ALTERATION OF THE SOIL MANTLE BY STRIP MINING IN THE NAMAQUALAND STRANDVELD

by

H.P. Prinsloo

April 2005

Thesis presented in partial fulfilment
of the requirements for the degree of
MSc Agric
at the University of Stellenbosch

Study leader: Prof. M.V. Fey Co-study leader: Dr. F. Ellis

Declaration

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously in its entirety or in part been submitted at any other university for a degree.

Signature: ……………… Date:……………

ABSTRACT

The purpose of this study was to investigate and identify the occurrence of specific soil properties that may be important for vegetation functioning and the possible effect of the loss of or changes in these properties on rehabilitation success on the sandy coastal plains of the West Coast, South Africa. The study area covered approximately 9 400 ha on the Namaqualand coast in the vicinity of Brand-se-Baai (31º18'S 17º54'E), approximately 350 km north of Cape Town and 70 km north-west of the nearest town, Lutzville.

A soil survey was done to reveal the presence of important pedological features. The 20 soil profiles surveyed are situated within six vegetation communities. Pedological features such as surface water repellency, permeable apedal subsurface horizons, subsurface impediments such as cemented (calcrete or dorbank) hardpans and significantly more clayey (cutanic, luvic) horizons were identified.

A comparative study between rehabilitated and natural soils indicates that mining operations result in the formation of saline sand tailings, stripped of a large portion of the clay and organic matter fraction. The natural leaching of solutes, over a period of 25 months, is sufficient to lower salinity of the tailings to levels comparable to natural soils. This leaching can also results in lowering of soil fertility. Removal of the dorbank and the dense neocutanic horizon in the western side of the mine, loss of topographical features such as small dune systems and heuweltjies, destruction of natural soil profile morphology and the lowering of organic carbon and clay plus silt fraction can have detrimental effects on attempts at rehabilitation of this area to a natural condition similar to that which preceded the mining operation.

Infiltration fingering and deep percolation results in the development of an aquifer below the reach of shallow-rooted desert shrubs. A method of water acquisition by vegetation through water distillation is investigated as a possible solution to the apparent discontinuum between the shallow root systems and deeper-lying aquifer. Volumetric water content measurements indicated that precipitation of 29.5 mm, over a period of 10 days, did not result in any variation at 235 mm, 360 mm and 900 mm depths. An average volumetric water content increase of 0.4 mm per night was measured in the first 23.5 cm of soil surface. This amount is a significant source of water that can explain the shallow root distribution. Water vapour movement due to temperature gradients can explain the diurnal volumetric water content fluctuations observed. Further studies are necessary to determine to what extent the depth of water infiltration influences the capacity of subsurface dew to provide plants with a nocturnal water source.

Findings of this study can be summarised into two concepts namely:

- Heuweltjies, small dune systems, and variation in depth of cemented hardpans are the main features that contribute to pedosphere variation and possibly to biodiversity.

- Pedogenic features such as topsoil hydrophobicity, and cemented dorbank and dense more clayey (cutanic, luvic) subsurface horizons are important components of a soil water distillation process that could be a driving force behind vegetation functioning in this region.

Mine activities result in the loss of certain pedogenic features and soil properties that that could be key ingredients to ecosystem functioning. The inability to recognise their significance and ignorance thereof when planning rehabilitation methods might prevent sustainable restoration of the environment.

OPSOMMING

Die doel van die studie was om spesifieke grondeienskappe van die sanderige kusvlaktes van Suid Afrika se Weskus, wat belangrik mag wees vir plantegroei se funksionering, te identifiseer en ondersoek en om te bepaal hoe die verandering daarvan deur mynaktiwiteite die rehabilitasiesukses kan beïnvloed. Die studiegebied beslaan ongeveer 9 400 ha van die Namakwalandse kusgebied in die omgewing van Brand-se-Baai (31º18'S 17º54'O), en is omtrent 350 km noord van Kaapstad en 70 km noord-wes van die naaste dorp Lutzville, geleë.

‘n Grondopname is uitgevoer om verskeie pedologiese eienskappe wat in die studiegebied voorkom te bepaal. Twintig grondprofiele is in ses plantegroeigemeenskappe bestudeer. Die studie het pedologiese verskynsels soos hidrofobiese eienskappe van die grondoppervlak, waterdeurlaatbare suboppervlak horisonte, suboppervlak beperkings soos gesementeerde hardebanke (kalkreet of dorbank) en betekenisvolle meer kleierige horisonte (kutanies, luvies) geïdentifiseer.

‘n Vergelykende studie tussen gerehabiliteerde en natuurlike gronde dui aan dat mineraal ekstraksie met seewater tot die vorming van ‘n brak sandresidu, genaamd “tailings”, wat gestroop is van ‘n groot deel van die oorspronklike klei-inhoud en organiese materiaalfraksie, lei. Natuurlike loging oor ‘n tydperk van 25 maande, blyk genoegsaam te wees om tot laer soutvlakke, vergelykbaar met diè van natuurlike bogronde, te lei. Dit kan egter ook tot die afname in grondvrugbaarheid lei. Dorbank en digte neokutaniese horisonte in die westekant van die myn, topografiese verskynsels soos klein duinsisteme, termiet heuweltjies en natuurlike grondmorfologie is verskynsels wat ook deur mynaktiwiteite verlore gaan.

Waterinfiltrasie tot onreelmatige dieptes (genoem “infiltrasie vingers”), as gevolg van waterafwerende eienskappe van bogrond, dra by tot diep perkolasie. Dit het tot gevolg dat ‘n waterstoor opbou wat buite die bereik van vlak gewortelde struike se vermoë om dit te onttrek, val. Water distillasie vanaf die ondergrond na die bogrond is as ‘n moontlike oplossing vir die skynbare diskontinuum tussen vlak gewortelde struike en die dieper-liggende waterbron ondersoek. Volumetriese grondwaterinhoud-metings het aangedui dat ‘n neerslag van 29.5 mm, oor ‘n tydperk van 10 dae, nie tot variasie in grondwater by 235 mm, 360 mm en 900 mm dieptes gelei het nie. ‘n Gemiddelde toename in grondwaterinhoud van 0.4 mm per nag was gemeet in die eerste 235 mm gronddiepte. Dit kan as ‘n konstante en betekenisvolle bron van water vir vlakgewortelde plantegroei dien. Waterdamp beweging as gevolg van ‘n temperatuurgradient binne die grondprofiel kan die fluktuering in nagtelike grondwaterinhoud verduidelik.

Bevindinge van die studie kan opgesom word in twee konsepte naamlik:

- Termiet heuweltjies, klein duinsisteme, en variasie in diepte van gesementeerde hardebanke is die hoof verskynsels wat bydra tot pedo- en moontlike biodiversitiet.

- Die voorkoms van pedogenetiese verskynsels soos hidrofobisiteit in die oppervlaklaag, gesementeerde dorbank en digte, meer kleierige lae is belangrike komponente van ‘n grondwater distillasie proses wat die dryfkrag agter plantegroei funksionering kan wees.

Myn aktiwiteite veroorsaak die verlies van sekere pedogenetiese verskynsels en grondeienskappe wat “sleutel bestanddele” in die funksionering van die ekosisteem kan wees. Hierdie verlies moet in ag geneem moet word wanneer rehabilitasie beplan word.

ACKNOWLEDGEMENTS

The author wishes to acknowledge his sincere thanks to the following persons and institutions for their assistance in the execution of this study.

Namakwa Sands (Pty.) Ltd a subsidiary of Anglo American PLC, Eskom's Tertiary Education Support Programme, and the THRIP Programme of the National Research Foundation for financial support.

Prof. Martin Fey and Dr. Freddie Ellis whose continuous and enthusiastic guidance, advice and inspiration were essential for the completion of this study.

Mr. Willem de Clercq for his assistance and guidance relating to Chapter 5.

Dr. Eduard Hoffman, Dr Andrei Rozanov (Lecturers at the Department of Soil Science) and fellow post-graduate students for their on-going support, discussion and advice for the duration of this study.

Prof Sue Milton for her assistance and information regarding the vegetation of the study region.

Nicole Herpel and Eva Sinjan for their field assistance and support during the second year of this study.

Mr. Torsten Hälbich from Namakwa Sands mine, who initiated this project, for all his assistance and advice and Ninette Marks of the same organisation for her help during the field visits.

My family for all their support and understanding during the stretch of this study.

My dear wife, Mari, whose loving presence accompanied and encouraged me throughout the long hours of this project.

Finally the writer wants to confess his sincere gratitude to our Heavenly Father for providing the opportunity to undertake this research assignment and for His unending provision of the necessary insight, knowledge and wisdom to perform this research assignment.

