaporation losses must be taken into account, making the situation even less favourable for the karoo biome, because of higher evaporation rates and less favourable dam basin characteristics in the relatively flat topography of the central and western karoo regions.

Monthly streamflow characteristics

Seasonality of streamflow is best studied by analysis of monthly streamflow totals. The average distributions of MAR, C_v by month, and zero-flow for the winter, all-year and summer runoff regimes, are shown in Figure 3. There is a striking similarity in the pattern of monthly variability of the summer and winter runoff regimes in that the low-flow months are the most variable in both cases and that for both regimes the high-flow months have C_v's around 2,0, while the low-flow C_v's are around 3,0.

Monthly flow duration curves can be useful tools to gauge the so-called "reliability" of streams and also to compare the relative variability of low-flows among individual rivers and regions. Figure 4 shows a collage of monthly flow duration curves for the karoo biome, depicted as envelope lines that include the range of flow duration curves for each of the summer, all-year and winter runoff regions. The monthly runoffs are plotted in standardized form, ie each monthly total is divided by the mean monthly runoff (MMR). On the average the MMR is equalled or exceeded approximately 20% of the time in all regions, highlighting the spatial consistency in the reliability of medium-flows in the karoo biome. The winter runoff rivers of the karoo show much greater relative variablility of low-flows than the rivers in the other two runoff regimes. On the average, the median monthly flows (50% exceedance) are 8% MMR, 14% MMR and 21% MMR for the summer, winter and all-year runoff regimes respectively, pointing to real differences in low-flow reliability among the karoo regions.

Low-flow characteristics and droughts

The simplest measure of low-flow behaviour of a river is the percentage of time that streamflow ceases. An extreme case is the Swartdoring River (F5M01) on the west coast, where nine out of fourteen years produced no streamflow. Figure 5(d) indicates that in the long term, zero-flow months can be expected more than a third of the time. Figure 3 reveals that in both the summer and winter runoff regimes, between 20 and 30% of the months in the high-flow season, on the average, can be zero-flow months.

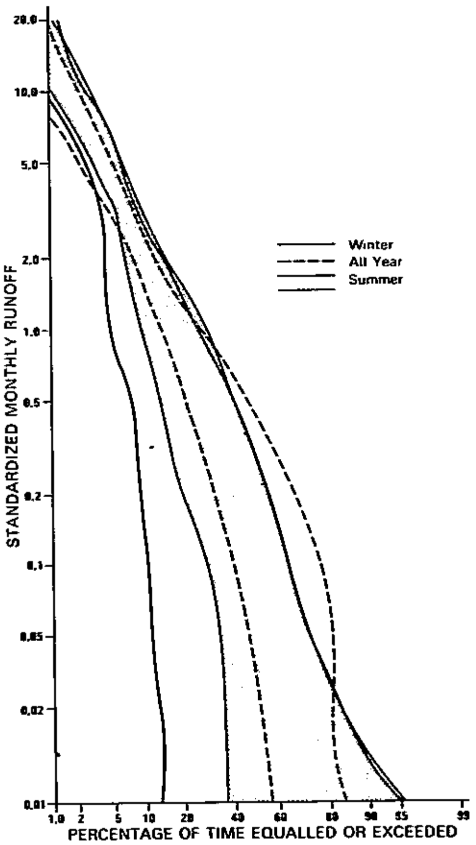

FIGURE 4. Standardized monthly flow duration envelopes for the karoo biome (Görgens and Hughes 1982).

A more general impression of low-flow behaviour of rivers can be obtained via an analysis of deficient-flow periods. Görgens and Hughes (1982) defined deficient-flow periods as continuous periods with monthly runoff totals less than the overall MMR. Figure 5 gives further illustrations of the lack of reliability of the karoo streamflows by showing that deficient-flow periods of six to nine months occur regularly in these streams (Figure 5(a)), and that 50% of the catchments studied have experienced maximum deficient-flow periods of longer than 2,5 years (Figure 5(b)).

Cumulative frequencies of deficient-flow periods are shown in Figure 6 as fields between upper and lower envelope lines for the three runoff regimes. The envelopes for the summer runoff regime enclose all but one (F5M01) cumulative frequency curve of the other two runoff regimes and may approximate general upper and lower envelopes for the karoo biome, excluding the arid north-west. On average, of all deficient-flow periods that occur, 19%, 8% and 20% exceed a 12-month period for each of the summer, winter and all-year runoff groups respectively (excluding F5M01).

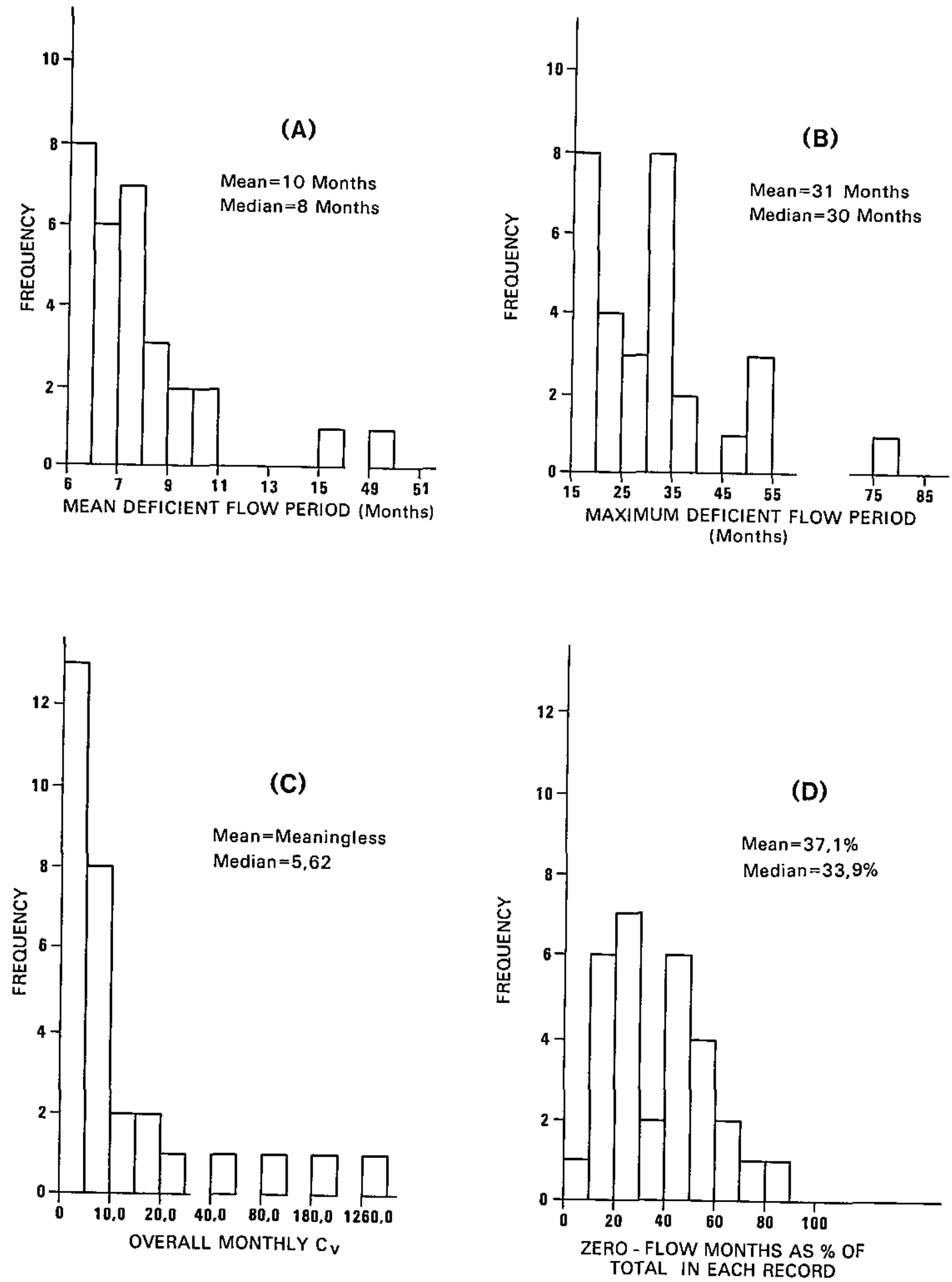

FIGURE 5. Frequency diagrams of various monthly streamflow characteristics:

(a) Mean deficient-flow period (monthly flow total less than MAR)

(b) Maximum deficient-flow period

(c) Overall monthly C_v

(d) Zero-flow month totals (Görgens and Hughes 1982).

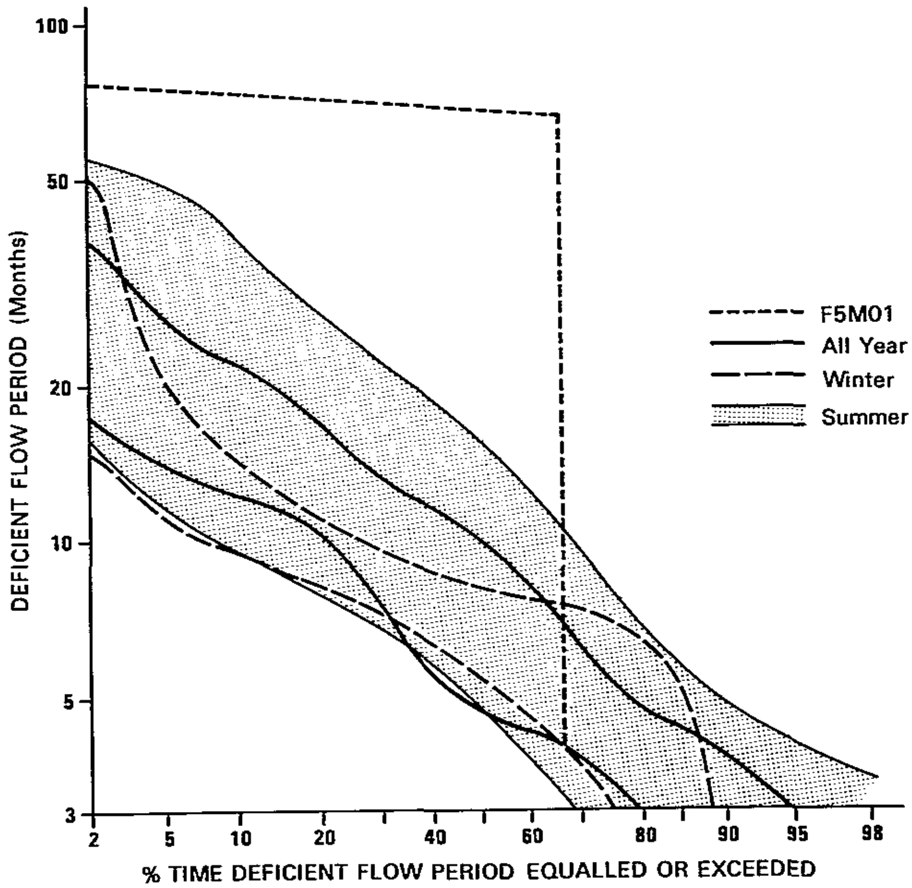

FIGURE 6. Cumulative frequency envelopes for deficient-flow periods for the karoo biome (Görgens and Hughes 1982).

Midgley and Pitman (1969) delineated South Africa into so-called homgeneous drought regions and suggested a generalized, dimensionless deficient-flow/duration/frequency relationship for each region. Those relationships applicable to the karoo region for a 3-year drought are shown in Figure 7, while the drought region boundaries are shown in Figure 8. For comparative purposes the relationship for a humid area, ie central and southern Natal, is shown. These curves illustrate the increasing aridity of the Karoo in the westerly direction very dramatically.

Some publications exist on the possibility of predicting long-term drought (and surplus-flow) periods in South Africa on the basis of quasi-periodicity observed in both rainfall and runoff records (Tyson et al 1975; Abbott and Dyer 1976). This was investigated by Alexander (1978) at 31 flow-gauging stations, of which 10 were karoo rivers. He found, what he termed, "a slight visual confirmation" of the 10-12 -year periodicity reported by Tyson et al (1975) for eight of the catchments in the southern and eastern parts of the karoo biome, but expressed doubts as to whether this periodicity could be used for predictive purposes.

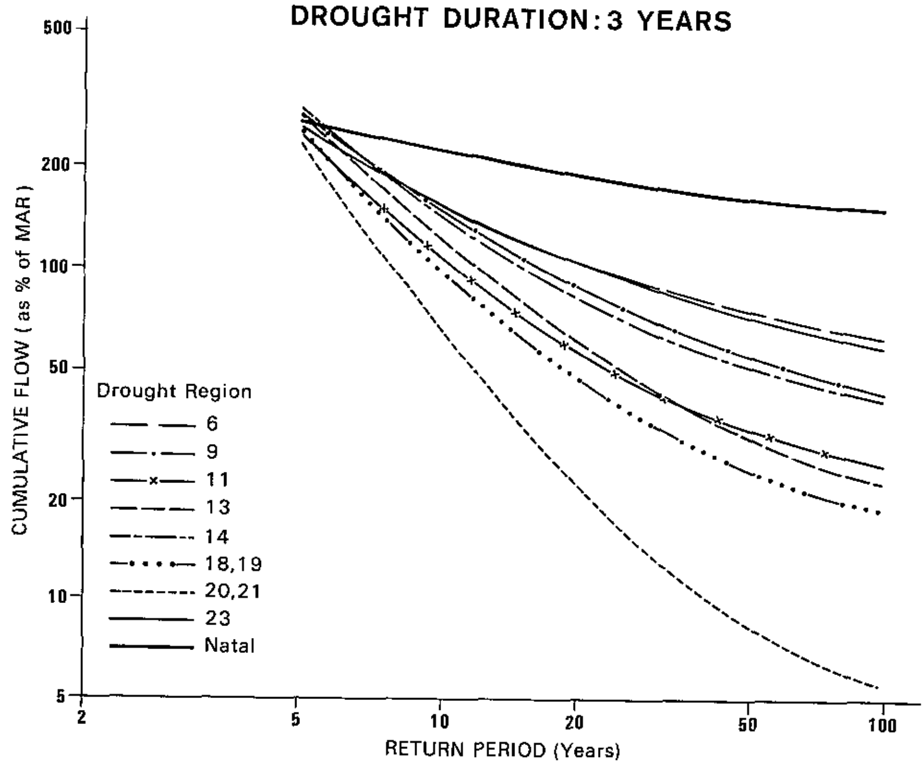

FIGURE 7. Generalized deficient-flow/duration/frequency curves for homogeneous drought regions of the karoo biome for a drought of 36 months duration (after Midgley and Pitman 1969).

Flood peak characteristics

As no studies dealing primarily with the flood characteristics of karoo streams could be found in the literature, Görgens and Hughes (1982) did a flood peak analysis on those flow gauging stations amongst the karoo sample of 30 for which annual maximum flood peak series could be extracted from published DEA streamflow data, namely the 15 river gauging stations.

Table 5 compares variability and skewness parameters of the karoo annual maximum flood peak series with those for the whole of South Africa (Adamson 1978, 1979) and for the arid zones of the world (McMahon 1979). Adamson (1978) calculated coefficients of variability, as well as skewness coeffients in both the log-domain and for natural data, for 42 South African annual flood peak series (longer than 30 years in length) which included 10 catchments in the karoo biome. In his world-wide study, McMahon (1979) executed an annual flood peak analysis on 63 of the semi-arid catchments referred to earlier, of which 16 were South African. Both the C_v and I_v values in Table 5 show that the karoo catchments experience a large variability in annual flood peaks. Just how severe this variability is can be determined by comparing the average karoo I_v (standard deviation

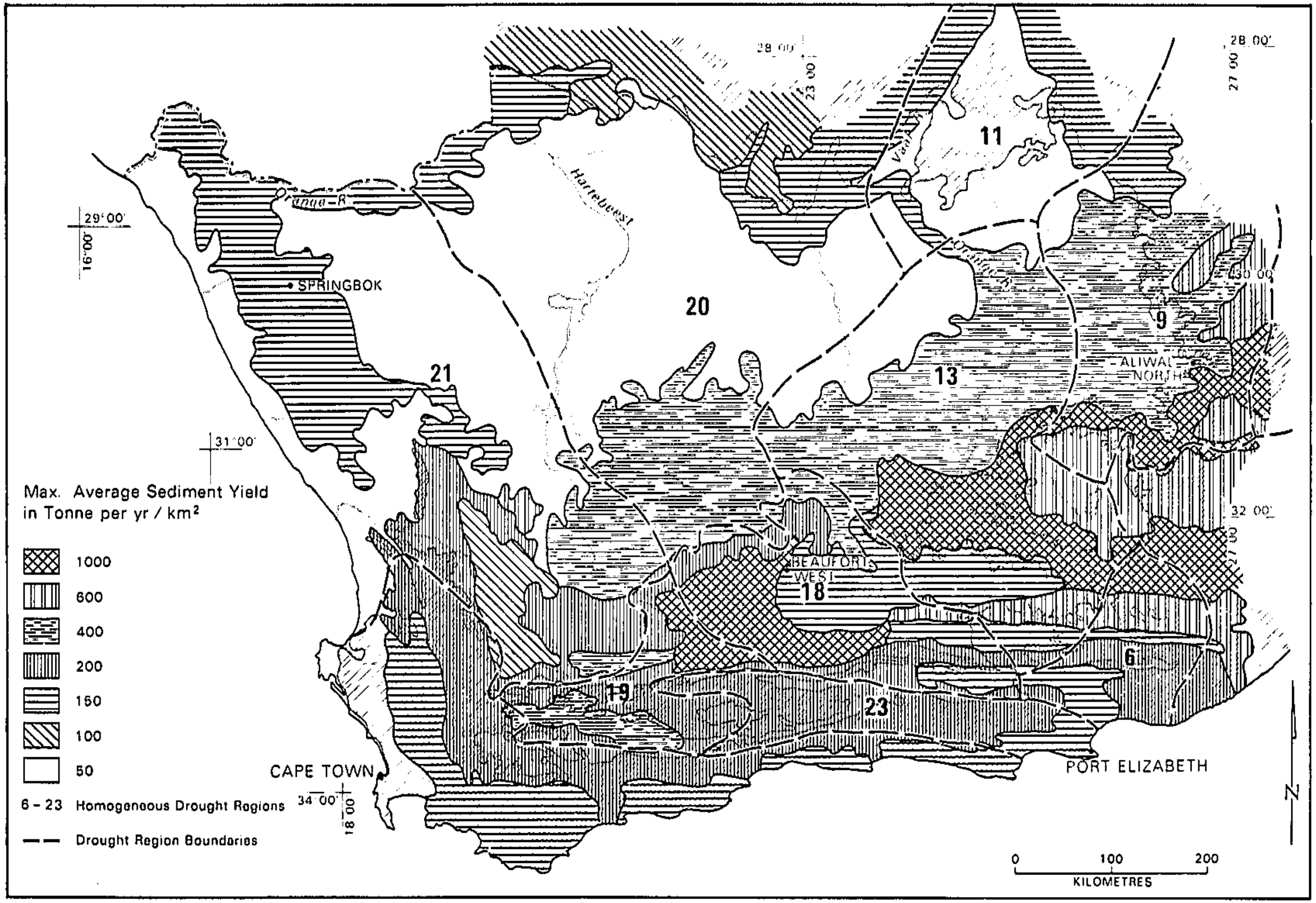

FIGURE 8. Map showing maximum sediment yield (after Rooseboom 1978) and homogeneous drought regions (after Midgley and Pitman 1969).

of logarithms of annual flood peaks) with typical I_v's quoted by McMahon (1979) for humid regions of 0,1 to 0,4. The skewness values in Table 5 suggest that karoo flood peaks may be less skewed than flood peak data from some other South African regions. However, the negative average skewness and the large standard deviations of skewnesses in the log-domain are important pointers to the difficulty of identifying suitable probability distributions for flood peak analysis on karoo data.

TABLE 5. Comparison of annual flood peak series variability and skewness among various studies

Author	Average coefficient variation C_v (natural)	Average index of variability* I_v	Average skewness C_s (natural)	Average skewness g (logs)	Standard deviation of g (logs)
McMahon (1979) Global total	-	0,55	-	-0,58	-
McMahon (1979) Arid Australia	-	0,65	-	-0,89	1,00
McMahon (1979) Arid South Africa	-	0,58	-	-0,76	1,00
Adamson (1978, 1979) All South Africa	1,13	-	2,25	-0,10	2,20
Karoo biome**	1,17	1,87	1,85	-0,41	1,1

* Standard deviation of the natural logarithms of annual flood peaks.
** Study by Görgens and Hughes (1982).

As far as historic floods in the karoo region are concerned, Görgens and Hughes (1982) found that the specific maximum flood peaks on record (expressed as peak discharge per unit area for more equitable comparison) cover a range of a few orders of magnitude. The same applies to the specific mean annual flood peaks. These observations suggest a great heterogeneity of flood generating conditions in the karoo environment - borne out by the fact that the karoo biome straddles all five of Kovàcs' (1980) homogeneous "maximum flood peak regions" for South Africa. In this context it is further notable that among the 20 biggest historic floods in South Africa listed by Kovàcs (1980), six karoo events can be found.

IMPOUNDMENTS

Apart from the large salt flats, pans and temporary vleis of the central, northern and north-western Karoo, there are no natural surface water storages of any size which can be described as lakes. However, a fair number of impoundments have been constructed, ranging in size from small farm dams to large man-made lakes. At present there are 20 with a full supply capacity of at least 10x106 m^3, as well as a number of smaller dams.

Their total capacity amounts to some 21% of South Africa's total MAR, including the enormous Hendrik Verwoerd and P K le Roux Dams on the Orange River. Exclusion of these two dams, however, reduces the above figure to a mere three per cent of the country's total MAR, but the remaining total capacity does in fact represent more than 40% of the karoo biome's total MAR.

The locations of most of the major karoo impoundments are shown in Figure 1, while Table 6 summarizes some characteristics of these reservoirs (extracted from Noble and Hemens 1978).

TABLE 6. Some characteristics of karoo impoundments (after Noble and Hemens 1978)

Impoundment	Station code	Altitude (m)	Catchment area (km^2)	Mean annual runoff ($10^6 m^3$)	Volume at full supply level ($10^6 m^3$)	Surface area at full supply level (ha)	Maximum depth (m)	Mean depth (m)	Suspended solids concentration H = High M = Moderate L = Low	Total dissolved solids ($mg\ l^{-1}$) H often 1000 M normally 200-1000 L normally 200mg^{-1}
Beervlei	L3R01	706	20 336	75	93,5	2 294	12,1	4,1	L	M
Bellair	J1R02	555	558	2	11,1	198	11,1	5,6	L	H
Boegoeberg	D7R01	886	342 956		21,1	787	6,7	2,7	L	M
Floriskraal	J1R03	598	4 001	23	62,9	787	16,6	8,0	M	M
Gamkapoort	J2R06	380	17 076	39	54,3	682	30,8	8,0	L	H
Grassridge	Q1R01	1 058	4 325	34	58,4	1 456	14,9	4,0		
Hendrik Verwoerd	D3R02	1 259	70 749	9 840	5 952,4	36 433	64,0	16,3	M	L
Tierpoort	C5R01	1 396	922		33,0	805	10,0	4,1		
Kalkfontein	C5R02	1 229	10 268	181	343,2	5 139	19,0	6,7	M	M
Kammenassie	J3R01	384	1 505	38	32,9	349	29,0	9,4	M	
Kammandodrif	Q4R02	1 018	3 623	42	66,7	893	43,0	7,5	H	H
Lake Arthur	Q4R01	898	4 497	68	30,5	881	18,7	3,5	H	
Leeuwgamka	J2R02	614	2 088	30	15,6	517	10,9	3,0	H	H
Mentz	N2R01	247	16 826	159	205,6	3 594	34,0	5,7	L	H
P K le Roux	D3R03	1 170	89 842		3 236,6	13 867		23,3		L
Poortjieskloof	H3R01	370	94	8	10,4	106	22,0	10,0		
Smartt Syndicate	D6R02	1 094	13 394	55	98,0	3 089	13,5	3,2		
Stompdrif	J3R02	444	5 235	27	61,2	642	32,9	9,5	H	M
Van Ryneveldspas	N1R01	788	3 681	36	51,8	1 094	10,5	4,7		
Van Wyksvlei	D5R02		1 339		75,3	3 726	7,0	2,0		

MINERALIZATION

Mineralization, or gross inorganic salt contamination of natural waters, is a problem of increasing importance in South Africa. Most drainage regions associated with the karoo biome have been identified as problematic in this respect, ie the Great Fish, Sundays, Breede, Gouritz, Bushmans, Groot and Olifants catchments (Hall and Görgens 1978). In rivers such as these, total dissolved solids (TDS) or specific ion (eg Cl^-) concentrations are frequently in excess of limits set for the different uses of the water.

A case in point is the Sundays River catchment: Lake Mentz (N2R01) is the supply source for the irrigation of extensive citrus orchards in the lower Sundays River valley. The Voël River, an important tributary of the Sundays River, flows directly into Lake Mentz. Chloride concentrations in Lake Mentz have, until recently, been satisfactory for citrus irrigation, for which the desirable maximum chloride concentration for that region was found to be 250 mg l^{-1} by Du Plessis (1975). However, during the period of above average rainfall of 1974-1977, continuous saline baseflow led to a severe deterioration in the quality of water in the impoundment; chloride concentrations rose to a high 700 mg l^{-1} by the end of September 1978. This phenomenon has allegedly had harmful effects on the irrigated citrus trees (Hall and Görgens 1979). Figure 9 shows a 22-year time series of chloride concentrations and storage volumes in Lake Mentz - note the dramatic increase in chloride after 1974. (The simulated values are the output from a conceptual rainfall-runoff-salinity catchment model applied by Hall and Görgens (1979). In Figure 10 an approximately inverse relationship between solutes and flow rate, which is typical for most unmanaged rivers, can be seen (Voël River) - notable are the long periods of baseflow with very high chloride concentrations and the rapidity with which chloride concentrations return to levels above the desirable limit of 250 mg l^{-1}.

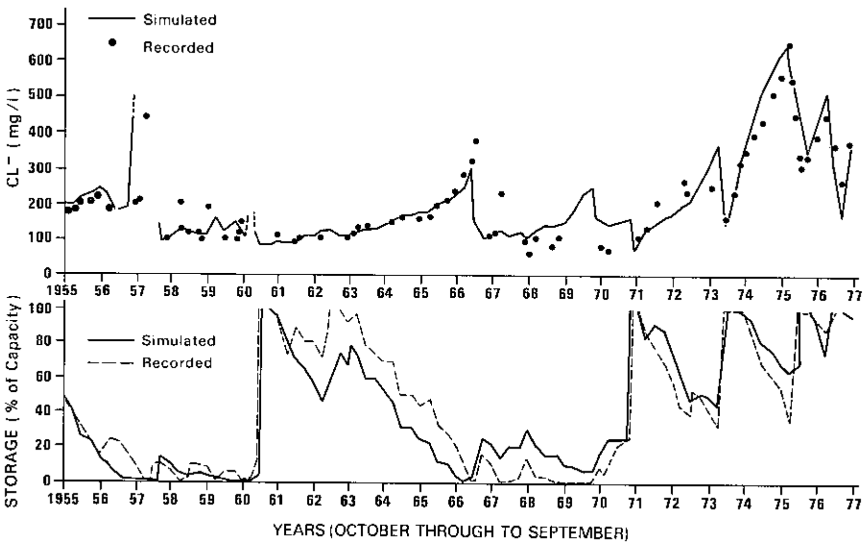

FIGURE 9. Recorded and simulated end-of-month storage volumes and chloride concentrations in Lake Mentz (after Hall and Görgens 1979).

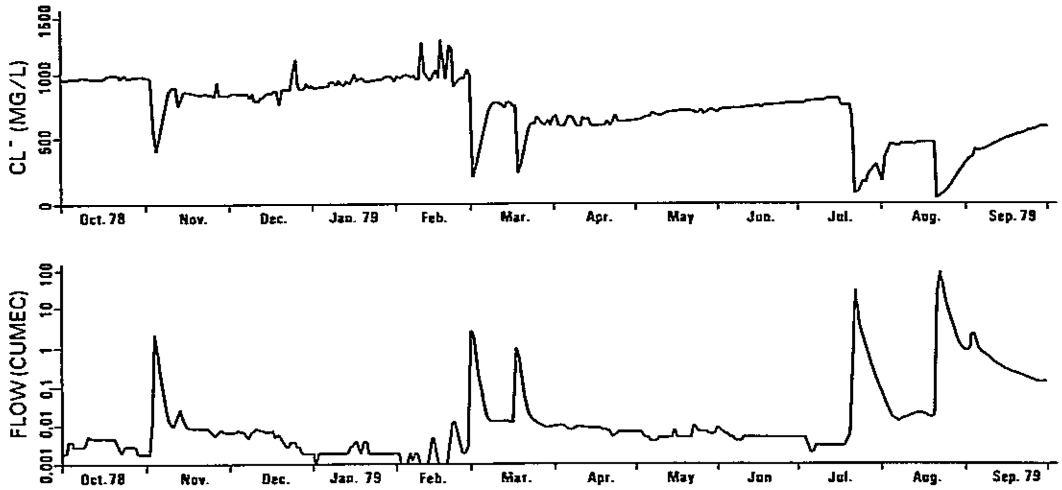

FIGURE 10. Streamflow and chloride (Cl^-) concentration time series observed at station N3M02 in the Voël River upstream of Lake Mentz (after Hall et al 1980).

In general, mineralization takes place whenever water comes into contact with soil and rock, and leaches inorganic salts released by weathering or concentrated by evaporation. The degree of mineralization of river runoff from natural catchments appears to depend largely on the physical and chemical properties of the soils and geologic strata of the catchment, as well as on the local climate - in particular the spatial rainfall patterns and the evaporation demands.

Although mineralization occurs naturally - to different degrees - in all drainage basins, it is of concern particularly in arid and semi-arid regions, such as the karoo biome, where evaporation exceeds precipitation by a wide margin and leads to relatively high concentrations of salt in runoff, groundwater and impoundments. Observations made by Schutte and Bosman (1973) in some karoo dams illustrate this point well. For instance, they found in the case of the Stompdrif Dam (J3R02) that storage volume depletions from 17% of full supply capacity to 15 to 9% due to evaporation losses, were accompanied by TDS increases from 541 mg l^{-1} to 610 mg l^{-1} to 840 mg l^{-1}, respectively.