TABLE OF CONTENTS

LIST OF TABLES

List of figures

CHAPTER 1

INTRODUCTION: STRIPMINING IN COASTAL NAMAQUALAND

The West Coast of South Africa has experienced a dramatic increase in strip-mining for diamonds, titanium, silver and gypsum (Milton 2001). These deposits are finite and the mining therefore temporary (Wells et al. 2000). Land residue resulting from mining operations might be in a much lower productive state than preceding mining operation. Lubke & Avis (1998) emphasise the importance of considering and planning for continuing land use after mining has stopped. Considering the well-being of the local people, it is important to rehabilitate the ecosystem for preferred land use, keeping in mind that it should be environmentally sustainable (Lubke & Avis 1998). Recognition of this situation resulted in the mining industry itself, through the leadership of the Chamber of Mines, being pro-active in ensuring that mining does not unreasonably impact on the environment (Wells et al. 2000). The design and the implementation of mitigation measures that will minimise the residual impact of mining are necessary to plan for successful closure (Wells et al. 2000).

In April, 1991 the South African mining industry accepted the concept of an environmental management programme (EMP) for prospecting and mining operations (Wells et al. 2000). An EMP includes the need for an environmental impact assessment (EIA) and also fully integrates environmental management into the planning and day-to-day operations at a mine (Wells et al. 2000). Wells et al. (2000) also indicate that before the commencement of mining operations, new prospecting and mining projects are required to submit an environmental management programme report (EMPR). One of the requirements of such an EMPR is a detailed description of the pre-mining environment.

Reconstructing an ecosystem that works the first time, is self-sustaining, is developed economically, and has the desired species and structure, requires a large number of operations that have to be carried out correctly to ensure proper functioning of ecosystem processes (Bradshaw 1983). Lubke & Avis (1998) also emphasise the importance of evaluating the true objectives of specific mine rehabilitation before the commencement of stabilisation and re-vegetation.

Strip mining processes result in the complete disruption of the surface, which affect the soil, surface water and near-surface groundwater, fauna, flora and all types of land-use (Lubke & Avis 1998; Wells et al. 2000). Success has been achieved during the rehabilitation of strip mined land in overseas countries such as Australia and in South Africa, for instance the heavy mineral dune mining at Richards Bay (Lubke & Avis 1998). Heavy mineral mining in West Coast of South Africa poses more challenges for rehabilitation due to the aridity of this environment (Milton 2001). Broad rehabilitation aims of Namakwa Sands Limited, a heavy mineral mining company in this region, are to:

- Minimise the non-rehabilitated exposed areas of the mine and stockpiles.
- Aim for a reasonable canopy cover of a variety of species, which should preferably be indigenous to the area.
- Aim for a return to natural, self-sustaining indigenous vegetation cover and species complement equivalent to that recorded prior to disturbance.
- Aim for the recreation of habitats that will attract a faunal composition (including invertebrates) similar to that recorded prior to disturbance (Environmental Evaluation Unit 1990; De Villiers et al. 1999)

Namakwa Sands is a heavy minerals mining and beneficiation business situated along the West Coast of South Africa (Figure 1.1) (Namakwa Footprint 2002). It is also the only heavy minerals operation within Anglo American plc and falls under the Anglo Base Metals Division (Namakwa Footprint 2002). The business comprises mining, mineral concentration, separation and smelting operations. The mine is located at Brand-se-Baai, 384 km North of Cape Town covering an area approximately 9 400 ha. Mining commences some 300 m inland from the high tide mark and reaching almost 14 km inland. The area stretches approximately 5 km along the coast. Namakwa Sands Mine has been divided into an eastern sector (Graauwduinen East) and a western sector (Graauwduinen West). Mining in the Graauwduinen West region reaches depths of between 2 and 45 m. This results in the removal of the dorbank layers to gain access to lower-lying mineral deposits. The mining process in Graauwduinen East results in the removal of sand up to depths of between 1 and 5 m. The top 50 mm of sand is removed and stored for rehabilitation before the bulk removal of heavy mineral rich sand begins. The fraction is then stockpiled and stored for approximately three months while mining progresses. Seawater is used as a medium to wash the mined sand for separation of the heavy mineral compound. The Mineral Separation Plant is located 7 km from Koekenaap (near Lutzville) where electrostatic, dry magnetic and gravity methods separate ilmenite, rutile and zircon.

Figure 1.1 Location of Namakwa Sand mining activities

Namakwa Sands is one of the first mines in South Africa that has had to undergo a full EIA before mining activities could commence (Environmental Evaluation Unit 1990, Mahood 2003). Requirements for rehabilitation of mined land are referred to in the EIA (Environmental Evaluation Unit 1990, De Villiers et al. 1999; Mahood 2003). De Villiers et al. (1999) conducted a vegetation survey of the mine area to serve as an inventory of the representative plant communities. The seed bank dynamics of the mining region was also investigated during a PhD research project (De Villiers 2000). Mahood (2003) carried out a research project to determine whether translocation of indigenous plants could facilitate the rehabilitation of area affected by the mining process. The objectives of that project were to investigate the effectiveness of rehabilitation practices such as top-soiling, irrigation and translocation of indigenous plants, for facilitating cost-effective return of the mined landscape to its former land use. Namakwa Sands instituted this research project at beginning of 2003 to investigate the impact of mining and rehabilitation activities on soil properties that may be important for successful restoration.

The provisions of the Minerals Act, No. 50 of 1991, and the Regulations to the Mines and Works Act, No. 27 of 1956, relating to the rehabilitation of mining surfaces, are largely aimed at soil conservation (Wells et al. 2000). The present study investigates the alteration of the soil mantle of the Namakwa Sands heavy minerals mine on the West Coast of South Africa by strip mining operations and the implications it has for rehabilitation. The destruction of certain properties of the soil mantle which can be key factors governing the functioning of this ecosystem, could result in failure to fully rehabilitate the mined environment. This study is divided into three parts to investigate possible key properties of the soil mantle and the effects that mining has on these properties:

1. What chemical, physical and morphological characteristics do the soils in their undisturbed state possess?
2. To what extend are these characteristics altered or destroyed by mining activities?
3. How is rain water received, transported, stored and made available to plants by soils in this region?

Although the investigation did not precede the commencement of mining activities the findings could still help to understand the success or failures of past rehabilitation attempts and to formulate recommendations for future rehabilitation procedures.

CHAPTER 2

MINING IN THE STRANDVELD AND RESTORATION OF THE ENVIRONMENT: A LITERATURE REVIEW

Soil changes with mining and might affect restoration and its sustainability. Before soil changes can be quantified and qualified it is important to know what soils there are and the role they play in the ecosystem. Certain soil properties could be crucial for ecosystem functioning. To achieve sustainable restoration it is necessary to discover such properties and to understand the role they play in ecosystem functioning. A thorough understanding of the operational environment of an ecosystem will guide the investigation to focus on relevant topics to be considered.

2.1 ECOSYSTEM FUNCTIONING

An ecosystem is the community of organisms and the environment in which they live, forming an interacting system (Tyler Miller 2004). A terrestrial ecosystem is a community of organisms of which a landscape unit forms the environment in which they live. From the plant-life growth forms of the earth's terrestrial ecosystems, it was found that plant varieties have adapted physiologically and morphologically to survive in almost all the adverse habitats (Salisbury & Ross 1992). Some of the most unfavourable and inhabitable conditions exist within the desert environment (Harris & Campbell 1981). Ecological processes can be defined as the processes within an ecosystem that result from interrelations between organisms and their environment. Natural ecosystems are characterised by successional development to a specific energy balance determined by its environmental conditions (Kent & Coker 1996. Water is an essential compound and medium for the functioning of all biochemical processes or organisms (Salisbury & Ross 1992) and will be the controlling factor in the specific energy balance and biomass production found in desert environments. Restricted water availability that is directly and indirectly influenced by biotic and abiotic factors of desert ecosystems will increase the difficulties of plant survival (Harris & Campbell 1981). A thorough knowledge of the ecosystem's abiotic environment, especially water distribution and availability, is essential if successful rehabilitation of a disturbed arid ecosystem is planned.

2.2 THE STRANDVELD SUCCULENT KAROO

The Succulent Karoo biome forms part of the greater Cape Flora region and has a recorded area of 100 251 km^2. Namaqualand, or the Namaqualand-Namib (N-N) domain as it has recently been recognized (Cowling et al. 1999), is regarded as the strongly winter-rainfall region of the Succulent Karoo biome. The Namaqualand-Namib domain has an approximate area of 50 000 km^2 and is situated on the South African West coast, bordering the Atlantic coastline. This region is well known for its flower display in spring. This region has a predictable winter rainfall and moderate temperature throughout the year. Leaf succulents of the Namaqualand have shallow root architecture, even when growing in deeper soils (Cowling et al. 1999; Esler et al. 1999).

There is a fundamental difference between the leaf succulent-dominated vegetation of the Succulent Karoo and that of other shrub-dominated desert ecosystems (Jürgens et al. 1999). The Succulent Karoo contains a remarkable dominance and unique diversity of shallow-rooted, short to medium-lived leaf-succulent shrubs (5–15 years) with regular recruitment and rich geophyte flora (Esler et al. 1999; Jürgens et al. 1999). The local and regional plant species diversity is also exceptionally high for an arid environment and is considered to be the highest recorded for any arid region in the world (Esler et al. 1999). Notwithstanding the extraordinarily high level of endemism, Van Jaarsveld (1987) also determined that more or less 30% of the world's 10 000 succulent species occur within this relatively small biome.

Reliable winter rainfall results in successful seedling establishment and little advantage in allocating resources for persistence (Jürgens et al. 1999). Fine scale habitat differentiation and rapid population turnover (Jürgens et al. 1999) result in minimum competitive interactions among functionally similar and speciose leaf succulent shrubs (Prentice & Werger 1985; Eccles 2000). Another interesting phenomenon is that vegetation occurs in the form of clumps or micro-communities (Eccles 2000). But why does this highly diverse, shallow-rooted, leaf-succulent, non-competitive and medium-lived plant species flourish in this environment and why is the vegetation spaced within clumps?

2.3 WHY SO UNIQUE? A PROPOSED MODEL

Gibson (1996) defines succulence as drought-tolerant, remaining alive with low cell water content, and drought-avoiding, using adaptations to maintain higher tissue water potential than in soil. Its extremely low rate of water loss, due to a thick cuticle and stomata closure during daytime, enables its existence for long periods without added moisture (Salisbury & Ross 1992). High positive water potential and an own water reserve enable a succulent photosynthetic organ to maintain a positive daily carbon balance (Gibson 1996).

Some succulent species, especially cacti, utilise shallow infiltrated water after a storm with an extensive shallow root system (Salisbury & Ross 1992). Another physiological adaptation to water stress is the crassulacean acid metabolism (CAM) physiological adaptation of various succulent plants. Some species even have the ability to switch from CAM to C-3 photosynthesis when water becomes available (Bowie 1999). The succulent characteristic of this biome indicates that plants have had to evolve the ability to store water for survival, growth and reproduction. Life history and functional morphology of warm desert plants are closely linked to the seasonality of precipitation (Gibson 1996). Gibson (1996) states that species from the Aizoaceae family with prominent bladder cells occur most abundantly in southern Africa. Gibson (1996) quotes von Willert et al. (1980) that Aizoaceae species containing bladder cells on the epidermis are said to be ‘opportunists’ with higher water turnover, higher growth rates but poorer adaptations for surviving drought. The high representation of these species within the Succulent Karoo indicates adaptation to a unique climate.

In a working model (Figure 2.1) devised previously to explain some of the unique aspects of plant form and function in the Succulent Karoo, Cowling et al. (1999) and Esler et al. (1999) proposed two aspects of the climate that had an overwhelming influence on the evolution and the diversification of plant species, especially Mesembryanthemaceae, in the Succulent Karoo. The first component is the high rainfall predictability reflected by the low annual coefficient of interannual variation for this area. The second unique component is the moderate temperature regime (Esler et al. 1999), influenced by the cold Benguela current. According to all relevant literature, the strong selection towards a succulent growth form in the Succulent

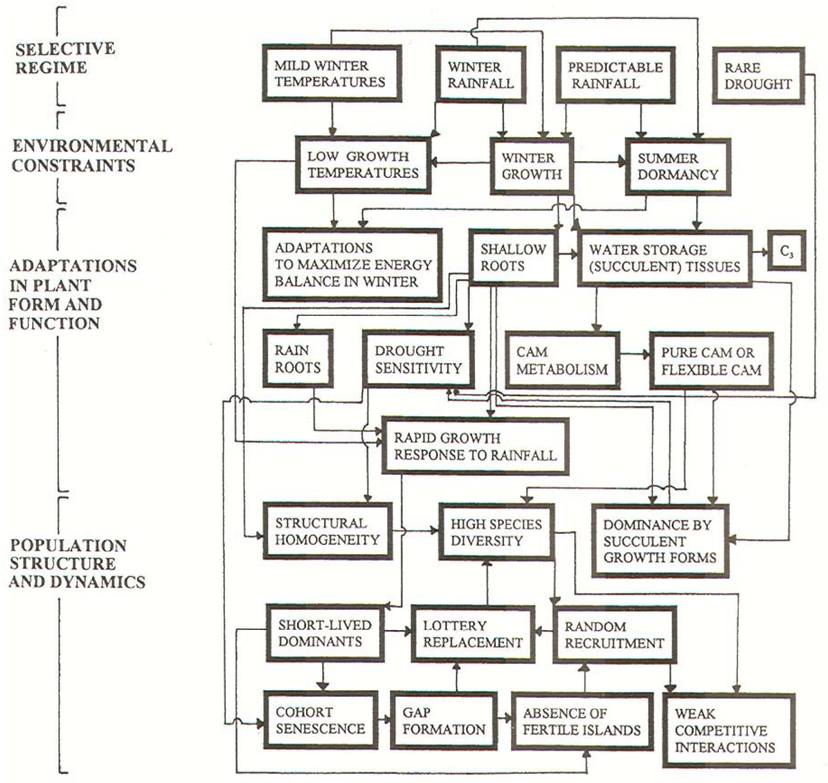


Figure 2.1: An empirical model to explain aspects of plant form and function as well as population structure and turnover in the N-N domain (Taken from Esler et al. 1999)

Karoo, has enabled the utilisation of predictable winter rains due to shallow root systems and a high water-use efficiency in the dry summer months due to CAM metabolism (Cowling et al. 1999; Esler et al. 1999; Midgley & Van der Heyden 1999). Bowie (1999) indicates that *Stoeberia utilus* and *Zygophyllum prismatocarpum* of Mesembryanthemaceae possess the ability to induce CAM photosynthesis when severely water stressed. These species maintain C3 metabolism when watered. This phenomenon indicates that these species have the ability to switch to C3 metabolism during rainfall events (Bowie 1999). Shallow root systems are more cost effective due to lower carbon allocation and allow the plants to respond opportunistically to the enrichment of shallow water pools due to rainfall events (Midgley & Van Heerden 1999; Rundel et al. 1998).

2.4 CLIMATE

The study area has a mediterranean type climate with hot dry summers (November to March) and rain during the winter months (April to September). This area receives an average rainfall of 160 mm per annum increasing to a cumulative precipitation value of 282 mm with fog and dew included. Most of this, as is the case in the Namaqualand district, falls within the winter. Fog and dew are a regular occurrence. The study site experiences an average of 100 fog days per annum. How and if desert plants derive direct or indirect benefit from fog events is still unclear (Desmet & Cowling 1999). Annual average temperature is 15.8 ºC with little seasonal variation due to marine influence. The maximum average monthly temperature for January (summer) and the minimum average monthly temperature in July (winter) are 24.1 ºC and 7.5 ºC respectively. Wind is a very important climatic feature of this area (Desmet & Cowling 1999).

2.4.1 Irradiance and temperature effects

Above a certain irradiance level, called light saturation, increasing light no longer increases photosynthesis (Salisbury & Ross 1992). Due to the lack of cloud cover, desert environments are subjected to high irradiance levels. To prevent solarisation, a light-dependent inhibition of photosynthesis followed by oxygen-dependent bleaching of chloroplast pigments, plants should have developed the ability to cope with, or to prevent high irradiance levels (Salisbury & Ross 1992). High solar irradiance can also result in high leaf and soil surface temperatures. This can be beneficial if it enables a leaf to operate closer to the thermal optimum, or detrimental if it results in less favourable water-use efficiency, higher transpiration rates or reduced enzyme activity (Gibson 1996; Salisbury & Ross 1992). Clear skies can also result in high radiative heat loss at night. Leaf orientation or light reflectance by trichomes (Ehleringer & Cook 1987) or glaucous epicuticular wax (Mulroy 1997), is protective adaptations against high irradiance levels in a desert environment (Gibson 1996). Colder growing conditions during the winter months of the Succulent Karoo could have resulted in the development of geophytes with broad, flattened leaves which lie flat on the ground surface (Esler et al. 1999). Large diurnal temperature extremes may provide the driving force that may be a basic factor in sustaining desert life (Thames & Evans 1981).