In two low-flow studies that reveal the magnitude of mineralized inflows from diffused sources along a major river, Viljoen et al (1981) made the following observations in the Great Fish River: the cumulative salt loads attributable to diffused seepage entering only the main channel (ie excluding tributary inflows) along a 180 km irrigated reach of the river averaged 137 tonne day^{-1} in July 1973 and 719 tonne day^{-1} in July 1977. These salt loads represented average cumulative seepage flow rates (actually measured) of 0,51 m^3 s^{-1} and 3,2 m^3 s^{-1}, respectively.

It is unclear what proportion of these salt loads is due to irrigation return flows and what is natural seepage, but it is well known that irrigation practices can often be associated with deteriorating salinity conditions in cultivated soils and in downstream riverflows. The concentrating effects of evaporative processes combined with multiple re-use of irrigation water along the reach of a river are the causes of this deterioration, which, again, is more pronounced in the semiarid to arid environment, than in the nonarid regions.

Published mineralization studies

Collaborative research programmes on the mineralization of the Great Fish and Sundays River systems in which the CSIR's National Institute for Water Research (NIWR), DEA, Department of Agriculture and Fisheries and a number of universities participated, were executed in the period 1970-1981. These programmes represent the only systematic attempt to study mineralization in karoo catchments and led to a number of publications.

In the light of the importance of the Orange-Fish-Sundays inter-catchment water transfer system built as part of the Orange River Development Project (South Africa 1962), the known mineralization of the rivers in the above network caused enough concern to warrant more than a decade of intensive research in the area. Central to this research was the development and application of a mathematical model to shed more light on the principal mineralization processes and to provide a means for predicting and managing future water supply and mineral quality conditions in the Fish/Sundays system. Görgens (1976) and Hall and Görgens (1978) sketched the philosophy and structure of this research. The first published application of the model was the simulation of chloride concentrations in Lake Mentz by Hall and Görgens (1979), (Figure 9) while the final model applications are reported in Hall and Du Plessis (1981a,b).

Supporting the modelling studies were numerous field surveys of water quality with respect to low-flows, irrigations, irrigated soil and groundwater. These are reported in Viljoen, Du Plessis and Hall (1981) while selected data are published in Viljoen, Du Plessis, Hayman and Hall (1981). Other water quality related studies in the Great Fish catchment are those by Tordiffe (1978) and Tordiffe and Botha (1981). A collection of papers presented at a workshop on all aspects of natural mineralization of semiarid catchments, has been published by the Water Research Commission (1980) and represents a reasonable summary of the state of the art in South Africa.

Streamflow chemistry

The monitoring of streamflow chemistry in the rivers of the karoo biome is a relatively recent undertaking by the DEA and in most cases dates back to the middle seventies or later. Monitoring takes the form of the chemical analysis of grab samples taken mostly at selected DEA riverflow gauging stations or in reservoirs. Most sampling is done on an approximately weekly or monthly basis, with daily sampling restricted to a few key sites. In the karoo biome as defined in this study, there are about 50 operational DEA water quality monitoring sites of which 25 are not subject to monitoring large-scale upstream works or influences. The mean number of analysed samples for all 50 sites is 115 with a range of 5 to 513.

From the DEA records all karoo stations without upstream interference, where a sampling frequency of at least one sample per month seemed firmly established, were identified. This yielded a total of 22 stations. Some statistics of the streamflow chemistry at these stations are given in Table 7, while Figure 1 shows the location of these stations. The overall median TDS concentrations vary over more than an order of magnitude, but the picture that emerges is that natural salinity levels seem much higher in the southern, eastern and central parts of the karoo biome, than in the northern and western parts. To form an opinion of the relative seriousness of natural mineralization among the various karoo regions, TDS values that are exceeded 90% of the time may be used. Considering that 500 mg l^{-1} is the normally recommended TDS concentration for domestic use, it is notable that in only five out of the 16 southern, central and eastern catchments, 90% of the samples did not exceed 500 mg l^{-1}. In the latter rivers, Na^+ and Cl^- are consistently very important ions, which has a bearing on the usefulness of the water for agricultural use.

Surprisingly, Table 7 does not reveal great seasonal differences in streamflow chemistry. In the summer and all-year runoff regimes there is a clear tendency for higher salinities in summer than in winter, but the sample studied is too small for definite conclusions.

SEDIMENT

The removal of sediment and its subsequent transport and deposition by rivers is often detrimental to man's activities. Common examples in South Africa are gully erosion on agricultural lands and storage losses due to reservoir sedimentation. These problems can be particularly severe in semi-arid regions, such as the karoo, where the climatological and hydrological regimes are conducive to high rates of erosion.

The quantity of sediment carried by rivers is a function of the amount available for removal, as well as the transport capacity of the river flow. The sediment transported by most South African rivers is very fine and the majority of the annual sediment production happens during periods of high flow when the rivers have large transport capacities for fine sediment, usually in excess of material available for transport. It is therefore found that for most South African rivers no unique relationship exists between channel discharge and sediment load (Rooseboom and Harmse 1979), as the availability of sediment is the controlling factor.

In the arid to semi-arid karoo regions, the hydrological sequence of events plays a major role in determining sediment loads. Drought periods lead to great amount of in situ chemical and mechanical weathering, which, if followed by flood events, give rise to high sediment loads. However, after long periods of above average rainfall less sediment remains for transport and the improved vegetal cover and channel vegetation retards removal such that, even during flood flows, sediment loads are lower.

Estimation of sediment yield

Because of the lack of consistent relationships between channel discharge and sediment concentration, it has been necessary to find other approaches to the estimation of sediment yield. The sediment production map in Figure 8 is extracted from a map for the whole of South Africa by Rooseboom (1978) from which the values for sediment yield in Table 8 are estimated. The map

TABLE 7. Some chemical characteristics of karoo rivers and dams not subject to major upstream disturbances

Station	Location in Fig 1	Catchment area (km^2)	Total No samples analysed	TDS($mg\ l^{-1}$) exceeded in 90%	Overall median TDS($mg\ l^{-1}$)
RIVER GAUGING STATION					
C5M12	a	2 372	120	272	523
E2M02	b	6 903	15	34	53
E2M03	c	24 044	34	71	179
H3M09	d	14	33	135	243
H4M08	e	101	24	798	1 686
J3M04	f	4 305	87	745	1 516
L1M02	g	3 675	85	910	1 460
L6M02	h	675	105	958	2 709
N3M02	j	1 590	123	1 055	1 817
P1M03	k	1 476	75	635	1 661
O3M04	m	872	77	717	1 088
Q4M03	n	1 300	134	403	722
Q6M02	o	819	101	551	762
Q8M04	p	808	140	526	1 089
RESERVOIRS					
C5R01	q	922	53	155	257
D3R01	r	255	49	380	635
E4R01	s	18	36	121	195
J1R01	t	558	25	559	1 387
J1R03	u	4 001	123	288	388
J1R04	v	251	35	416	816
L3R01	w	20 336	515	684	1 743
Q4R02	y	3 623	27	229	483

Median winter concentration ($mg\ l^{-1}$)				Median summer concentration ($mg\ l^{-1}$)			
TDS	Na	Cl^-	Highest other anion *	TDS	Na	Cl	Highest other anion *
533	61	32	TA:266	505	59	33	TA:255
-	-	-	-	-	-	-	-
125	26	43	SO_4:14	242	26	54	SO_4:16
-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-
1 516	375	493	SO_4:234	1 523	330	481	TA:253
1 470	272	451	SO_4:320	1 450	272	453	SO_4:319
2 640	643	930	SO_4:431	2 976	781	1 128	SO_4:461
1 769	375	684	TA:205	1 915	411	781	TA:212
1 418	340	614	TA:194	2 032	535	893	TA:205
1 028	185	150	TA:351	1 126	225	208	TA:325
729	92	154	TA:253	719	106	125	TA:251
772	122	163	TA:303	758	126	152	TA:281
1 035	160	203	TA:354	1 126	179	226	TA:360
261	27	17	TA:136	252	25	16	TA:130
614	98	63	TA:259	660	-	-	-
200	17	22	TA:91	166	11	16	TA:80
-	-	-	-	-	-	-	-
395	55	68	TA:134	387	57	74	TA:129
-	-	-	-	-	-	-	-
1 644	396	561	SO_4:335	1 861	450	588	SO_4:384
-	-	-	-	-	-	-	-

*TA - Total alkalinity as $CaCO_3$

TABLE 8. Sediment yield for some karoo dam catchments (from Rooseboom 1978)

Station number	River	Dam name	Catchment area (km^2)	Period of record	50 year sediment volume (10^6m^3)	Sediment yield ($t\ km^{-2}\ yr^{-1}$)	Full supply capacity (last survey)* 10^6m^3
C5R01	Kaffer	Tierpoort	940	1922-1961	5,35	154	33,00 (1960)
C5R02	Riet	Kalkfontein	10 277	1938-1959	31,10	82	343,00 (1938)
D3R01	Bethulie	Bethulie	254	1921-1959	3,30	351	4,66 (1949)
D5R01	Hartbees	Rooiberg	72 208	1935-1960	15,70	6	4,43 (1962)
D6R01	Dorpspruit	Victoria West	243	1924-1955	0,56	62	3,66 (1954)
J1R01	Prins	Prinsrivier	761	1917-1962	2,82	100	2,86 (1962)
J1R02	Brak	Bellair	546	1920-1946	1,27	63	11,10 (1946)
J2R01	Nels	Calitzdorp	176	1917-1946	0,18	28	4,98 (1957)
J2R02	Leeu	Leeugamka	2 222	1920-1930	2,58	31	13,30 (1967)
J2R03	Cordiers	Oukloof	148	1929-1965	0,28	51	4,50 (1970)
J3R01	Kammanassie	Kammanassie	1 505	1923-1955	6,64	119	32,90 (1955)
L3R01	Groot	Beervlei	20 300	1958-1967	6,60	235	93,50 (1967)
N1R01	Sundays	Van Ryneveldspas	3 740	1925-1973	28,00	202	53,10 (1966)
Q1R01	Groot Brak	Grassridge	4 483	1924-1966	37,00	223	58,40 (1966)
Q4R01	Tarka	Lake Arthur	4 460	1925-1951	86,00	521	29,70 (1966)

*Date of last survey according to the DEA (South Africa 1970), however, some of these reservoirs are known to have been resurveyed since 1970.

is based upon the subdivisions of Harmse (1975) who used soil type, geomorphology and geology to map yield potential. It should be noted that the values determined for relatively large catchments and smaller subcatchments can have much higher yields.

Sediment yields may also be estimated from observations of reservoir sedimentation rates based on tacheometric or sonar surveys of dam basins, figures for which (in terms of reduced storage capacities) are given in DEA publications (South Africa 1978). However, the values for reservoir storage capacity reduction have to be corrected for the consolidation and compaction of the deposited sediment.

Rooseboom (1976a) followed a procedure where the volume of a deposit (V_t) after t years is translated to an equivalent volume after 50 years (V_{50}) by means of the equation:

$$\frac{V_t}{V_{50}} = 0,376 \ln \frac{t}{3,5} \qquad (1)$$

Values of V_{50} for a number of reservoirs within the karoo region are tabulated in Table 8, and multiplying by the 50-year density (an average value of 1 350 kg m^{-3} dry density has been found in South Africa) gives the net deposited load over 50 years. For total sediment yield, allowance has also to be made for deposits lying above full supply levels, as well as sediment that has passed through the reservoir.

The following additional references may be relevant to sediment aspects of the karoo biome: Smuts (1949); Menne and Kriel (1959); Greyvenstein (1964); Schwartz and Pullen (1966); Rabie (1968); Doornkamp and Tyson (1973); Roberts (1973); Rooseboom (1975, 1976a,b, 1978); Jacobz and Crosby (1980).

INFLUENCE OF LAND USE ON THE KAROO HYDROLOGY

Streamflow

Changes in land use can have a marked effect upon catchment water yields by affecting the runoff response of the catchment to rainfall. This is particularly true in semi-arid regions where the proportion of rain that runs off is so low and therefore sensitive to alterations in land management practices. Changes such as urban development can cause increases in MAR while others such as soil conservation works or afforestation can cause reductions. Other effects on MAR may be caused by construction of a number of farm dams or large reservoirs or river abstractions.

In the report of the Commission of Enquiry into Water Matters (1970), mention is made of a general decrease in runoff over the previous 20 years in all areas with MAP less than 600 mm, which would include most of the karoo biome. The Commission ascribes this phenomenon to intensified agriculture and consequent increasing retention and use of runoff in the catchments themselves. Alexander's (1978) search for periodicities and trends in South African streamflows by cumulative residual mass curve analysis, confirmed the Commission's finding in the case of six eastern karoo catchments.

The most significant land-use change noted by Braune and Wessels (1980) in the karoo catchments was the extensive use of soil conservation measures during the thirties and also following on the 1946 Soil Conservation Act. Whitmore (1959) found a decrease in MAR, as a percentage of MAP, from 5,57% to 2,97% following the intensive application of soil and water conservation measures on a tributary of the Tarka River. The reduction in runoff is caused by the construction of conservation works which retard runoff and allow a greater time for evaporation as well as "biological control measures" (Whitmore 1959), such as pasture subdivision, grazing control, stock reduction and the protection of water courses with vegetation.

Trends in rainfall/runoff relationships were investigated by Braune and Wessels (1980) by plotting cumulative annual precipitation against cumulative annual runoff. Rainfall trends are thus removed and the diagrams illustrate long-term changes in the rainfall/runoff relationship. Table 9 summarizes the changes that were found by Braune and Wessels (1980) on 14 karoo catchments that they investigated. Some runoff trends cannot be explained by known land-use changes, while others are partially attributable to flow measurement station changes such as the rerating of channel sections, or weir modification.

Further reference can be made to the following reports and publications for additional information on the effects of land-use changes on runoff in South Africa: Whitmore (1967); Whitmore and Reid (1975).

TABLE 9. Runoff trends and land-use effects on runoff in karoo catchments (after Braune and Wessels 1980)

Station no	Records from to	Runoff change (% MAR before 1st change in record)	Approx year of change	Comments
D1M01	1912-1977	-40	53/54	Possible effect of farm dam construction
D3R01	1929-1975	-	-	No effect of farm dams
D5R01	1933-1974	+77	65/66	Unknown effect
E2M02	1923-1976	-46	54/55	Unknown effect
E2M03	1916-1973	-37	59/60	Possible station changes
H7M04	1951-1976	-	-	No effect on farm dams
J1R01	1916-1976	-32	36/37	Possible soil conservation effects
J1R02	1920-1973	+76	48/49	Effect of reservoir capacity change
J2R01	1919-1976	-38	43/44	Possible soil conservation effects
J2R03	1930-1976	+111	65/66	Unknown effect
J3R01	1922-1976	-53	49/50	Possible soil conservation effects and/or station changes
N1R01	1928-1975	-62	33/34	Soil conservation effects
Q1R01	1924-1973	-34 -76	33/35 51/52	Soil conservation effects and/or possible station changes
Q4M01	1914-1972	-54	54/55	Soil conservation effects

Mineralization

Little quantified information on the effect of land use on the mineralization of karoo rivers is available. However, the three most significant land-use effects can be expected to be those associated with irrigation practices, dry-land cultivation and stocking and grazing practices on farms.