2.4.2 Wind effects

Strong and often turbulent winds are common in many arid regions (Gibson 1996). De Villiers (2000) reviewed a report by Washington (1990) indicating that this region is characterised by a strong wind regime. South and south-south-east winds occur with the highest frequency from September to March. Easterly berg winds, blowing from the interior, result in hot and dry conditions at the coast (Cowling et al. 1999; De Villiers 1999; Mahood 2003). These winds result in high evaporative demands and can have an important influence on the natural ecology. Hot dry winds will increase transpiration when stomata are open. Air with extremely low humidity may also cause stomata to close (Schulze et al. 1974; Grantz 1990). Vegetation with succulent leaves and stems using CAM to photosynthesise will have a competitive advantage during such conditions. Except for the humidity effect, strong winds can also result in above-ground damage of plant organs (Dunn De Araujo (internet link); Gibson 1996), preventing strong upward vegetative growth. Wind can also play an important role in leaf temperature control by decreasing the leaf boundary layer and evaporative or transpiration cooling (Salisbury & Ross 1992). This will only be possible with a sufficient water source to prevent stomata closure.

2.4.3 Humidity effect

The rate at which evaporation takes place depends on humidity and the availability of water to the evaporating surface (Gay 1981). A low summer rainfall combined with high rates of evapotranspiration drastically reduces the available soil water content for plant growth. Certain plant species that are highly adapted to prolonged droughts, can survive during the dry period by using the water stored in the soil or water adsorbed from the atmosphere during the night (Kosmas et al. 1998).

2.4.4 Precipitation

Except for the indirect effect that precipitation has on vegetation through increasing soil water availability, the direct effect must also be taken into consideration. Due to the low canopy cover and volume, retention of precipitated water by the vegetation canopy should not significantly influence precipitation effectiveness. It can, in fact, act as a mechanism to collect and channel water directly to the root zone through stemflow (Martinez-Meza & Withford 1999; Devit & Smith 2002). Another adaptation of plants that can ensure survival is the direct uptake of entrapped water through leaves or stems (Gibson 1996). This will especially be an advantage in an area such as the Succulent Karoo where fog and dew precipitation frequently moisten leaf and stem surfaces. Gibson (1996) mentions that it has been suggested that species of Aizoaceae with bladder cells may have the ability to absorb water through nocturnal stomata opening

2.4.5 Salts

De Villiers et al. (1999) found a relationship between the occurrence of plant communities and distance from the sea. One of the contributing factors he states is the salt spray. Bezona et al. (1996) state the importance of selecting salt tolerant landscape plants for home gardens near the coast. Salt deposition by wind-carrying ocean spray can be damaging to plants. The tolerance or response of plants to salt can vary with the plant's age and growth stage, environmental conditions, soil fertility, and the intensity of other stresses on the plant. In addition, some plants may be tolerant of salt in the soil but intolerant of salt deposited on their leaves, or vice versa (Bezona et al. 1996). An internet article on the vegetation and flora of the Cabo Frio Region states that near the ocean low shrubby vegetation (averaging 3 m tall) grows on slopes exposed to salt spray and sea breezes. The shrubs are densely packed and have thin trunks. In more protected spots, humid ravines or on the mountains farther from the sea (e.g. *Sapiatiba*), the vegetation is much more robust.

2.5 VEGETATION OF SUCCULENT KAROO

Vegetation of the study area is classified according to Acocks (1988) as Strandveld Proper (veld type 34 b). The northeastern part of the study site includes Namaqualand Coast Belt Succulent Karoo (veld type 31 a) (Acocks 1988). Low & Robelo (1996) classify this vegetation as Strandveld Succulent Karoo (55) with a Lowland Succulent Karoo inclusion in the northeastern region. There are only two reports that present detailed descriptions of the Strandveld communities on and in the vicinity of the study site. Boucher & Le Roux (1989), describes the communities in the coastal strip between the Olifants and Spoeg Rivers according to five main vegetation sub-types: strand communities, strandveld communities, Succulent Karoo, sand plain fynbos and river and estuarine vegetation.

2.5.1 Vegetation structure

Above-ground structure

In his review, Eccles (2000) states that the vegetation is divided into three structural groups based largely on the height of the vegetation (Boucher & Le Roux 1989). The Short Strandveld community, with an average shrub height of between 10 and 35 cm, has a basal cover of less than 50%, the Medium Strandveld community has an average shrub height of between 50 and 100 cm and covers between 50 and 60% of the soil surface, and the Tall Strandveld covers 60–70% of the soil surface with most of the shrubs reaching a height of between 1 and 2 m. The vegetation is composed mainly of drought-deciduous and succulent species that are spaced in multispecies clumps with annuals and grasses spaced between clumps (Eccles 2000, De Villiers 1999 and Van Rooyen 2001). Although high in species diversity, this area has a low functional diversity and is structurally homogeneous (Cowling et al. 1994).

Root architecture

The bulk of the root systems found in the area are spaced within the top 20 or 30 cm. A study on root biomass and distribution by Eccles (2000), reveals that 90% of the fine root biomass of Short Strandveld is found in the top 30 cm and that 60% of the root material is spaced within the top 30 cm of Medium Strandveld. Although the root system of the Strandveld is vertically enclosed within the top 30 cm of the soil profile, studies by Eccles (2000) show that the horizontal distribution of roots in the Short and Medium Strandveld is regularly distributed between the clumps of above-ground vegetation. The vegetation structure can thus be simply classified as a clumpy shrub veld with a shallow, fibrous root mat.

A detailed vegetation survey of the mine region, carried out by De Villiers (1999), to identify plant communities in the pre-mined area of the study site is more relevant in terms of this study. The study area was divided into six vegetation communities that were sometimes individually subdivided into several variants. A total of 230 plant species were recorded.

2.5.2 Vegetation composition

Vegetation community 1: (*Ruchia tumidula – Tetragonia virgata* Tall Shrub Strandveld)

This community is situated the furthest inland and found on small dune systems. The four variants of this community are classified according to the vegetation composition on and between dune systems (De Villiers 1999). This area receives the least amount of fog and salt spray and is the driest of the communities in the study area (De Villiers 1999). A wide range of soil depths characterises the soils in this area with munsell colours occurring mostly within the yellow-brown and red range. *Ruschia tumidula*, *Galenia africana*, *Leysera gnaphalodes* and *Pharnaceum lantanum*, *Oncosiphon suffruticosu*m and several *Pteronia* species were diagnostic species of this vegetation community. This vegetation community consisted of four variants. The mining process will destroy a large part of this community. For this study the most eastern part of this community contains "heuweltjies", and was investigated as a separate subgroup.

Vegetation community 2: (*Eriocephalos africanus – Asparagus fasiculatus* Tall Shrub Strandveld)

This community is found on small, stabilized dune systems. The two community variants are respectively situated on the dunes and in the dune valleys. Prominent shrubs found within this community include *Asparagus aethiopicus*, *Nestlera biennis*, *Eriocephalus africanus*, *Asparagus capensis* and *Pharnaceum aurantium*. Abundant herbaceous species are *Manulea altissima* and *Oxals* species (De Villiers 1999). This area receives more fog and salt spray in relation to community 1, but the intensity is still less than the communities' closer to the sea. Soils from the variants on the dunes are deeper than the soils in the dune valleys (De Villiers 1999). Soils from this area have munsell colours that qualify as red. Just a small part of this area will be subjected to heavy mineral mining.

Vegetation community 3: (*Salvia africana-lutea – Ballora Africana* Tall Shrub Strandveld)

This community occurs mainly on a large sand dune called Graauwduine (Figure 1). The vegetation is taller than the vegetation in the surrounding communities (De

Villiers 1999). Deep yellow sands characterise the soils. Nearly 40 % of this community is included in the area to be mined. This area receives more fog and salt spray than community 1 does but less than communities 4, 5 and 6 (De Villiers 1999). A slight depression on the top of the sand dune shows a change in vegetation composition and physiognomy. The soil in this depression contains a higher clay content than soil from the surrounding dune and is characterised by the occurrence of a shallow dorbank.

Vegetation community 4: (*Ruschia versicolor – Odyssea paucinervis* Dwarf Shrub Strandveld)

Community 4 is found in the southern part of the survey area and incorporates most of the area to be mined. This area receives more fog and salt spray in comparison to communities 1, 2 and 3, but less than communities 5 and 6 (De Villiers 1999). The soils from this area changes from a firm, dark red sand in the east to loose yellow sand in the west. This vegetation community comprises of three variants that are located in the central, eastern and southern part of the dwarf shrub Strandveld (De Villiers 1999). The soil survey was conducted on the mine face in the central variant.

Vegetation community 5: (*Cephalophyllum spongiosum – Odyssea paucinervis* Coastal Strandveld)

This vegetation community is situated on a narrow footslope before the terrain rises steeply to the coastal plain. It stretches along the southern coast of the study area with a wave-cut rocky platform. The soils from this community comprises of a deep yellowish sand (De Villiers 1999). Mining activities will not directly influence this community.

Vegetation community 6 (*Cladoraphis cyperoides – Lebeckia multiflora* Coastal Strandveld)

This community is found on a white coastal dune system next to a beach in the northern part of the study area. This white dune Strandveld community (Boucher & Le Roux (1989) is often associated with river estuaries and gets easily disturbed resulting in dune movement. The soils from this community comprise regic sands.

2.6 FAUNA

A resident bird population of approximately 83 species are confirmed as occurring at the mine site, with a breeding population of about 52 species been reported in the study area. An additional 66 species could be expected to occur on the study site (Mahood 2003). There were also 38 species of reptiles and one amphibian. A lack of studies in this region complicate the determination of the importance of various amphibian and reptile species in the ecological functioning of the west coast ecosystem. Nineteen mammal species are reported within Namakwa Sands. Another 16 mammal species could be expected to occur on the study site. (Environmental Evaluation Unit 1990; Mahood 2003).

The most obvious indication of the role of insect fauna in the functioning of the West Coast ecosystem of the Succulent Karoo is the occurrence of well-established termite mounds or “heuweltjies”. Heuweltjies occur as circular mounds of approximately 5 – 15 m in diameter and 1 m in height. From 10 – 15 % of an area can be covered with heuweltjies (Ellis 1988). Ellis (2002) showed a relationship between the occurrence of heuweltjies, caused by the harvester termite *Microhodotermes viator*, hardpan (petrocalcic, petrogypsic or petroduric horizons) occurrence and rainfall gradient in the West Coast of South Africa.

2.7 GEOLOGY

The coastal plain of the Namaqualand, in which the study area occurs, consists of a complex sequence of marine and wind-blown sands ranging from weathered, fine-grained deposits from the late Tertiary to Quaternary age to the recent white and calcareous sand of the coastal margin (Cowling et al. 1999). These sediments are mostly “soft geological materials” (unconsolidated) and vary in depth and composition (Ellis 1988). Hardpans of various siliceous and calcitic composition and metamorphic rocks of the Namaqualand granite-gneiss suit, and metamorphosed Vanrhynsdorp Group underlies most of the sandy landscape (Cowling et al. 1999; Watkeys 1999; Environmental Evaluation Unit 1990; Ellis 1988). Some outcrops of silcrete of Tertiary origin are also exposed in places (Ellis 1988).

2.8 GEOMORPHOLOGY

The study area is part of a geomorphological subdivision of the Namib Desert, and is referred to as the Namaqualand Sandy Namib. The retrograding coastline of the study area trends in a north-north-west direction, exposing the coastal land to the strong southerly winds in the summer. The coast consists of a wave-cut rocky shoreline, separated by isolated beaches and a large primary dune belt, Graauwduine, stretching approximately five kilometres long and 500 m wide. The inland is characterised by an undulating landscape with vegetated sand dune systems that is roughly aligned parallel to the prevailing north-south wind direction. The terrain rises in most places steeply from the coast inland (Environmental Evaluation Unit 1990).

2.9 SOILS

The study site is located within the West Coast South region as described by Ellis (1988). Although cemented heuweltjies extend over the largest portion, 45.7 % of this area, it only occupies a small northeastern section of the study site (Ellis 1988). Ellis (1988) stated that of the broad soil patterns that occur within the area, red apedal soil with high base status dominates. Regic sands and other red and yellow apedal high base status soil are also frequently found within the study area (Ellis 1988).

All soils contain predominantly sandy A horizons (< 6 % clay). The dominant underlying material occurring within this region is dorbank with unconsolidated material such as alluvium, marine clays, pedisediment and recent sands being subdominant (Ellis 1988).

Buol et al. (1997) state that soil has been defined as ‘the medium for growth of land plants’. The definition of soil actually varies according to the speciality field of the definer and the role that soil plays within its field. Ecologists define soil as the part of the environment that is conditioned by organisms and that in turn influences the organisms (Buol et al. 1997). For a pedologist, soil is a natural body of mineral and organic matter that changes, or has changed in response to climate and organisms (Buol et al. 1997). The main difference between the two viewpoints lies in the concept of time. Where an ecologist focuses on the current effect that soil properties have on the biota, a pedologist looks at current soil conditions as indicators of historical processes. Both concepts are necessary to understand the environment we live in.

2.9.1 Soil properties: A pedological perspective

Vegetation uses the soil as a medium for gaining physical stability and life-supporting nutriment and water (Brady & Weil 1996; Salisbury & Ross 1992). Different plant species growing in the soil, influence the soil in several important ways and soil properties will again exert control over the plant species composition (Buol et al. 1997). When gaining knowledge about the influence of the abiotic environment on ecosystem functioning, it is of uttermost importance not to think of soil only as a medium directly influencing the rhizosphere conditions, but also as an indicator to determine the environmental history that would have effected ecological development.

According to Van der Watt & Van Rooyen (1995) the pedosphere is a shell or layer of the earth in which soil-forming processes occur. Pedogenic material occurring within the solum is a product of the action that environmental conditions have on weatherable parent material (Buol et al. 1997). Although the pedosphere can be seen as a product of the environment, it is still an entity in space and time that keeps on developing into a direction, depending on the continuously changing environment it is located in. A soil form, at a specific time (tn), is the result of climate, flora, fauna and terrain relief influences on the initial characteristics of parent material from time zero to tn (Buol et al. 1997). Water is the sole contributor to salt and clay movement within the pedosphere and contributes significantly to soil profile development (Harris & Campbell 1981). It also shapes drainage pathways through regional topography (Harris & Campbell 1981). The salt balance and subsequent nutrient availability of a specific environment have a twofold explanation. The topographical relationship of an identified pedoregion with the surrounding environment will result in an open or closed drainage system. With sufficient precipitation a closed system will result in the net influx of particulate sediment and salts with water (Buol et al. 1997). These areas are characterised by specific soil properties such as carbonate and silica-cemented horizons or high salinity levels. The Hartebeeskom, near the study site, is an example of a macroscale closed system while the depressions between dunes can induce a microscale closed system. Secondly, desert systems are naturally characterised by losing nearly all water gained through precipitation to evaporation losses (Bailey 1981). This will prevent moisture surplus to accumulate as surface waters that perennially flow to the sea (Bailey 1981). Salt influx into such a system or geological inherited salts will thus expose soils to potential high salinity and pH levels. Ellis (1988) indicates that the presence of silica or calcium-cemented hardpan horizons, such as the dorbank horizons found in the study site, can be the result of insufficient leaching, due to aridity, of dissolved silica and calcite out of the soil profile. In contrast, Ellis (1988) also describes the presence of an E horizon that is sequentially underlain by a more clayey and dorbank horizon in the soils of the southern West Coast of South Africa. According to the Soil Classification Working Group (1991) this horizon is formed due to the removal of reduced iron, clay and salts via accumulated water. This sequence of horizons indicates that water accumulation took place in a soil that previously experienced insufficient leaching. Although the explanations can be numerous, they reveal an historical overview of the soil hydrological processes that have taken place. The importance of understanding water availability, movement and distribution in an arid or semiarid region, emphasises the need to study all signs of pedogenic process, as indications of the past and present soil water regime.

2.9.2 Soil properties: An ecological perspective

Plants, as any other living organism on earth, have certain nutritional requirements to live, grow and reproduce. Van der Watt & Van Rooyen (1995) define nutrients as elements, which are absorbed and necessary for the completion of the life cycle of organisms. For plants, this definition would classify water, oxygen, carbon dioxide and various salt ions. Soil properties influence some control over the availability of these nutrients and consequently over the types of plants that grow and flourish in it (Buol et al. 1997). Thames & Evans (1981) mention that vapour movement in the soil, which has little or no importance in humid systems, may allow some desert plant species, particularly the lower forms, to survive and even thrive in the absence of liquid flow. Bailey (1981) states that the lack of water represents the most effective extreme of all climatic factors in arid regions.