Hall and Du Plessis (1979) calculated the long-term average annual contribution of upstream irrigation return flows to the chloride concentration in Lake Mentz (Sundays River) as being of the order of 14%. Hall and Görgens (1978) report increases in average seasonal TDS concentrations (based on daily sampling) along a 90 km irrigated reach of the Breede River, of 707% and 440% for the summers of 1975 and 1976 respectively. Interpretation of these salinity increases is difficult without knowing the simultaneous flow patterns in the Breede River, but as this is a winter rainfall area, the increases could well be related to irrigation practices.

No research on the effect of dry-land cultivation on downstream mineralization of karoo catchments has been reported in the literature. A study which may provide some guidelines in this regard is that by Fourie and Görgens (1977) on the mineralization of the Berg River in the western

Cape. They found that increased dry-land cultivation in the middle to lower catchments (which has a climate bordering on the semi-arid) during the past two decades, is one of the important factors contributing to a general tendency towards increased salinities in the lower Berg River, especially noticable during the winter-rainfall season. They state that cultivation improved the natural infiltration characteristics of the catchment, resulting in relatively fresh surface runoff being replaced by saline subsurface flow through weathered Malmesbury Shale formations (the dominant geologic formation in the middle to lower catchment).

Downing (1978) suggests that the replacement, since 1850, of the wild herbivore population in South Africa with selective feeders in the form of cattle, sheep and goats, has resulted in severe ecological imbalances of the large grass plains. As no specific data are available, the effects of selective or injudicious grazing and overstocking on the mineralization of karoo catchments can only be speculated upon. Notable at this point is the conclusion of Daniel (1980) after a survey of 159 farms in the Great Fish and Sundays drainage regions during the early seventies. He found that 27% of the farms in the False Karoo veld type regions (Acocks 1975) and 36% in the Grassveld areas were overstocked - with average numbers of excess small stock units per overstocked farm of 448 and 350, respectively. It can reasonably be expected that overstocking and abuse of natural grazing will largely alter the infiltration characteristics and vegetation cover of catchments, leading to changes in the previously suggested delicate hydrological equilibrium of the karoo environment. This must of necessity result in altered patterns of salt distribution and transport in affected catchments. Mineralization changes of this nature are bound to be insidious and subtle and may only really be noticed during or after extreme climate phenomena like severe drought or a few years of abnormally high rainfall.

Sediment

Land use can effect sediment yield from rural catchments in either a negative or a positive context: the negative effects of increased top soil losses, gully and donga formation and river bank erosion are related to overstocking; abuse of natural grazing; injudicious ploughing; veld-burning and vegetation clearance; and poor watercourse management. Amongst these practices, overstocking may well be the most prominent in the karoo areas (Downing 1978; Daniel 1980; Roux and Opperman this volume) and certainly is one of the more dangerous because of its insidious development and enduring effects on the vegetational and hydrological environment. The positive context comprises structural catchment rehabilitation, soil conservation and erosion control programmes and the biological control measures referred to earlier in this section.

An indication of the magnitude of the effect of controlled rehabilitation of a much eroded catchment on sediment yield is given by Whitmore (1959). She found that the loss in capacity of Lake Arthur (Q4M02, Tarka River), due to sedimentation, decreased after the introduction of large-scale soil conservation farming from a preconservation average of 2,1 million m^3 per year. She attributes this reduction in runoff volume from the catchment (mentioned earlier), and not to any reduction in the sediment yield per unit of runoff.

In contrast to Whitmore (1959), Rooseboom and Harmse (1979) have illustrated a reduction in sediment load in a negative context: they found that the sediment load of the Orange River at Upington decreased by a least 50% during the period 1929-1969, and indicate that this was due to a marked decrease in sediment yield over mostly the central karoo regions of the drainage basin. They suggest that after an initial period of greatly accelerated erosion in the second and third decades of this century due to human abuse in these catchments, sediment production started decreasing due to a decrease in availability of erodable top soil. They show that the largest decrease in sediment production started well before the introduction of major soil conservation and stock reduction programmmes in the affected areas and conclude that the susceptibility of a region to continuous erosion does not depend primarily on the original vegetation cover and its subsequent deterioration. The soils, geomorphology and geology are the main factors which determine the susceptibility to erosion and the recovery potential of an area within a specific climatic zone.

DEFICIENCIES IN KNOWLEDGE

In earlier sections of this chapter it was shown that the available streamflow records are adequate to provide reasonable insight into the general hydrology of the karoo region. However, currently we have little knowledge of, and cannot quantify at all, the specific effects of land-use changes on the water quality of karoo rivers. The concentrations of suspended sediments and solutes in these rivers will increasingly be a determining factor in the effective utilization of the surface water resources of the karoo region. Controlled experiments, both at the plot and catchment scales, are the most useful techniques for acquiring the detailed knowledge necessary to improve our understanding of changing land-use effects on the hydrological balance.

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CHAPTER 5. GEOHYDROLOGY

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INTRODUCTION

The karoo biome is characterized by a general scarcity of surface water sources. The agricultural industry, as well as the majority of towns found in this region, are therefore greatly dependent on groundwater for their daily needs. The nature, occurrence and distribution of groundwater in this region can usually be linked to a variety of factors. Aspects which play an important part in the yield and in the quality of the water are the following:

- The permeability of rocks is one of the most important factors determining the yield of a borehole. The greater the permeability of the rocks, the greater is the delivery of the borehole.

- The most important factor determining the protracted delivery of a borehole is the quantity of groundwater which is stored underground in a specific area. Groundwater systems with high storage properties can be utilized for long periods on end without detrimental effects such as the overtaxing of the system taking place.

- The quantity of rainfall, ie the measure of replenishment of the groundwater system in a specific area, is a factor which could influence both the protracted delivery as well as the quality of the water. Areas with high rainfall are generally characterized by the high delivery potential of groundwater sources and the accompanying high quality of groundwater. On the other hand, the possibilities for protracted delivery of groundwater sources in arid areas are less bright. Often the quality of these sources is not as desired.

- The rock type in which the groundwater occurs is one of the main determining factors controlling the quality of this water in a particular area. Thus the groundwater quality is poorer where it occurs in rocks with a high concentration of soluble salts.

- A final factor which plays an important part in the groundwater quality of a particular area is the gradient of the water table. In areas in which steep gradients are found, for example in the proximity of mountains, the quality of groundwater generally is better than that of similar sources situated in the vast karoo plains.

It must be realized that one of the above-mentioned determining factors can exclusively determine the nature of a groundwater system. One of the factors could indeed play a dominant role in characterization of a groundwater source, but each one of the factors does make a contribution. By means of combinations of above-mentioned factors and by varying the influence of these, a great variety of groundwater types and a considerable variation in the groundwater delivery properties of an area can be obtained. Due to the great variety of rock types, rainfall distribution and topographical irregularities occurring in the karoo biome, it is not possible to establish a typical and comprehsnive groundwater characteristic. It is therefore required that the area is subdivided into smaller sections in which more uniform groundwater characteristics are found. Thus it is possible to subdivide the karoo biome on the basis of each of the above-mentioned five factors. An arbitrary subdivision, however, is not desirable since a relation must be found between this and other chapters of this contribution. The method of subdivision which probably best meets these requirements is that of subdividing the karoo biome according to rock types. The same subdivision is that used in the geological text is utilized for this.

GROUNDWATER OCCURRENCE AND DISTIRBUTION

Groundwater in the pre-Cape rocks of Namaqualand

Groundwater in this remote, dry and sparsely populated area is mainly associated with joints, cracks and faults. Due to the intense metamorphism which these rocks underwent, the area is interspersed with prominent joint systems. Faults are also common. Cooling cracks can be recognized in the intrusive rocks.

Although the Namaqualand rocks generally are characterized by marked structural deformations, the majority of joints, cracks or faults are sealed due to secondary precipitation of calcite or quartz. As a result of this, cavities and openings in the rocks are filled up. Their permeability is low and the quantities of groundwater stored in the system are small. A drastic decrease in the quantity of rainfall from east to west is also present. In view of this, the statement can be made that the yield and the water quality in the western areas are poorer than in the east.

The Namaqualand Complex also consists of a great variety of rock types. Rocks with little soluble salts will naturally contain water of a better quality than that found in rocks with many soluble salts. Thus it was found in the Prieska area (Potgieter et al 1980) that the best quality water is found in the quartzites of the Namaqualand complex. On the other hand, the metamorphic rocks such as amphibolite and vulcanic rocks such as andesite lava usually contain groundwater with high aggregates of dissolved salts. As an example of the extent to which the quality of groundwater in a particular area could vary, a number of analyses from the Prieska district (Potgieter et al 1980) was indicated by dots on the Piper diagram (Figure 1). This procedure for groundwater analyses on the diagram briefly involves the following: the major cations, (% meq l^{-1}), are noted on the left-hand triangular diagram. The major anions are dotted down on the right-handed triangle in a similar fashion. Projections of these points are then made on the central diamond-shaped figure. The dotting procedure is also illustrated in Figure 2. From the dotted positions in Figure 1 it is clear that a great variety of groundwater qualities are found in the area. General trends can, however, be noted. This can be ascribed to the normal evolutionary process of groundwater which is trapped in the ground for protracted periods. It can be concluded on the grounds of chemical data, that the annual replenishment of the groundwater system in the particular area is slight. There is also little dynamic flow of groundwater. Intensive pumping out will therefore result in the overtaxing of the groundwater source.

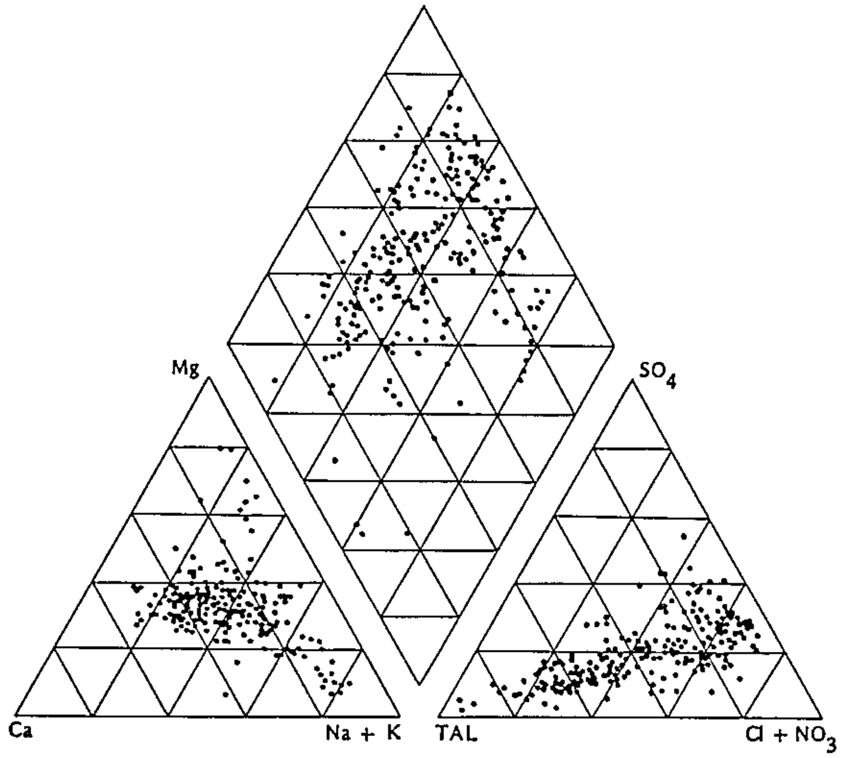

FIGURE 1. Positions on the Piper diagram of groundwater samples from the Cape rocks in the Prieska area.

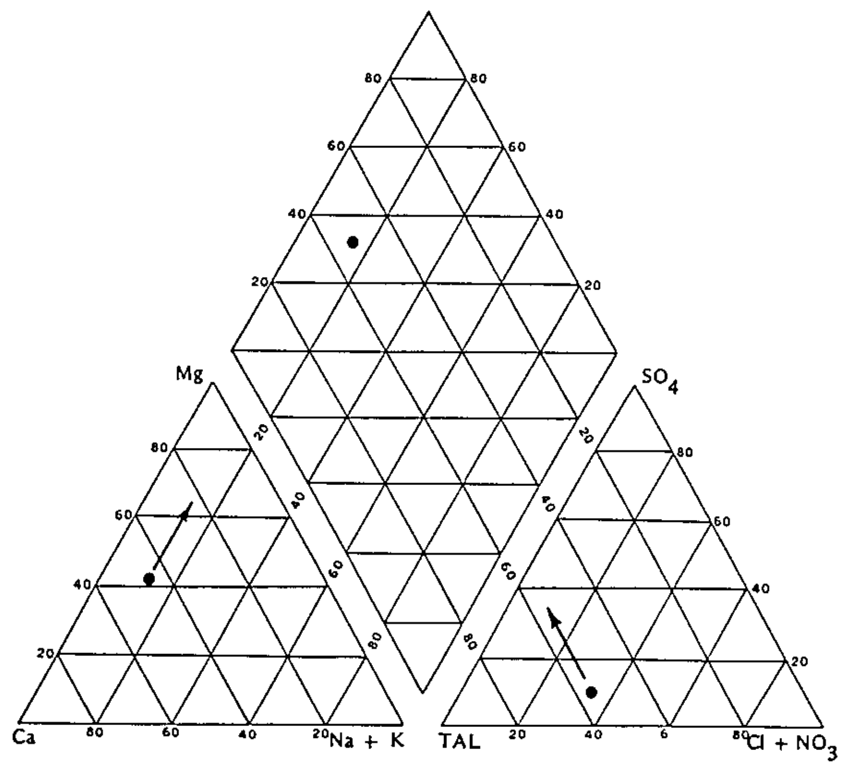

FIGURE 2. Examples of the plotting procedure on the Piper diagram. The particular sample contains 44% calcium, 42% magnesium, 14% sodium and potassium, 53% bicarbonate put as total alkalinity, 12% sulphate and 35% chloride and nitrate.

From an agricultural point of view the quality of the groundwater can be evaluated on the grounds of the sodium absorption relation diagram (Figure 3). According to this diagram it is clear that crops irrigated with water from this area, would be subject to salinification as well as to a sodium hazard.

From the above-mentioned it is therefore clear that the potential use of groundwater from the Namaqualand complex is limited.

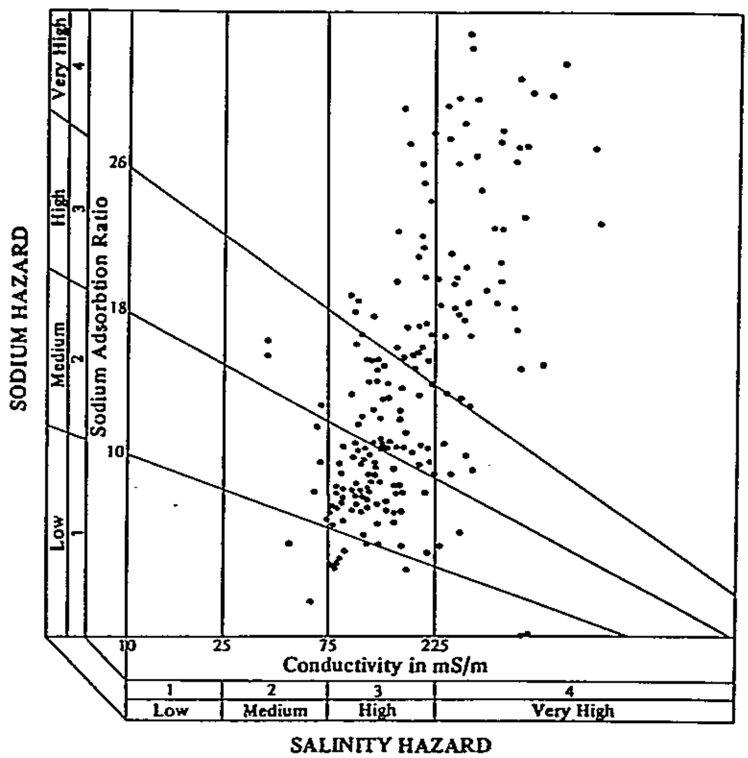

FIGURE 3. Sodium absorption relation diagram of groundwater samples from the Prieska area.