Mineralogy

The silt and sand fractions of these soils mostly consist of quartz with some feltspatic particles (Ellis 1988). The coastal beach systems contain primary carbonate deposits. These are mainly residual, weathering resistant, primary minerals from parent material weathering (Hillel 1998). The weathering product, or secondary minerals, mostly comprises the clay fraction (Hillel 1998). Clay content and mineralogy is the most influential textural fraction of soil. Numerous clay minerals exhibit a comprehensive variation in prevalence and properties and the way they affect soil behaviour (Hillel 1998; Schulze 2002; Sparks 2003). Various clay minerals differ in the extent that they adsorb water and hydrate, thereby causing the soil to swell and shrink upon wetting and drying (Hillel 1998). Isomorphous replacements or substitution of ions in the crystalline structure of aluminosilicate clay minerals result in internal unbalanced negative charges (Hillel 1998). Along with incomplete charge neutralisation of terminal atoms on lattice edges, the cation adsorption capacity of these unbalanced negative charges are called the CEC (cation exchange capacity). These negative charges result in an electrostatic double layer with exchangeable cations in the surrounding solution (Tan 1994; Hillel 1998). Phyllosilicate clay minerals exhibit a strong influence on the chemical as well as physical properties of soils due to their generally small particle sizes, high surface areas and unique cation exchange properties (Schulze 2002). These characteristics greatly influence the fertility status of soils. The current lack of quantitative and qualitative clay mineralogical data can result in the inability to capture the essence of ecological processes and patterns of this unique region.

Soil organic matter

The organic carbon content is very low and averages around 0.28% in A horizons from the southern West Coast region (Ellis 1988). Organic matter is derived from the soil biomass and consists of both living and dead organic matter. The organic fraction of the soil affects the physical, chemical and biological conditions in soil (Tan 1994; Deng & Dixon 2002). Physically it improves soil aggregation of soil particles for the formation of stable soil structures and increases water-holding capacity (Tan 1994; Hillel 1998; Deng & Dixon 2002). Chemically it increases the CEC (cation exchange capacity) (Tan 1994; Hillel 1998; Deng & Dixon 2002; Sparks 2003) and increases the soil's fertility by increasing nutrient content. Decomposition of organic matter yields CO_2, NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} (Deng & Dixon 2002; Sparks 2003). Organic matter is the main source of N in soil and also the main source of food and energy to soil organisms (Tan 1994). Hydrophobic characteristics are caused by a range of hydrophobic organic materials (King 1981).

Soil texture

As has been reviewed in the description of the study site, the soils from this region are naturally coarse textured. Hillel (1998) defines soil texture as the permanent, natural attribute of the soil and the one most often used to characterise its physical makeup. Texture is quantified in terms of the sand, silt and clay content. These are defined in the USDA and South African classification system as particles with effective spherical diameters of <0.002, 0.05 – 0.002 and 0.05 – 2.0 mm of clay, silt and sand respectively. The clay fraction has a far greater surface area per unit mass compared with the sand fraction, and due to the resulting physiochemical activity, it is the decisive fraction which has the most influence on soil behaviour (Tan 1994; Hillel 1998; Schulze 2002). Clay has the dominant influence on soil water dynamics. Water-holding capacity of soil decreases in accordance to lower clay content of soils (Gay 1981; Hillel 1998). Clay is a reservoir of nutrients, especially cations, and profoundly influences plant and microbiological life (Coleman & Crossley 1996).

Soil structure

Soil structure refers to the arrangement and organisation of the particles in the soil (Hillel 1998). Soils from the study site are weakly structured to apedal (Ellis 1988). Hillel (1998) states that soil structure affects the retention and transmission of fluids, including infiltration and aeration, and mechanical properties of soil such as stable aggregate formation that inhibits compaction and erosion. Optimal conditions for plant root growth require a loose and highly porous and permeable condition. The ability of clay minerals to swell and shrink profoundly influences the structural properties of soils (Hillel 1998). The low clay content of the soils from the study site will reduce the swell and shrink potential of these soils, preventing structure formation. These characteristics will make soils from the study site prone to wind erosion and dune movement when disturbed.

Soil pH

According to Ellis (1988) soils in the study area generally have a high base status with neutral to high pH levels. Soil pH measurements done by Mahood (2003) indicate the presence of soils with pH levels below 5. Soil pH greatly affects numerous soil chemical reactions and processes (Sparks 2003). It affects the availability of plant nutrients and microorganisms. High pH levels decrease the solubility of elements such as iron, zinc, copper and manganese due to precipitation (Sparks 2003; Salisbury & Ross 1996; Tan 1994). Phosphate is more easily absorbed as a monovalent $H_2PO_4^-$ ion at pH levels of 5,5–6,5. High pH values result in the formation of divalent HPO_4^{2-}, which is less readily absorbed, with the formation of insoluble calcium phosphate at even higher pH values. Low pH values will result in the precipitation of phosphate with aluminium ions (Salisbury & Ross 1996; Tan 1994). High aluminium, iron and manganese concentrations at low pH levels (below about 4,7) can also inhibit growth due to toxic effects (Sparks 2003). Salisbury & Ross (1996) review that hydroponic techniques to study various plant species that prefer different pH levels indicated reasonably good performance over a wide pH range. This result was attributed to competition in nature, where a slight advantage of one species over another can eventually lead to elimination of the less well adapted. Except for some acidious subsoil horizons and the alkaline, carbonate rich coastal beach dunes (Mahood 2003; Ellis 1988), no significant pH inhibitory effects are expected in this region.

Soil salt content

Soil resistance measurements indicate that the topsoil of the southern West Coast region has generally low salinity levels increasing to lower depths (Ellis 1988). The salinity levels of recently deposited material are also low (Ellis 1988). Mahood (2003) also indicates generally low salinity levels present in undisturbed topsoil and subsoil horizons. Salt-affected soils can be classified as saline, sodic and saline-sodic (Sparks 2003). Saline soils have high levels of soluble salts, sodic soils have high levels of exchangeable sodium, and saline-sodic have high contents of both soluble salts and exchangeable sodium. Problems that plants face in highly saline soils is that of attaining water from a soil of low negative osmotic potential, dealing with the high concentrations of potentially toxic sodium, carbonate, and chloride ions and nutrient imbalances resulting from high concentrations of Na and Mg relative to Ca (Salisbury & Ross 1996; Hagenmeyer 1997; Donner & Grossl 2002). Plants have developed mechanisms to resist the effect of high salt concentrations. Hagenmeyer (1997) describes these mechanisms in detail. He reviews that plants can achieve resistance to salt stress either by tolerating or avoiding the stress. Salt tolerance may depend on salt exclusion from the cytosol as well as the change in the microenvironment of the enzymes. Hagenmeyer (1997) reviews that the *in vitro* salt tolerance of the enzyme PEP-carboxylase is increased with an increase in the substrate (PEP) concentration.

Plants have developed various methods to avoid or regulate salt stress. The foremost strategy for the limitation of salt accumulation in plants is the inhibition of salt ions uptake through roots (mangroves) or restriction of salt uptake into sensitive organs or tissues (Salisbury & Ross 1996). Other methods of avoidance or regulation are the excretion of salts through bladder hairs and salt glands, the dilution of salts through morphological and structural changes such as succulence and the osmotic adjustment through compartmentalisation and sequestration in vacuoles (Gibson 1996). Although no serious salinity-induced limitations to plant growth was documented in previous studies (Mahood 2003; Ellis 1988), the name of this biome in which the study site is situated, indicates that plants in this area have the ability to avoid salt stress through dilution in succulent leaves.

Soil permeability

Soil permeability is a qualitative term that refers to the ease with which gasses, plant roots or, more usually, liquids penetrate or pass through soil (Van der Watt & Van Rooyen 1995). Soil permeability is influenced by the combination of various soil properties, for example porosity, pore-size distribution, pore tortuosity and internal surface area (Hillel 1998). The main influential factors on permeability of the soils in the study site are the lack of structural development, the low clay and silt content and cementation of the soil matrix by silica or carbonate deposits. The dominant subsurface material occurring is dorbank (Ellis 1988). Porous sandy substrate of the dune fields in this region can result in deep water infiltration after big rainfall events and unimpeded root growth to reach most sand one or more metres below the dune surface (Gibson 1996). Unconsolidated material is subdominant, including alluvium, marine clay, pedisediment and recent sands (Ellis 1988). Dorbank material is highly impermeable and will thus greatly decrease water penetration depth.

2.9.3 Soil water regime

Due to its scarcity, water has the most dominant influence on arid ecosystem form and function. It is essential to understand the method of water distribution and provision to terrestrial ecosystems before rehabilitation of an ecosystem can take place. Soil, as a mediator, intercepts, distributes and provides this life-giving resource for living organisms. Harris & Campbell (1981) state that water has a profound influence on soil profile development and maturity as well as the shape of drainage pathways through local and regional topography. A thorough investigation of soil profile morphology and topography can cast light on the understanding of a water balance model in the surrounding environment. Temperature is a very important component of the soil-plant-atmosphere energy budget (Hillel 1998) and it is of great importance to investigate the effect of diurnal soil temperature fluctuations as a driving force on the water movement in desert systems.