The Cape Supergroup

Rocks of the Cape Supergroup occurring in the karoo biome consist of the Table Mountain, Bokkeveld and Witteberg Groups. Groundwater movement mainly takes place in joints or faults in these rocks. Du Toit (1928) indicated that the yield of boreholes in these rocks generally is fairly good. Even in regions such as Prince Albert, Oudtshoorn and Willowmore, which have a scanty rainfall, yields of two to five litre/second is common. However, in the Uitenhage district the average yield is lower - only 0,5 litre/second.

Frommurze (1937) furthermore indicated that the permeability of rocks increase, due to their tilted and jointed nature. This also facilitates the seeping in of rainwater. The average depth at which water is found, usually is much less than 30 m (Bond 1947).

Quite a number of smaller towns are situated on these rocks. The majority of these towns, however, obtain their water supplies from mountain torrents from the Table Mountain Sandstone. The quality of water from the latter source is much better than that of the groundwater in the Bokkeveld and Witteberg Group, which is generally brackish.

Karoo Sequence

Due to the vastness of the Karoo Sequence in the karoo biome, a great variety of groundwater types are present. Groundwater is generally found in joints in Karoo Sandstone. It is also often associated with dolerite intrusions such as dolerite dykes and, to a lesser extent, dolerite sills. Due to its fine texture, Karoo Shale does not contain sufficient groundwater supplies which can be released from boreholes.

The five determining factors which were mentioned as the controlling factors in groundwater yield and quality, in the introduction of this chapter, also play an important part in the Karoo Sequence. Cracks in the Karoo Sandstone and along dolerite intrusions are relatively abundant. The possibility of intersecting more than one of these cracks in a single borehole is relatively high. Truly dry holes seldom occur. The permeability of these cracks, however, is relatively low. The yield of boreholes in the eastern section of the karoo biome averages four litres per second, while poor delivery, in the region of one litre per second, is generally found in the western area.

Since only the cracks in the karoo rocks are able to release water, little storage of groundwater takes place in the Karoo Sequence. Exhaustion of the system is often caused by intensive pumping. Rainfall plays an important part in the replenishment of supplies. A few examples of the water-level reaction with respect to rainfall (Kok 1975) are given in Figure 4. From this it is clear that periods of high rainfall are often followed by a rise in the groundwater level.

The quality of groundwater in the Philippolis district is indicated in Figure 5 (Van der Linde and Hodgson 1977). From the geohydrochemical principles at issue here, the deduction can be made that this water is mainly of a calcium/magnesiumbicarbonate composition. The rare deviations which are also illustrated can be ascribed to exceptional occurrences of deep seated groundwater sources. The latter sources, which are especially found in the southern Orange Free State, are usually rich in sodium chloride or sodium bicarbonate, and are furthermore characterized by a slightly increased temperature (up to 30°C) and a hydrogen sulphide odour. Water levels in the latter boreholes are not influenced by local replenishment from rainfall as is the case in Figure 4.

The quality of groundwater in the Karoo Sequence is greatly dependent on the local rock types. The high sodium chloride content of groundwater found in the Dwyka sediment is typical. The salt content of the water in the Dwyka sediments from the Prieska district and several rocks in the Namaqualand Complex is illustrated in Figure 6. The great influence of the rock type on water quality distribution is evident from the great variations in the diagram.

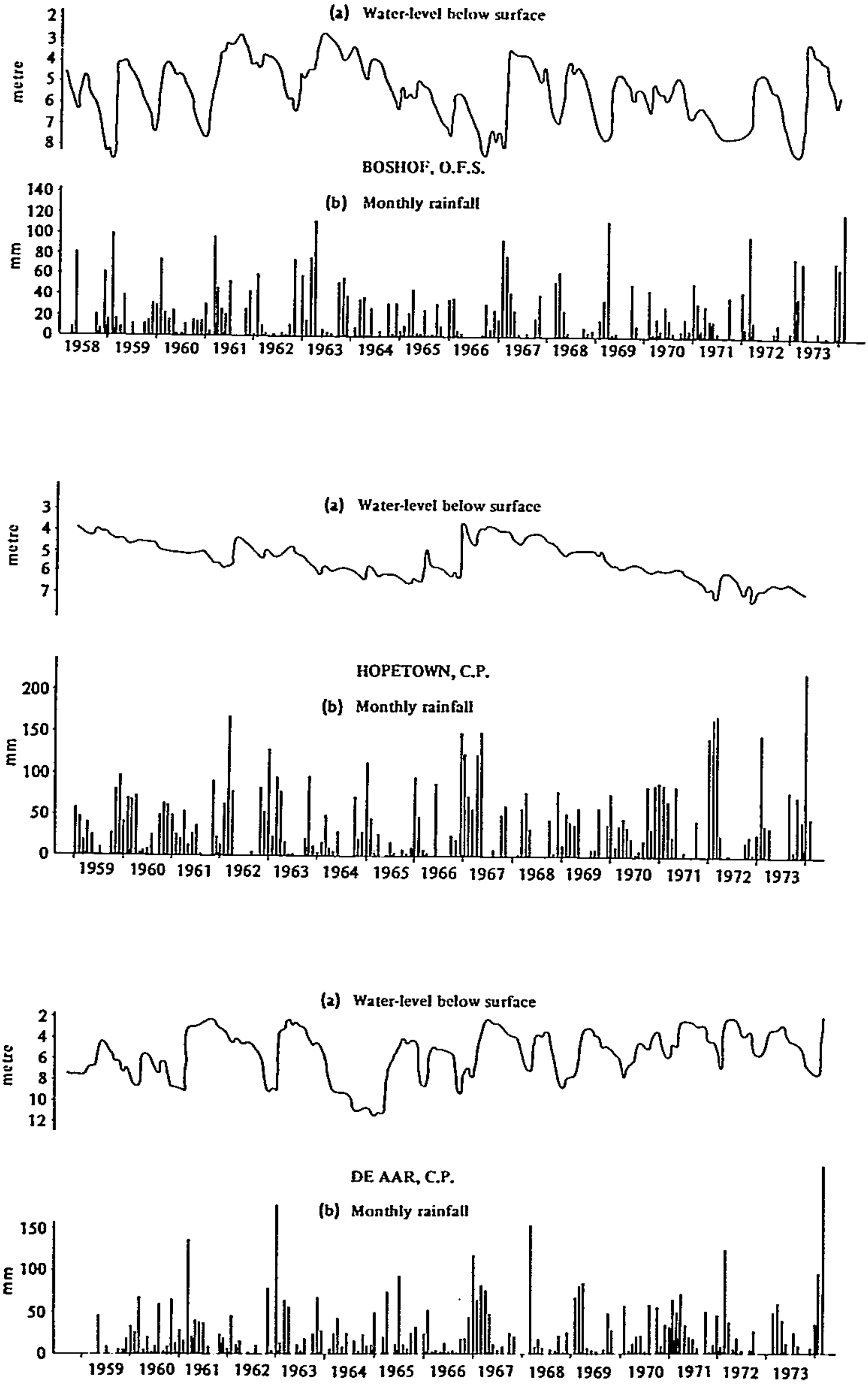

FIGURE 4. Groundwater levels and rainfall quantities from various localities in the Karoo Sequence.

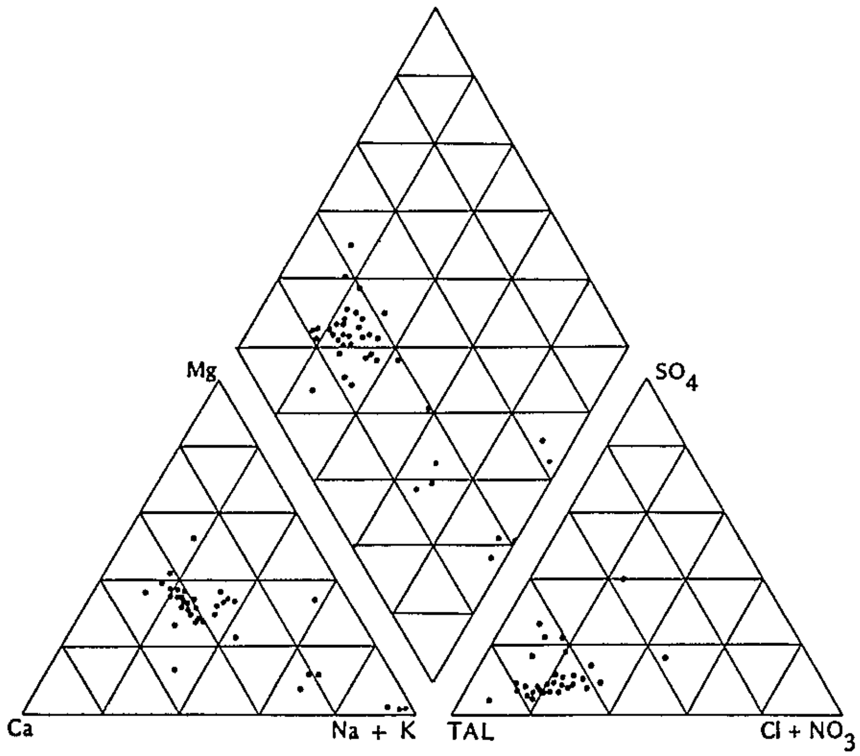

FIGURE 5. Positions on the Piper diagram of groundwater samples f om the Karoo Sequence in the Philippolis district.

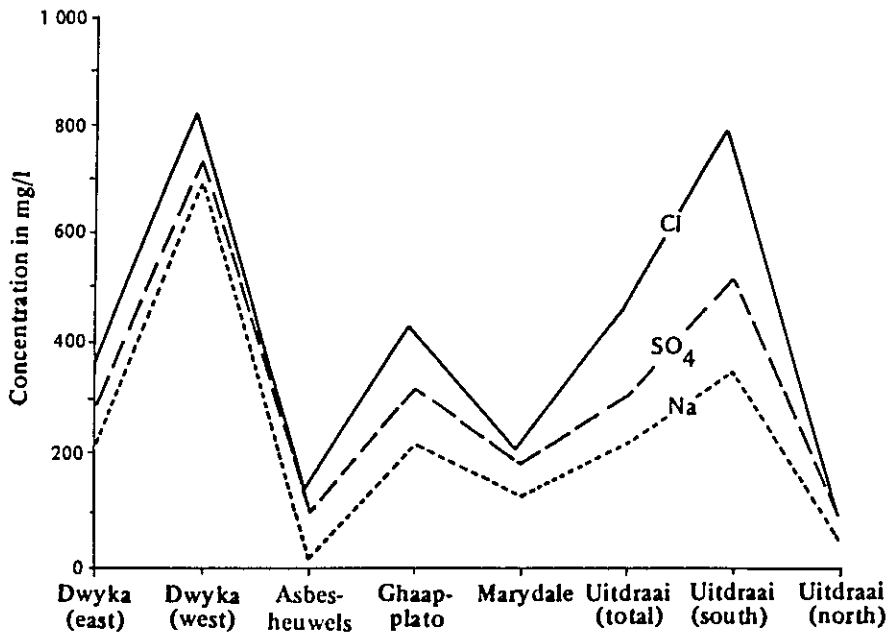

FIGURE 6. Average chemical composition of groundwater samples according to various rock types in the Prieska district.

Post-Karoo rocks

A few examples of post-Karoo rocks are also found in the karoo biome. Generally incidences of groundwater in these rocks are limited. Usually, replenishment is extremely local and brackish water is often associated with these deposits. Limited development of these groundwater sources did, however, take place in the past. Boreholes in the vicinity of De Aar, as well as boreholes in the sand depositions along the west coast, serve as examples.

SUMMARY

Groundwater yield and groundwater quality vary greatly in the karoo biome. Generally, these two facets are most closely related to the rock types and the rainfall of a particular area. Thus groundwater of a better quality and higher yields is generally found in the eastern part of the karoo biome, which is characterized by higher rainfall. It is found that a drastic deterioration of the quality of the water takes place from east to west.

Due to the general low rainfall over the karoo biome the amount of rainfall reaching the water table is limited. Groundwater sources which are subjected to intensive withdrawal are therefore likely to be depleted.

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CHAPTER 6. SOIL EROSION

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INTRODUCTION

Soil erosion in the karoo biome varies from moderate to extremely severe. The symptoms of erosion are sometimes conspicuous, such as gulleys, and in other cases inconspicuous, like sheet erosion - though possibly equally serious.

The causes of erosion are twofold, viz natural or geological erosion and man-made or accelerated erosion. Accelerated erosion at present forms an integral part of the so-called desertification process; this process is associated with the degeneration of the natural resources (UNCD 1977).

Although geological erosion (physical and chemical weathering) is continuously in progress, it is of such an imperceptible and gradual nature that it can only be evaluated significantly in terms of millennia. This includes the disintegration, exfoliation, oxidation, carbonization and hydration of rocks. In marked contrast with this, man, during the course of his history, has been directly responsible for the destruction of sometimes whole regions of land through overexploitation (Hofmeyr and Booysen 1956). This impact has many ramifications and involves a complicated interaction of physical and biological factors. One of the interwoven factors is the economic survival of man and the maintenance of styles and standards of living that set high demands on natural resources.

According to Stallings (1959) accelerated erosion must be seen as a result of the incorrect treatment of land and the use of land for purposes for which it is not suited. In the karoo biome, for instance, small stock farming may be considered to run counter to the maintenance of the natural veld (Director, Karoo Region 1981). By the same token, the adverse effect that the cultivation of crops has on marginal areas - such as the western Orange Free State (Director, OFS Region 1981) - may also be construed as a sign that such cultivation is inconsistent with the maintenance of a stable environment.

The seriousness with which the erosion problem and the resultant degradation of the natural resources, especially the agricultural resources, was treated by the authorities in the past, is reflected in the number of committees and commissions that were appointed to investigate the matter. As far back as 1923 (Drought Investigation Commission 1923) a thorough report was given on, inter alia, the erosion problem. This report dealt mainly with areas situated in the karoo biome.

Other reports and documents which emphasized the erosion problem and its consequences in South Africa were those of Van Reenen (1935), Tidmarsh (1948), Desert Encroachment Committee (1951) and many more. Everything considered, the erosion problem, and accompanying desertification, is one of the biggest environmental and agricultural problems in the RSA.

This process of destruction started in the final decade of the previous century and appears to have reached a climax before 1940. Figure 1 provides a classic example of large scale destruction in the upper reaches of a catchment area.

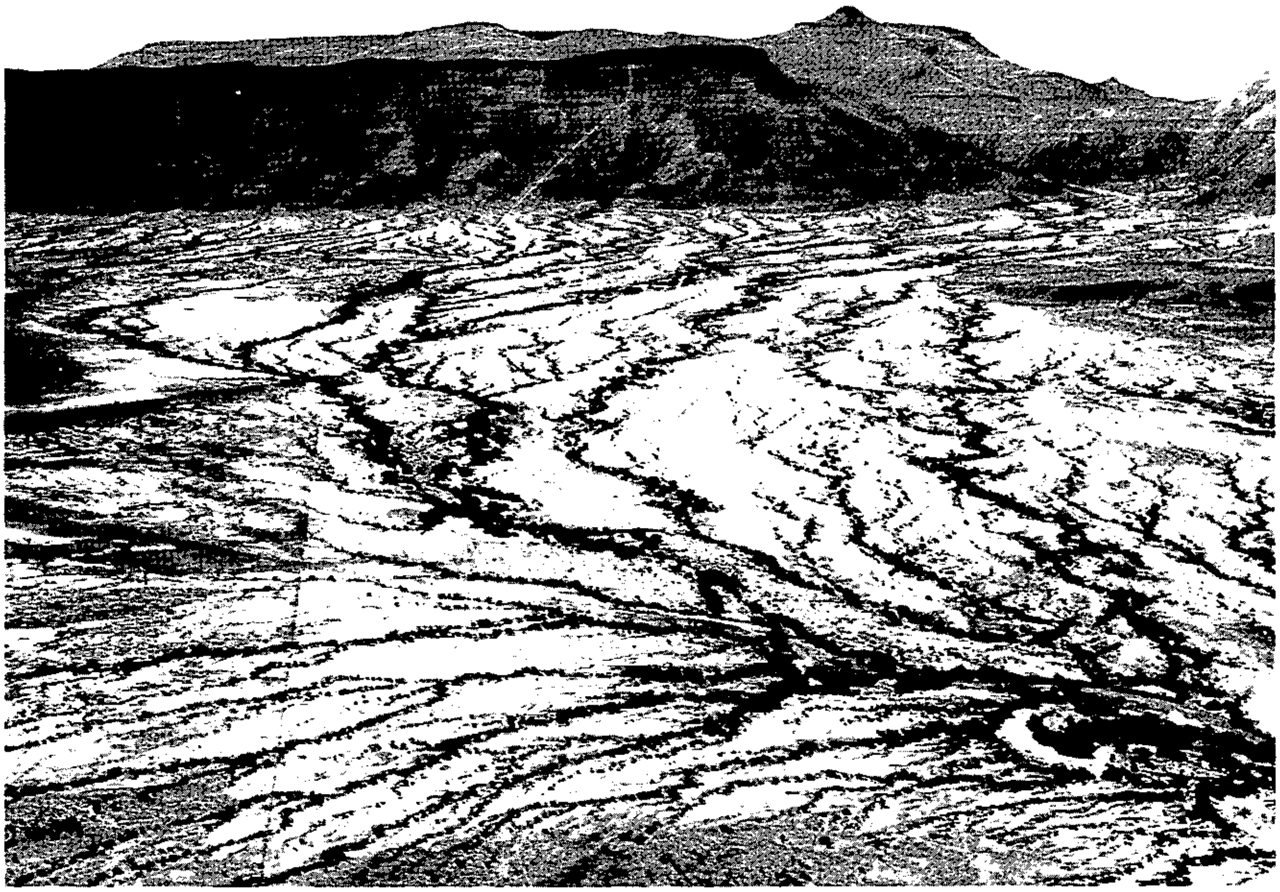

FIGURE 1. Extensive and advanced gulley sheet erosion in the upper reaches of the Tarka River in the Hofmeyr district in 1941.

CAUSES OF EROSION

Overgrazing by farm animals

The chief cause of accelerated soil erosion in the karoo biome is the degradation of the plant cover under grazing pressure of an established extensive small stock industry, traditionally conducted in that area (Roux 1979). Sheep numbers in South Africa reached a peak in 1930, amounting at that stage to about 48 million (De Wet 1980). In 1980 the number was about 34 million.

Woolled sheep numbers in 1933 peaked at 40,3 million and dropped to 24,3 million in 1946 (Pienaar 1967). Woolled sheep numbers in the Karoo Agricultural Region are at present approximately 7,0 million, with a total small stock number of about 10 million (Director, Karoo Region 1981).

According to estimates of grazing capacities in the Karoo Agricultural Region, a "safe" stocking rate is considered to be about 7,0 to 7,5 million small stock units. It is clear, therefore, that the area is overstocked by 30%.

The effect of cattle farming on the plant cover is less severe than that of small stock, provided overstocking does not take place. It is well known that cattle, as a result of their grazing habits, cause less damage to plants than sheep do (Roux 1968).

Accelerated erosion probably started actively as early as the beginning of the 19th century (Hofmeyr and Booysen 1956) when the fast expanding stock industry was compelled to open up new grazing fields to accommodate growing livestock numbers. Later this expansion began to take place at the expense of the natural agricultural resources, which in time were seriously damaged. Erosion processes were soon set in motion, which today cannot easily be brought under control owing to their extensive nature.

During the early development stages of the livestock industry, vulnerable grazing lands like vleis, valleys, and fountain areas were made more grazeable by burning the vegetation, while vleis and marshy areas were allowed to drain by breaking natural embankments and making furrows. Predators and bloodsucking insects were also controlled in this way and watering places were opened up and made safer. Furthermore, this drained and cleared ground was ploughed up and lands were established. These areas were also denuded by selective grazing and trampling by stock under the kraal system (Drought Investigation Commission 1923).

The fear that sheep were detrimental to karoo vegetation was expressed as early as 1864 by J H Davis of Colesberg; also by Shaw in 1875 (Tidmarsh 1948). That stock have an adverse effect on veld, especially as a result of overgrazing, has been suggested by numerous authors (Drought Investigation Commission 1923; Gorrie 1935; De Klerk 1947; Tidmarsh 1948; Desert Encroachment Committee 1951; Roux 1962, 1979; Heady 1975; Departementele Komitee Insake Veldagteruitgang 1980).

It is clear that too many animals per farm unit, accompanied by the failure to apply efficient feld management practices, is the largest single cause of the degeneration of the plant cover and the consequent acceleration of erosion.

<u>The physical impact of the grazing animal</u>. As a direct and indirect erosion agent, the physical impact of farm stock on the soil and vegetation is of cardinal importance. The intensity of trampling is extreme. It has bearing especially on the destruction of vegetation, the pulverization of soil and the formation of footpaths (Figure 2). These effects increase erosion vulnerability and weatherability of soil and in many cases, initiate progressive erosion. Often, especially on heavier and brack soils the hoof action of stock - particularly sheep - cause adverse compaction of the soil surface.

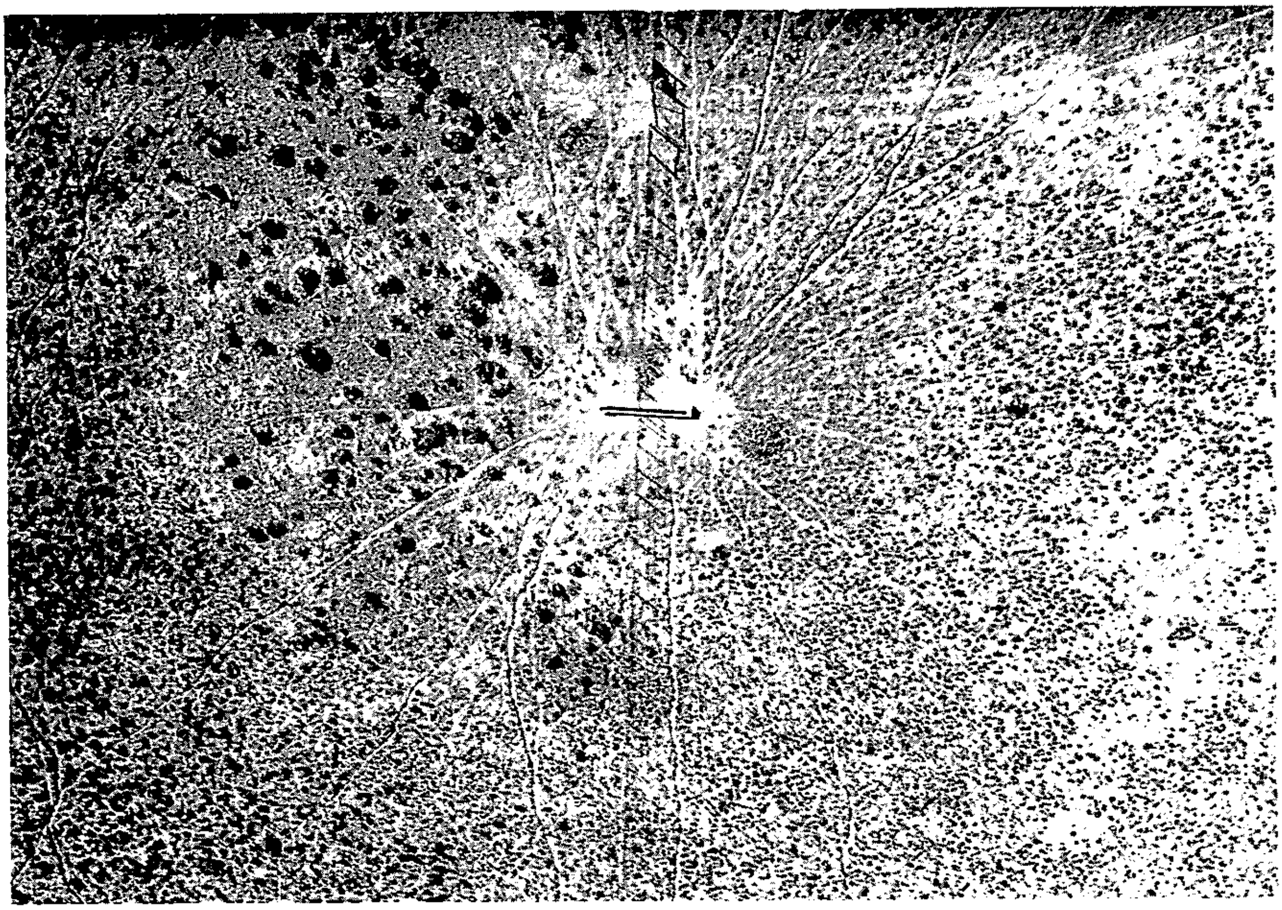

FIGURE 2. Typical footpath development around a stock watering point caused by the trampling of sheep (Middleburg Cape district).

Advantageous effects of trampling are the tramping in of seed and the breaking up and tramping in of organic material which provides an improved seed bed. Generally trampling by stock is seen as an important agent in the advancement of erosion.

Different animal types have different so-called trampling indices. Relative trampling indices for the most important kinds of animals have tentatively been drawn up by Roux (1980a). The speed and extent of piosphere development (zone trodden bare, for instance around a water trough) are directly correlated with stock numbers and size of camp. The greater the number of stock in a camp, the higher the trampling density will be at stock collection points.

Research on the physical impact of small stock on the vegetation and soil deserves imediate attention.

Drought

During droughts erosion is accelerated considerably. The karoo biome is subject to droughts (when rainfall is 60% or more below average) between

30 and 50% of the time (Weather Bureau 1949). In the western half of the karoo biome area, droughts lasting up to two to three years or even longer are not unusual (Du Plessis 1967). During drought the ground-cover provided by vegetation reaches a low point, the soil dries out and is easily eroded by wind; wind and whirlwinds are general phenomena and wind erosion can be severe.

The influence of drought and low soil moisture status on the erodibility of soil should be investigated.

Fencing Act of 1912

A factor which has ostensibly caused a drastic change in the exploitation of veld was the Fencing Act (Act No 17 of 1912). It is interesting to note that the Drought Investigation Commission (1923) indicated that the carrying capacity of the veld could be increased considerably by subdividing the veld into camps. Basic subdivisions were carried out on large scale and stock numbers were increased with dire consequences.

A peak was reached in 1933 when numbers totalled 40,3 million in the Union of South Africa. This number dropped to 24,3 million in 1946, but by 1982 had risen to about 28 million.

Other human activities which either directly or indirectly caused erosion were veld burning which temporarily exposed soil to the elements; road building, the excavation of gravel and ground quarries; irrigation with attendant salinization of soil; stripping and destruction of the plant cover around built-up areas and in commonages; the laying dry of soil below raised roads and railway lines; the injudicious building of contour banks; weak dam walls that break; the driving of vehicles in the veld and the construction of aerodromes; etc. As contributing factors to the greater erosion problem, all these activities may, however, be considered negligible.

THE INFLUENCE OF INDIGENOUS FAUNA

Springbok

The springbok (Antidorcas marsupialis) is one of the herbivores, excluding farm animals, which have the greatest influence on the vegetation of the karoo biome. Prior to 1850, springbok roamed the South African plains in their millions (Skead 1980). These springbok, in conjunction with other game, were responsible for bare patch and pan formation and general erosion.

The extent to which springbok at present contribute to erosion is apparently negligible. In the future their influence may become a factor in the erosion process.

The rock rabbit (dassie)

This animal (Procavia capensis), which is commonly found in karoo ridges and hills, is primarily herbivorous. The rock rabbit is sometimes responsible for the drastic thinning out of vegetation which in turn can lead to erosion on slopes.

Other animals

Other animals are at present insignificant both as far as numbers and influence on the plant cover is concerned. Animals which are responsible for localized and limited soil disturbances and exposure are the graatjie meerkat (Suricata suricatta), spring hare (Pedetes capensis), Cape ground squirrel (Xerus inaurus), antbear (Orycteropus afer), field mice, rats, moles, red meerkat (Cynictis penicillata), bat-eared fox (Otocyon megalotis) and the porcupine (Hystrix africae-australis).

Insects

In general, the effect of insects on soil erosion is very slight compared with that of farm animals.

The most important insect plague which causes direct damage to vegetation, and which can increase soil erosion is the harvester termite (Hodotermes mossambicus) (Coaton 1958), karoo caterpillar (Loxostege frustalis) (Möhr 1982) and the brown locust (Locustana pardalina) (Annecke and Moran 1982). Other termites like the anthill termite types (Microhodotermes viator and Trinervitermes spp) are of lesser importance although they are also responsible for the harvesting of vegetation.

There is as yet not enough knowledge about the direct and indirect influence of insects - especially termites - on the erosion process.

EROSION PROCESSES

The physical, chemical and biological processes involved in erosion are well known (Stallings 1959). The erodibility of soil and proneness to water erosion are extremely important elements in the erosion process and erosion vulnerability. These factors are influenced and determined by the physical and chemical properties of soils. The erodibility of soils in the Karoo varies from highly erodible by water (especially those soils formed from mudstones and soft shale), to highly erodible by wind (like the generally sandy soils on the plains). It is clear that large gaps still exist in the knowledge about erodibility and erosion tempo of soil in the karoo biome.

Wind erosion

In the karoo biome wind can be labelled as the primary erosion agent (Weather Bureau 1975). Wind has in recent times become more destructive in the erosion process as a result of the environmental utilization practices of man. The intensity of wind erosion is sometimes evident in the ripple marks which occur on exposed ground.

Wind erosion and season

The windbreak effect of karoo bush cover can be seen as both effective and ineffective. A common reasonably dense stand of karoo bush is merely able to provide partial protection against wind erosion, since karoo bush seldom if ever form a closed canopy cover.

In some cases animal footpaths serve as wind channels, causing them to be deflated by wind. Where desert pavement develops, as in the arid north-western karoo areas, the effect of wind on footpaths is sometimes very conspicuous.