Figure 2.2 illustrates a water budget for desert systems (Campbell & Harris 1981). Precipitation is the most important source of water for most desert systems (Campbell & Harris 1981). Precipitation variation is normally statistically expressed by the coefficient of variation (Bailey 1981). The variability of precipitation normally increases as rainfall decreases (Fogel 1981). The Strandveld Succulent Karoo is subjected to winter precipitation (Esler et al. 1999) that is generally the result of cold fronts, affecting fairly large areas (Fogel 1981). Water availability, as a scarce resource in the Succulent Karoo for plant growth, is relatively predictable because of the fog-moisture input, and low interannual variation of winter rainfall (Esler et al. 1999). Due to the low vegetation density, canopy surface storage plays a relatively small role in water storage of desert systems. Precipitation that exceeds interception and infiltration into the soil becomes runoff (Hekman (Jr.) & Berkas 1981). Stemflow is a very important mechanism to channel especially dew and mist precipitation to the root zone (Devit & Smith 2002; Martinez-Meza & Withford 1999). Infiltration rate is controlled by both the suction and gravitational head gradient (White 1997). The suction gradient dominates the early stages of infiltration (White 1997). The lack of fluvial systems, originating from the study area, indicates that the loss of water due to

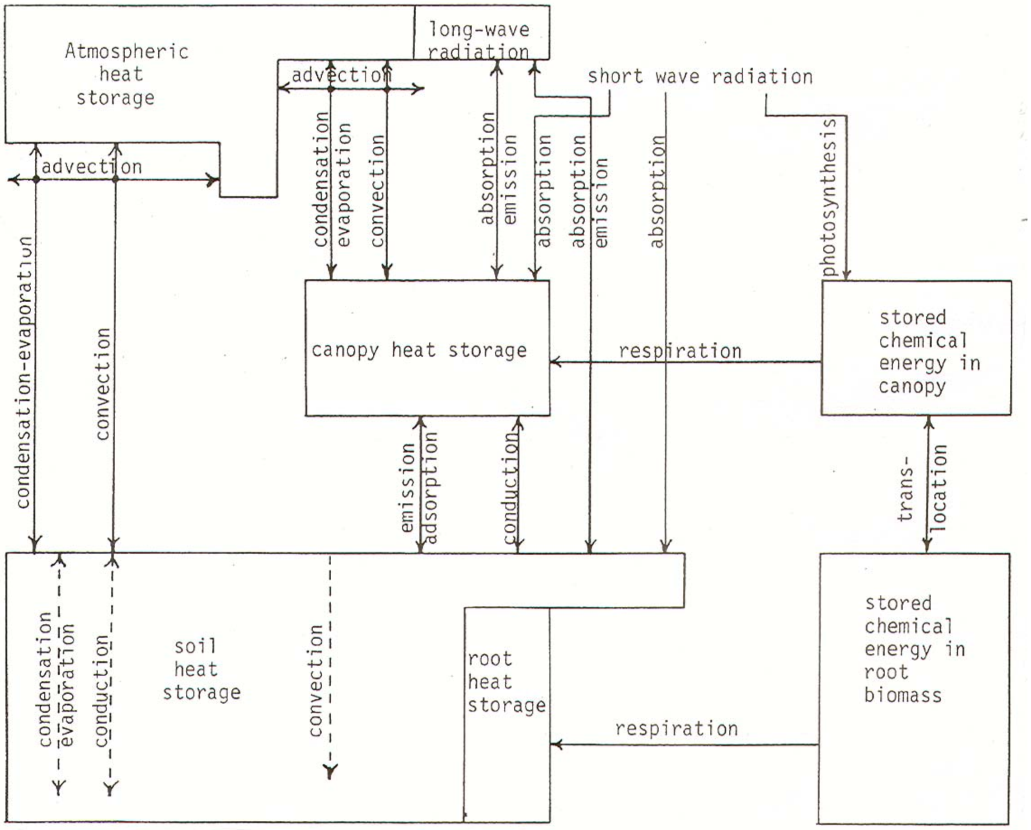


Figure 2.2: Water storage and exchange in a soil-plant-atmosphere system (Campbell & Harris 1981)

surface flow is prevented due to total infiltration of precipitated water. Coarse texture of soils from the Strandveld Succulent Karoo can result in high infiltration rates. Depending on rainfall intensity and degree of water saturation, rainfall can result in the loss of water through deep infiltration. Although a saturated sandy soil conducts water rapidly through the water-filled macropores, the opposite is often the case when unsaturated conditions prevail (Hillel 1998). Intense rainy events can thus result in water runoff on dry unsaturated sand, increasing the possibility of preferential infiltration zones in soil surface depressions between shrubs. These preferential infiltration zones can result in deep percolation of water. Low precipitation intensity and extensively occurring water impenetrable more clayey (cutanic, luvic) and dorbank horizons will prevent deep percolation of water. The water storage reservoir can be divided into a shallow and deep storage compartment (Campbell & Harris 1981). A shallow water storage compartment is subjected to high intensities shallow-rooted uptake and evaporative loss. Deep-stored soil water is mostly depleted by deep-rooted perennials and not by evaporation. The lack of deep-rooted perennials in the Strandveld Succulent Karoo questions the occurrence of deep-stored soil water.

According to Campbell & Harris (1981) water is transferred from one zone to another by liquid flow and evaporation condensation. Liquid flow tempo is largely controlled by the degree of saturation and textural properties of soil (Hillel 1998). Mass liquid flow in a water-saturated soil largely takes place by tube flow through water-filled pores while an unsaturated soil may conduct water either through film creep along the walls of wide pores or as tube flow through narrow water-filled pores (Hillel 1998). Mass liquid flow of water within the soil matrix is primarily influenced by differences in soil water potential (Brady & Weil 1996; Hillel 1998; White 1997;). Total soil water potential is composed of various forces. The most important contributors to the total soil water potential are the gravitational, pressure (matric) and osmotic potential (Hillel 1998). Osmotic soil water potential is only important when considering the interaction between plant roots and soil, and in the processes involving vapour diffusion (Hillel 1998). Accumulation and saturation on a less impermeable soil horizon and the consequential formation of a seasonal water table, result in gleying and the formation of an E horizon due to lateral flow downwards on a descending slope (White 1997). Campbell & Harris (1981) mention that, although thermal-induced water vapour flow is insignificant in magnitude related to other components of the water budget, it can significantly influence and contain physiological processes of some plant species during specific times of the year. Vapour movement within the soil matrix is governed by differences in vapour density gradients (White 1997). Water vapour, at any point in the soil matrix that is thermodynamically equilibrated with water, is affected by temperature, osmotic potential and matric potential of the soil water (Jury et al.1981; White 1997). Matric and osmotic potential have a negligible influence on soil vapour density except for extreme conditions of salinity and dryness (Jury et al.1981; White 1997). High fluctuations between day and night temperatures are common features in a desert environment. Cloudless skies result in intense heating of the soil surface in the daytime and high radiative cooling at night. Thermal gradients within the soil can cause water transfer through evaporation condensation that can be an important mechanism for water transfer in desert soils (Jury et al. 1981).

2.10 THE MINING AND REHABILITATION PROCESS

2.10.1 Mining

Namakwa Sands Mine has been divided into an eastern sector (Graauwduinen East) and a western sector (Graauwduinen West). The Graauwduinen West region extends over approximately 1 400 ha, and mining of sand reaches depths of between 2 and 45 m. Mining in Graauwduinen West results in the removal of the dorbank layers to gain access to lower-lying mineral deposits. The mining process in Graauwduinen East results in the removal of sand up to depths of between 1 and 5 m. The dorbank layer and the overlying neocutanic horizon are not excavated in the Graauwduinen East region. The Graauwduinen East region is approximately 3 370 ha in size (Environmental Evaluation Unit 1990; Mahood 2003).

The top 50 mm of sand is removed and stored for rehabilitation before the bulk removal of heavy mineral rich sand begins. This top layer of soil is removed by a bulldozer and thus contains plant material and organic debris and deeper soil material captured by plant root systems. Namakwa Sands is exempted from the preservation of 300 mm of topsoil, suggested by the Department of Minerals and Energy, Western Cape, to be stored to serve as growth medium in rehabilitation. The fraction is then stockpiled and stored for approximately three months while mining progresses. Mined sand is then transported to a mineral separation plant via conveyer belt. Seawater is used as a medium to wash the mined sand for separation of the heavy mineral compound. The residue after mining exists of a sand fraction, called tailings and a silt plus clay fraction, called slimes. The slimes fraction is deposited in evaporation slimes dams where the clay is flocculated and left to dry out (Environmental Evaluation Unit 1990).