Erosion potential is increased and erosion is also most severe when the grazing of a paddock takes place during the period of the highest windspeed, the lowest rainfall (driest ground) and the vegetation is at its most dormant and sparse stage. The highest wind frequency in the karoo biome usually occurs from August till October. During these months the veld is still very dry although vegetation has already begun to grow. It can be accepted that wind erosion is at its severest during August and September. During March the wind is comparatively calm, rainfall high and the plant cover usually at its densest; it may be assumed that the erosion is low at this stage. In the winter months, May to August, which are the driest months (except in winter rainfall areas) and the plant cover becomes increasingly sparse, wind erosion is at its lowest owing to low wind speeds and calms.

The plant cover on karoo biome plains is seldom of such a nature that it can effectively prevent wind erosion. Consequently, one of the most important aims of veld management in practice is to develop the densest and most permanent productive plant cover and in this way also limit erosion.

Water erosion

Water erosion is a general phenomenon in the karoo biome. Water erosion in the form of splash erosion is especially significant in the Great Karoo, Upper Karoo and the Grassridge Basin, and can be considered as an active form of water erosion in the karoo areas. The formation of extensive bare patches is a direct consequence of splash erosion (Walters 1951).

The average runoff, measured over a period of 604 days on karoo bushveld with a slope of 1 on 60, was only 4,6% (P W Roux unpublished) under an annual average rainfall of 360 mm.

After a high intensity rain-hail storm of 19,5 mm the runoff intensity measured on the same veld increased by as much as 73,6%. High intensity thunderstorms (Weather Bureau 1974) often occur in the karoo biome and can give rise to severe splash erosion.

Erosion caused by running water in the associated hydrological aspects are described by Lobeck (1939) and Stallings (1959). The serious scale on which gulley erosion can take place is illustrated in Figure 1.

LANDSCAPE IN THE KAROO BIOME AND EROSION

The typical landscape forms in karoo areas are the result of erosion. The geomorphology of the karoo biome and erosion processes are described by Le Roux (this volume).

At present the severest water erosion occurs on basal pediments (apron veld), valley floors and mountain slopes.

The Great Escarpment

The great single topographical characteristic in the karoo biome is the recessionary erosion escarpment called the Great Escarpment (King 1951) which dates from the so-called African Erosion Cycle.

This escarpment divides the karoo biome roughly into four geographical areas, viz Namaqualand to the west; the Great Karoo to the south (on the southern boundary of the Great Karoo folded mountain ranges running east-west enclose the Little Karoo); the Upper Karoo - an inland plateau basin - to the north; and the Fish River Basin to the east.

The Upper Karoo divides into three sections, viz a western and eastern area south of the Orange River, and an area north of the Orange River.

Each of the geographical areas mentioned above are drained by a dendritic network of consequent and accordant fluvial systems. The rivers are mainly episodic and are therefore subject to periodic floods which carry away large quantities of silt. As a result of low relief in the western Upper Karoo (the so-called North-West), retarded drainage has led to the development of extensive pans and floors with shallow silt deposits.

The erosion situation in these four main areas is as follows:

Namaqualand

The altitude varies from sea level to 800 m above sea level. The rainfall is low (50 to 125 mm) and severe and protracted droughts occur. In general the vulnerability of this region to erosion is low.

Namaqualand is subject to severe deflation, the seriously eroded plains of which Knersvlakte is a typical example. In a limited area north-east of Van Rhynsdorp, an active build-up of sandy aeolian deposits is taking place.

The coastal belt is highly subject to shifting sands, dune formation and aeolian deposits in the adjacent interior. The sand causes serious conservation problems as it engulfs vegetation and renders roads impassable. This coastal belt adjoins the Namib Desert to the north.

As a result of low rainfall, water generally plays a minor role as far as erosion is concerned. During exceptional floods, however, driftsand and soil deposits in gulleys, rivers and on slopes, are washed away.

Old grain lands in the southern and central areas are subject to serious sheet erosion which create conservation problems.

The Great Karoo

The Great Karoo, which averages 650 m above sea level and has a mean annual rainfall of 150 to 300 mm, is an extensive inland plain. It can be described as a plain with inselbergs.

The vegetation consists of sparse to dense karoo bushes with a component of sparsely scattered shrubs and grass. The removal of the thin layer of top soil - about 20 to 100 mm - can be detrimental to the growth and re-establishment of plants. The resilience of the Great Karoo vegetation is low.

The landscape was eroded in geological times by apparently both water and wind. At present wind erosion is completely dominant as can be seen by aeolian deposits in and around bushes. Episodic floods sometimes contribute significantly to serious sheet erosion, the incision of pediments and gulley formation. The general erodibility of the region may be considered as low.

The salinization of vast low-lying areas has occurred on an extensive scale in the southern central areas.

Upper Karoo

The average altitude of the Upper Karoo is between 800 and 1 300 m. The rainfall varies from 100 mm in the west to 350 mm in the east.

The plant cover changes from west to east from Bushmangrassveld, sparse to dense karoo bushveld to mixed karoo where grass dominates. The resilience of the area is average to good.

Wind is usually the predominant erosion agent. Dust storms are a common phenomenon. Water erosion increases from west to east owing to the increase in rainfall and higher relief. Splash erosion appears to play a major role. The general vulnerability of the area to erosion may be classified as relatively low. Water runoff is generally low in the west, but periodic floods sometimes cause damage.

The area north of the Orange River (west and south-west OFS) consists, in the east, of plains with scattered mountains, ridges and hills. Sandy plains are typical of this area. Sand deposits are becoming a serious problem in cultivated areas. The eastern area similarly is a flats area, though less often interrupted by ridges and mountains. It also has a higher rainfall and a better vegetal cover.

The Fish River Basin

The rainfall varies from 50 to 400 mm. The vegetation on the plains consists of karoo bushes with an inferior grass component. On the ridges and eastern borders, grass and bushes occur in equal quantities. The resilience of this basin is average to low.

The general vulnerability to erosion is low over the greater area, but high near the mountains where deep silt and alluvial layers occur.

Wind erosion appears to be predominant, although water erosion in the form of gulley and sheet erosion is very conspicuous in places. Runoff comes mainly from the surrounding mountains of the Great Escarpment. On the eastern mountain borders where mudstones, shales and sediment-filled valleys occur, water erosion has assumed such proportions in the past that about 22 000 hectares of land had to be expropriated by the State during the 1940's for conservation purposes.

EROSION AND VEGETATION

The density, composition, height and permanence of the vegetation are the most important elements in the protection of soil against erosion. According to Stallings (1959), a dense short cover (like grass) prevents splash erosion more effectively than does a rough cover (like karoo bushes and shrubs) which rests on or is elevated above the ground. Under comparable circumstances, according to Stallings, the protection afforded by plants against splash erosion varies more or less directly according to the amount of coverage.

Vegetation structure and erosion

The protection that grasses usually afford against soil erosion is superior to that afforded by most bush species. The reason for this is that, with an equal canopy cover, a tuft of grass affords a better protective cover than a bush (Roux 1981). Protection against raindrop erosion by canopy interception is however, very similar in the case of both grass and bushes.

Grass has the further advantage that it binds the soil better with its typical network root system, whereas most bushes are less effective in this respect, owing to the fact that they generally have a taproot system. In the veld where grass has become mainly replaced or ousted by bushes, erosion is more prevalent (Tidmarsh 1950; Roux 1981). Furthermore, as is apparent from root distribution studies (Van Heerden 1948; Skinner 1964; Theron 1964; Roux 1969), grass affords decidedly better protection to the top soil layer owing to the network of roots situated directly under the soil surface.

Sheet erosion under grass and bushes

The protection provided by a grass cover as opposed to a bush cover against sheet erosion (water and wind erosion) was determined experimentally on the site of a pasture research project which commenced in 1934. Results were obtained from two adjacent experimental camps situated on a sandy loam apron veld with a 3° slope. In one camp a predominantly grass cover was developed, and in the other a predominantly bush cover.

Sheet erosion was measured over a period of 16 years. The method used is described by Tidmarsh (1950). A loss of 4,9 mm was measured under the grass cover as opposed to the 20,7 mm loss under bushes. It could not be established to what extent aeolian deposits may have compensated for these losses. In the grass component this factor may have been significant owing to the slightly better ability of grass to more evenly retard the flow of wind.

Measurements of the microtopographical development (surface roughness) over a period of 35 years on basal pediment showed that, over a linear distance of 30 m, the direct soil surface length was 35,2% and 87,4% longer than the linear distance under grass and bush respectively.

On a plain the direct soil surface length under grass cover was 90,3% longer than the linear length; under a bush cover it was 175,5% longer. These measurements represent erosion over a period of 29 years. Surface erosion was 3,9 mm as against 17,5 mm over a period of 16 years for the two respective experimental camps (Roux 1981).

Erosion on slopes under grass

On karoo ridges and mountainous veld, exposed rock and stone usually cover 40 to 60% of the slope surface (Department of Agriculture and Fisheries unpublished data). With rains, a correspondingly high runoff is delivered to the ground between the rocks. Where plant cover on such slopes is sparse, excessively high runoff gives rise to severe soil erosion. This leads directly to a decrease in soil moisture and, in turn, adjustment in plant cover, composition and density.

The phenomenon of "shale runoff" occurs on the eastern boundary of the karoo biome. Here silt derived from soft red mudstones and shales is carried by runoff to slopes and pediments and are deposited there. The result is that the soil surface becomes sealed with a hard impenetrable silt layer which leads to the drying off of the vegetation. No successful measures have as yet been developed to combat this adverse erosion phenomenon.

Erosion of the Orthic-A horizon

In most cases where bare brack patches develop in low-lying areas, it is as a direct result of the stripping of the orthic-A horizon. The former usually consists of a compacted sediment layer. The A horizon generally consists of a sandy loam which supports both grass cover (such as *Eragrostis* species) and bushes, or only bushes. With the thinning out of the A horizon vegetation as a result of mismanagement, the A horizon is removed by erosion and the B horizon becomes exposed. Owing to its usual physiological dryness and compaction, the B horizon can support only specialized plant species like, inter alia, *Salsola* species, *Zygophyllum incrustatum*, *Nestlera* species, and brack resistant grasses like *Sporobolus usitatus* var *iocladus*. If subjected to further hoof action of stock, splash erosion and deflation, the B horizon surface becomes worn down to an almost even and smooth bare patch.

Where degenerative changes in the vegetation reach an advanced stage as a result of overexploitation over a long period, erosion becomes the main agent responsible for further vegetation change. This situation occurs under experimental conditions on karoo plains when continuous grazing has been applied for a period of 25 years (Department of Agriculture and Fisheries unpublished data). In this case the orthic A horizon of about 15 cm deep was eroded away and was washed to another part of the experimental plot, leaving exposed a B horizon rich in lime.

THE RESULTS OF EROSION

The consequences of erosion can be measured by the development of microtopography; sheet erosion; gulley and drainage systems; the accumulation of sediment; decrease in soil fertility; change in soil structure and texture; change in soil moisture status; salinization and compaction of soil; water runoff; increase in stream density and lowering of the water table. These aspects correspond with the description of the consequences of erosion by Lobeck (1939), Stallings (1959). Where the A horizon has overlain the B horizon, an erosion step has developed. With the active wearing away of the step, the B horizon enlarges gradually and becomes covered by typical B horizon vegetation. The unaffected A horizon is usually inhabited by a mixture of Pentzia incana, Chrysocoma tenuifolia, Lycium arenicolum and Aristida species. The B horizon becomes covered only with P incana. With erosion of the B horizon itself the succulent Ruchia ferox becomes dominant.

This is a typical example of where an erosion process is initiated and becomes virtually independent of any further influence from the grazing animal. This type of erosion, where the degradation of the erosion slope (recession) takes place, is difficult to control even if grazing is stopped. This situation occurs in many parts of the veld in the karoo biome and it is no longer possible to re-establish the original A horizon vegetation in these areas.

Surface erosion and seedling establishment

Removal and disturbance of the surface layer (one to five millimetres) of the soil by wind, water or trampling of stock during germination and early stages of establishment of the seedlings can lead to the death of seedlings (Roux 1960).

Experimental results have shown that seedlings growing on heavier and more fertile soil are exposed to destruction by surface erosion for shorter periods and therefore are less vulnerable. Perennial grass seedlings which are sensitive to surface erosion are Themeda triandra, Digitaria argyrograpta, Sporobolus fimbriatus and Eragrostis curvula var conferta. There probably are many more grass and bush species which can be added to this list.

The reason for this sensitivity of grass species to surface erosion is that the developing seedling is perched on the soil surface and is not firmly implanted in the ground. During erosion the soil beneath the embryo and developing root system is removed. Even light wind movements cause the plantlets to topple over and the root system dries out. Some grass species like Stipagrostis are well adapted to establish themselves on unstable sandy surfaces in spite of surface erosion and consequent exposure of the root system.

Bush species, and especially the hardy species with their fast-developing taproot systems, are not less sensitive to soil surface disturbance. This possibly explains why many bush and shrub species are able to establish themselves on eroding and unstable surfaces. An example of a species that can establish itself under extreme conditions of surface disturbance and trampling is Psilocaulon absimile, which even grows very successfully around stock watering points (Figure 2).

As is clear from research results, surface erosion can be of great significance in the determination of vegetation composition and that active surface erosion can serve as a selection agent by allowing the establishment of adapted species and eliminating the sensitive types.

Deposition of silt and sediment

There are strong indications that the tempo of erosion increased since the beginning of the century and that a peak was probably reached during the 1930's and 1940's (Roux 1980b). According to the distribution scale of the gross long-term average annual sediment deposition (Midgley undated) about 60% of the karoo biome area delivers a sediment deposition of 48 million m^3 and less, 30% between 48 and 96 million m^3, and 10% between 96 and 240 million m^3. The total area delivers an average of about 32 million m^3 of silt per year. Sediment deposition for the Orange River, Namaqualand, has also been mapped, by Pitman et al (1981); delivery varies from 1 000 tons per km^2 per year to as little as 50 tons per km^2.

The extent of active soil erosion in the eastern karoo biome areas is reflected in the deposition of silt in large irrigation dams. Lake Arthur at Cradock, for instance, has over a period of 44 years, lost 60,4% of its holding capacity. The silt is delivered from a catchment area of 4 882 km^2. The large Grassridge irrigation dam near Cradock has silted up by 24% over 46 years, and the Kommandodrift dam seven per cent over eight years.

According to statistics supplied by the Engineering section of the Department of Water Affairs at Cradock, the average volume percentage of sediment in suspension and deposition in the Sundays River is at present 2,43%, in the Great Brak River 2,96% and in the Tarka River 7,02%. By contrast, the figure for the Orange River, measured at Bethulie, is only 0,80%. This comparatively low figure may possibly be attributed to the fact that the catchment area is covered predominantly with grass, while, in the former cases, the vegetation consists of bushes, shrubs and grass.

It would appear, however, that perceptible erosion (active gulley formation and depositions) is on the decrease in the karoo biome (Roux 1981). This decrease is mentioned by Alexander (1978). It can possibly be attributed to the fact that the more easily transportable and erodible material has already been removed. This decrease in erosion could also be attributed to the thickening-up of the plant cover in the so-called Phase 3 of vegetation change as postulated by Roux (1981).

Zones of deposition

As far as aeolian deposits are concerned, it would appear that there are extensive zones of deflation and broad zones of deposition in the karoo biome. The zones of deflation in the Karoo are mainly on the plains. The zones of deposition are situated on the eastern borders of the karoo biome where grass is abundant. The sandy appearance of the soil possibly confirms this assumption. The low ridges in the eastern Karoo also display considerable accumulations of wind depositions at their bases. There is a strong suspicion that the main breeding grounds of the brown locust are associated with zones of deposition. The extent and situation of zones of deflation and deposition have not yet been established.

Another zone of deposition is Great Bushmanland, with its usually favourable stands of Bushman grass (Stipagrostis obtusa, S ciliata and S uniplumis).

A restricted zone of blown sand accumulation occurs north-east of Van Rhynsdorp. In the zone an extensive community of Eragrostis spinosa has developed over the centuries. These deep sands probably come from the coastal sand as well as from the adjacent Knersvlakte.

Salinization of soil

The leaching of salts and the salinization of soil is an integral part of the erosion process in arid areas. Dissolved salts in runoff water and in rivers varies from 300 mg l^{-1} to over 2 000 mg l^{-1}. In irrigation areas, like the Smartt Sindicate (near Britstown) and the Fish River valley, brack has already assumed critical proportions (500-2 000 milli Siemens cm^{-1} as is also the case in Golden valley (in the Fish River area). Extremely costly draining and leaching systems are required to remove the excess salts for the benefit of crop production.

In the veld brack occurs mainly in low-lying areas. In the Arid Karoo, where the relief is low and low-lying areas are badly drained, brack has in many instances given rise to the establishment of salt-tolerant vegetation like Salsola species, Zygophyllum incrustatum and Kochia species, which establish themselves in brack patches. Usually brack areas are covered sparsely with vegetation, which favours the processes of the erosion agents and leads to the enlargement of exposed soil surfaces and the formation of bare patches.

Brack bare patches

The occurrence of bare patches in the karoo biome is a clear sign of a specific erosion process. Bare patches are the result of the combined effects of a number of physical and chemical processes, aggravated by grazing, on specific soil types.

Walters (1951) describes three groups of bare patches, viz:

- those found on sloping aspects having sandy loam soil;

- those found on local depressions in the catchment area of large valleys with deep clay loam soil; and

- those found in large valleys on very deep clay loam soil.

Saltpans are recognized as a fourth group.

Tunnel formation

Tunnel formation takes place where salt is leached out of the soil profile and the soil develops a loose crumbly structure (so-called sugar brack). As a result of the filtration of water through this porous profile, a flow of water is caused in the soil layer, which in time forms tunnels which drain into gulleys. Typical examples of this phenomenon occur generally in the Vlekpoort River near Hofmeyr.

THE INFLUENCE OF SOIL CONSERVATION WORKS

The role that soil conservation planning has played in the reduction of soil erosion cannot be overlooked. Already over 650 key soil conservation works have been erected in the karoo biome and more than 75% of the total number of farms have been planned. The influence of resting of veld grazing programmes, and the Stock Reduction Scheme, although largely incalculable, probably contributed significantly to the decrease of erosion. The development of the so-called Phase 3 vegetation (Roux 1981) was however, probably the most important factor responsible for the reduction in erosion since 1950.

Control of erosion

The first serious effort on the part of the authorities to control erosion was the expropriation of drastically eroded catchment areas in 1940. The Vlekpoort area near Hofmeyr is a good example of such an expropriation.

In an attempt to limit or prevent the retrogression of the natural resources, especially the veld and soil, the Soil Conservation Act was promulgated in 1946 and was amended in 1979 to suit changed circumstances and to fulfil new requirements. In terms of this Act, accompanied by a system of state subsidies, scientific farm planning is carried out on private property by the Department of Agriculture and Fisheries.

In accordance with the farm planning programme which was launched for the whole country after 1946, large scale physical and biological planning followed.

To date more than 70% of all farms in the karoo biome area have been planned; it cannot, however, be said with conviction that the implementation of the plans has occurred on the same scale; it is alleged by certain authorities that merely six to 10% of all farm plannings are actually carried out.

Apart from these activities on farm level, a programme of so-called State or key works has been launched. This programme includes the erection of large weirs at key positions in rivers presenting erosion dangers or which have already been subjected to severe erosion. The position and height of such concrete structures are based upon the so-called Dalweg theory. This involves the silting up of an eroded valley until it reaches its original erosion or natural base. The success achieved with such works is reported by Greyvenstein and De Villiers (undated).

The positive effect that these soil conservation works, State as well as privately erected, have had upon the erosion problem in the karoo biome cannot be underestimated.

At present the situation is such that there is no river or major gulley which has not entirely or in part been stabilized by means of soil conservation works. Although these constructions reduce or eliminate the symptoms of erosion, the actual cause of erosion resulting from water runoff from the catchment areas have not yet been sufficiently contained. This will only be curbed satisfactorily when the plant cover can be developed to match the potential of the catchment area. More recently it appears that a thickening of the plant cover has taken place and is continuing (Roux 1979).

Serious problems are being experienced with blown sand on the west coast. This sand inundates vegetation and sometimes also roads, causing disruption of traffic. The control of this erosion problem is a costly and largely artificial process. Use is made of artificial barriers and windbreaks, stabilizing with plastic sprays, planting of grass and bushes and mechanical conservation methods.

Research into soil erosion

Soil conservation research has been launched by the Department of Agriculture and Fisheries in various localities in South Africa. One of the most well-known research sites is situated in Vlekpoort in the Hofmeyr district where the research is being undertaken by the Division of Agricultural Engineering of the Department of Agriculture and Fisheries (Figure 1).

Originally research concentrated upon the design and construction of concrete weirs in strategic positions in rivers and gulleys. The accumulation of sediment in weirs has been monitored over a period of 25 years (Greyvenstein and De Villiers undated). Information which emanated from this study influenced methods of predicting sediment build-up behind weirs (Greyvenstein 1964). Other methods, applicable on farm level, have also been developed. These mainly involve stone barriers, gabions, pole crosses (Greyvenstein and De Villiers 1978), and wire matting etc. Research is also directed at the reclamation of bare patches by the application of mechanical methods, like the loosening of ground, ploughing, covering with plant material, stones, etc. For the scooping out of small hollows in the soil, the so-called "happloeg" was designed (De Jager 1982).

All pasture research conducted in the karoo region since 1934 has aimed at, inter alia the conservation of the natural resources, including the soil. To this end veld management measures, grazing methods and special grazing techniques are incorporated in all farm planning (Tidmarsh 1957; Roux 1968; Roux and Skinner 1969).

Since excessive grazing pressure is a primary cause of soil erosion, research programmes on cultivated fodder crops have been launched to find additional sources of stock feed to alleviate this pressure during critical periods (De Kock 1967).

One of the greatest shortcomings in all conservation efforts is the lack of a scientific method to determine grazing capacity objectively and accurately. Research on the empirical calculation of grazing capacity is presenty being undertaken by the Karoo Agricultural Region.

Seeing that man, in his endeavours to survive, is responsible for soil erosion, it has become necessary to conduct research in which the economic limits of a farming venture can be determined in order to evaluate the production potential of the natural resources. This should be especially aimed at the natural vegetation which is the most important natural asset.

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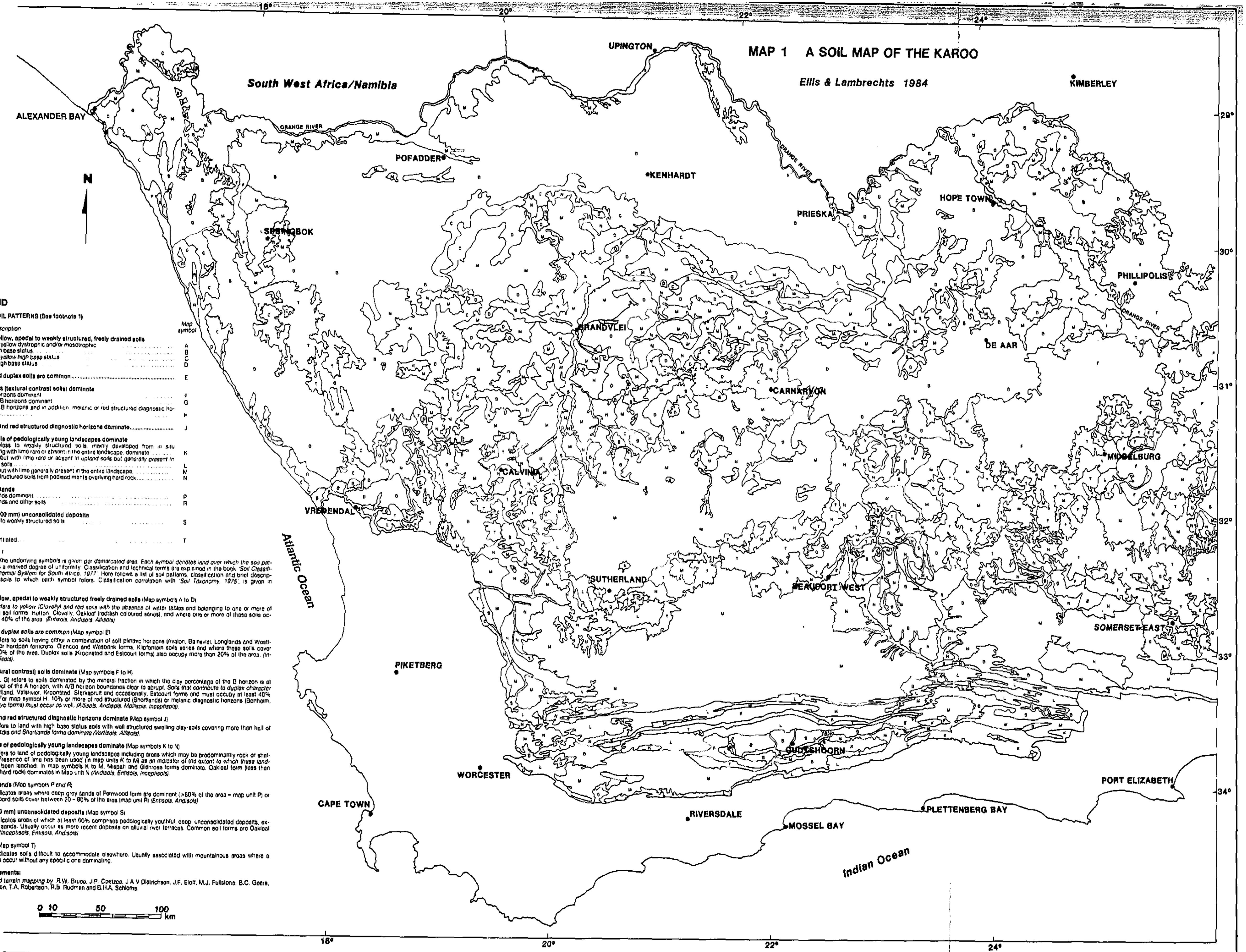
MAP 1 A SOIL MAP OF THE KAROO

Ellis & Lambrechts 1984



LEGEND

BROAD SOIL PATTERNS (See footnote 1)

General description	*Map symbol*
Red and yellow, apedal to weakly structured, freely drained soils	
Red and yellow dystrophic and/or mesotrophic	A
Red, high base status	B
Red and yellow high base status	C
Yellow high base status	D
Plinthic and duplex soils are common	E
Duplex soils (textural contrast soils) dominate	
Red B horizons dominant	F
Non-red B horizons dominant	G
Non-red B horizons and in addition, melanic or red structured diagnostic horizons	H
Red vertic and red structured diagnostic horizons dominate	J
Shallow soils of pedologically young landscapes dominate	
Structureless to weakly structured soils, mainly developed from *in situ* weathering with lime rare or absent in the entire landscape, dominate	K
As for K but with *lime rare or absent in upland soils but generally present in low-lying soils*	L
As for K but with lime generally present in the entire landscape	M
Weakly structured soils from pedisediments overlying hard rock	N
Grey regic sands	
Regic sands dominant	P
Regic sands and other soils	R
Deep (> 1 000 mm) unconsolidated deposits	
Stratified to weakly structured soils	S
Other soils	
Undifferentiated	T

FOOTNOTE 1

Only one of the underlying symbols is given per *demarcated area. Each symbol denotes land over which the soil pattern* displays a marked degree of uniformity. Classification and technical terms are explained in the book *'Soil Classification. A Binomial System for South Africa, 1977'*. Here follows a list of soil patterns, classification and brief description of the soils to which each symbol refers. Classification correlation with *'Soil Taxonomy, 1975'*, is given in parenthesis.

Red and yellow, apedal to weakly structured freely drained soils (Map symbols A to D)

This class refers to yellow (Clovelly) and red soils with the absence of water tables and belonging to one or more of the following soil forms: Hutton, Clovelly, Oakleaf (reddish coloured series), and where one or more of these soils occupy at least 40% of the area. *(Entisols, Aridisols, Alfisols)*

Plinthic and duplex soils are common (Map symbol E)

This class refers to soils having either a combination of soft plinthic horizons (Avalon, Bainsvlei, Longlands and Westleigh forms) or hardpan ferricrete, Glencoe and Wasbank forms, Klipfontein soils series and where these soils cover more than 20% of the area. Duplex soils (Kroonstad and Estcourt forms) also occupy more than 20% of the area. *(Inceptisols, Alfisols)*.

Duplex (textural contrast) soils dominate (Map symbols F to H)

This class (F, G) refers to soils dominated by the mineral fraction in which the clay percentage of the B horizon is at least twice that of the A horizon, with A/B horizon boundaries clear to abrupt. *Soils that contribute to duplex character* include Swartland, Valsrivier, Kroonstad, Sterkspruit and occasionally, Estcourt forms and must occupy at least 40% of the area. For map symbol H, 10% or more of red structured (Shortlands) or melanic diagnostic horizons (Bonheim, *Inhoek or Mayo forms) must occur as well. (Alfisols, Aridisols, Mollisols, Inceptisols)*.

Red vertic and red structured diagnostic horizons dominate (Map symbol J)

This class refers to land with high base status soils with well structured swelling clay-soils covering more than half of the area. *Arcadia and Shortlands forms dominate (Vertisols, Alfisols)*.

Shallow soils of pedologically young landscapes dominate (Map symbols K to N)

This class refers to land of pedologically young landscapes including areas which may be predominantly rock or shallow alluvial. Presence of lime has been used (in map units K to M) *as an indicator of the extent to which these landscapes* have been leached. In map symbols K to M, Mispah and Glenrosa forms dominate. Oakleaf form (less than 1 000 mm to hard rock) dominates in Map unit N *(Aridisols, Entisols, Inceptisols)*.

Grey regic sands (Map symbols *P and R*)

This class indicates areas where deep grey sands of Fernwood form are dominant (>60% of the area – map unit P) or where Fernwoord soils cover between 20 – 60% of the area (map unit R) *(Entisols, Aridisols)*

Deep (>1 000 mm) unconsolidated deposits (Map symbol S)

This class indicates areas of which at least 60% comprises pedologically youthful, deep, unconsolidated deposits, excluding regic sands. Usually *occur* as more recent deposits on alluvial river terraces. Common soil forms are Oakleaf and Dundee. *(Inceptisols, Entisols, Aridisols)*

Other soils (Map symbol T)

This class indicates soils difficult to accommodate elsewhere. Usually associated with mountainous areas where a variety of soils occur without any specific one dominating.

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