2.10.2 Rehabilitation

Sand tailings are deposited back into the mined-out area in such a manner that it fits within the surrounding landscape contours. The rehabilitated land must be hydrologically and visually compatible with the surrounding environment. Crushed dorbank, originating from Graauwduinen West, is used to stabilise the deep, back-filled sand for the west mine conveyer to stand on. Rehabilitation follows the mining in a north-eastern direction in Graauwduinen East and in a southern direction in Graauwduinen West. There is a decreasing time gradient in rehabilitated land age north-easterly in Graauwduinen East and southerly in Graauwduinen West. Stored topsoil is then spread over the sand tailings of Graauwduinen East and the crushed dorbank of Graauwduinen West. Windbreaks are used to protect the rehabilitated land from wind erosion. Windbreak nets consist of polyethylene shade nets (40% shade) with a height of approximately 1 m and are spaced at 4–5 m intervals perpendicular to the dominant wind direction. Windbreaks also act as seed and fog traps (Mahood 2003). Rehabilitated land younger than 27 months in Graauwduinen East is treated with topsoil spreading (Environmental Evaluation Unit 1990, T. Hälbich, personal communication, 2003).

2.10.3 Rehabilitation evaluation

Depending on the objective, revegetation can be divided into various levels of completeness, ranging from total restoration to the original form, rehabilitation or partial restoration to the replacement of the natural ecosystem with an alternative form (Bradshaw 1984). Restoration of natural vegetation communities frequently lies in the identification, understanding and overcoming of factors that prevent or restrict ecosystem development. The proposed outcome should thus be based upon knowledge of abiotic and biotic interactions that affect plant establishment (Pyke & Archer 1991). Of all the recommendations by Lubke & Avis (1998) on the development of a rehabilitation programme only one recommendation, soil type survey, was not completed before the start of this study. This was also the first recommendation mentioned, indicating the importance to rehabilitation. Major processes resulting in the accumulation of major nutrient levels in soil are: weathering of soil minerals; precipitation; biological movement from lower soil horizons by plant activity; and biological fixation. Bradshaw (1983) emphasises the importance of nitrogen increase in the soil for successful ecosystem reconstruction. The use of heavy machinery during backfill of tailings can cause severe compaction (Bradshaw 1983). Lanz (2003) mentions localised soil compaction as the possible cause of retarded plant growth in some areas of the rehabilitated land. Changes in soil structure, bulk density and porosity are important characteristics of successional development (Bradshaw 1983). The return of fauna such as burying rodents and termites can serve as important components to facilitate the recovery of consolidated soil and adjunct ecosystem rehabilitation.

A study done by Mahood (2003) to determine the soil fertility status of strip-mined areas indicated that tailings had a significant lower resistance and higher sodium content in comparison with undisturbed topsoil, undisturbed subsoil and stockpiled topsoil. Apart from a direct osmotic effect due to high soluble salt contents, high sodium and chloride can have a negative effect on plant growth. Mahood (2003) indicates that phosphorus, potassium, calcium and magnesium levels are significantly lower in mined sand tailings than in undisturbed soil. It was found that sodium, potassium, calcium and resistance return to levels observed in undisturbed topsoil and subsoil 15 months after backfill of tailings. Although stockpiled topsoil improves the survival of some species, the upper 50 mm of topsoil is considered not to be enough for rehabilitation purposes. It was also indicated that winter and spring irrigation negatively affects the return of biodiversity and the number of seedlings per square metre on rehabilitated land.

2.11 CONCLUSIONS

The coastal Namaqualand ecosystem is adapted to an environment that is unique in comparison to other warm desert ecosystems. High irradiance levels during summer, colder growing conditions in winter, a strong wind regime, low humidity, frequent fog and dew events, a low annual rainfall and a constant salt influx from the sea are all inductive to successional development of vegetation. This mild and relatively predictable arid climate, winter rainfall, extreme diurnal temperature fluctuation, combined with a sandy soil substrate, may induce a distinctive soil water regime that may be the driving force behind this unique ecosystem. Vegetation is usually the most obvious physical representation of an ecosystem (Kent & Coker 1996). The vegetation survey perform by De Villiers et al. (1999) divided the study site into 6 main vegetation communities. An ordination was conducted to identify characteristic environmental properties including distance from sea, soil colour, relief and fog events. Such an ordination of vegetation species composition according to environmental properties can be very useful to map out possible soil property variation. The most obvious influence of fauna in this ecosystem is the presence of termite mounds or “heuweltjies” in the north-eastern corner of the proposed study site. It is important to be aware of this phenomenon during rehabilitation planning. Fey et al. (2002) state that pedological features reveal subtleties of climatic and topographic effects that are key to ecosystem functioning and that the inability to recognise their significance may doom the rehabilitation effort to failure in the long run. Ellis (1988) identified the occurrence of pedological features such as soil horizons with signs of wetness or gleying, a dense neocutanic horizon and a silica cemented hardpan or dorbank horizon that may be essential to consider for rehabilitation purposes. These pedological features reveal significant information of the soil water dynamics. The current lack of quantitative and qualitative clay mineralogical data can result in the inability to capture the essence of ecological processes and patterns of this unique region. The mining technique results in the separation of the clay and silt fraction from the sand. It may also have a significant impact on organic matter content and other chemical and physical characteristics of the soil. Current rehabilitation techniques do not consider this potential impact of mining on mined soil. This may affect rehabilitation success. Shallow root architecture of the Strandveld vegetation indicates the occurrence of a shallow water source or impediment layers preventing deeper root growth. Successful rehabilitation of the ecosystem will be strongly dependent on the ability to recreate a soil environment with similar soil water regime preceding the mining operations.

CHAPTER 3

SOILS IN THEIR UNDISTURBED STATE: DESCRIPTION AND CLASSIFICATION

3.1 INTRODUCTION

Mining operations for diamonds and heavy minerals are destroying vast areas of the Strandveld Succulent Karoo. The remarkable dominance and unique diversity of short to medium-lived shrubs, the rich geophyte flora and lack of drought-deciduous shrubs and other long-lived perennials, highlight this biome as one of exceptional importance (Bowie 1999). Natural Strandveld vegetation exhibits a highly complex mosaic pattern. An understanding of the site-specific environmental conditions such as soil properties and various other biotic influences is necessary to determine the environmental driving forces associated with different components of the mosaic. Fey et al. (2002) state that pedological features reveal subtleties of climatic and topographic effects that are key to ecosystem functioning and that the inability to recognise their significance may doom the rehabilitation effort to failure in the long run.

The objective of the work reported in this chapter was to investigate soil formation in the Strandveld Succulent Karoo near Brand-se-Baai, as a clue to some of the ecosystem processes particular to this environment. This was done by describing and classifying 20 profile pits dug throughout the vegetation communities classified by De Villiers (2000). Soil horizons were identified and described in a way that would convey information about soil forming processes, especially those that might have some bearing on the quality of the soil in sustaining a cover of vegetation.

3.2 MATERIALS AND METHODS

A total of 20 soil pits were dug in the undisturbed areas around the mine (Figure 3.1). Profile pits were sited to reflect soil variation as much as possible. Location of vegetation communities (De Villiers 2000), variation in the colour observed on aerial photographs, variation in topography, textural and other variation observed in the field were used as indicators for siting profile pits.

3.2.1 Profile descriptions

Important morphological (Munsell colour, depth, diagnostic material, horizon transition), physical (texture, gravel content, structure, consistence, root density, moisture status, crust formation), chemical (presence of free lime) and other features such as recent deposits were documented. Root density was depicted by an index from 1 – 5 indicating a root density varying from very low to low, moderate, high and very high. Samples from each soil horizon were taken and selected soil samples analysed for soil chemical, physical and mineralogical properties. The soils were classified according to the South African (Soil Classification Working Group 1991) and the FAO-WRB (2001) classification systems. A combination of horizon symbols was used to indicate transitional soil horizons. Soils with transitional horizons were classified according to diagnostic properties that would reflect the soil physical, chemical and morphological properties of the transitional horizons. Soil horizons that were classified identically according to standard criteria, but in terms of additional criteria, were given a I or II suffix as separators. Neocutanic I and neocutanic II horizons were distinguished according to the overlying horizon sequence and consistence. A neocutanic II horizon is overlain by an orthic A horizon, a yellow-brown or red apedal B horizon and gleyed sand (Table 3.1). An orthic A or E horizon overlies a neocutanic I horizon. Dorbank I and dorbank II horizons were distinguished on the basis of a very high density and consistence, lighter brown matrix colour and presence of whitish layers, slightly effervescing with a 10% HCl solution, in the dorbank II horizon (Table 3.2).

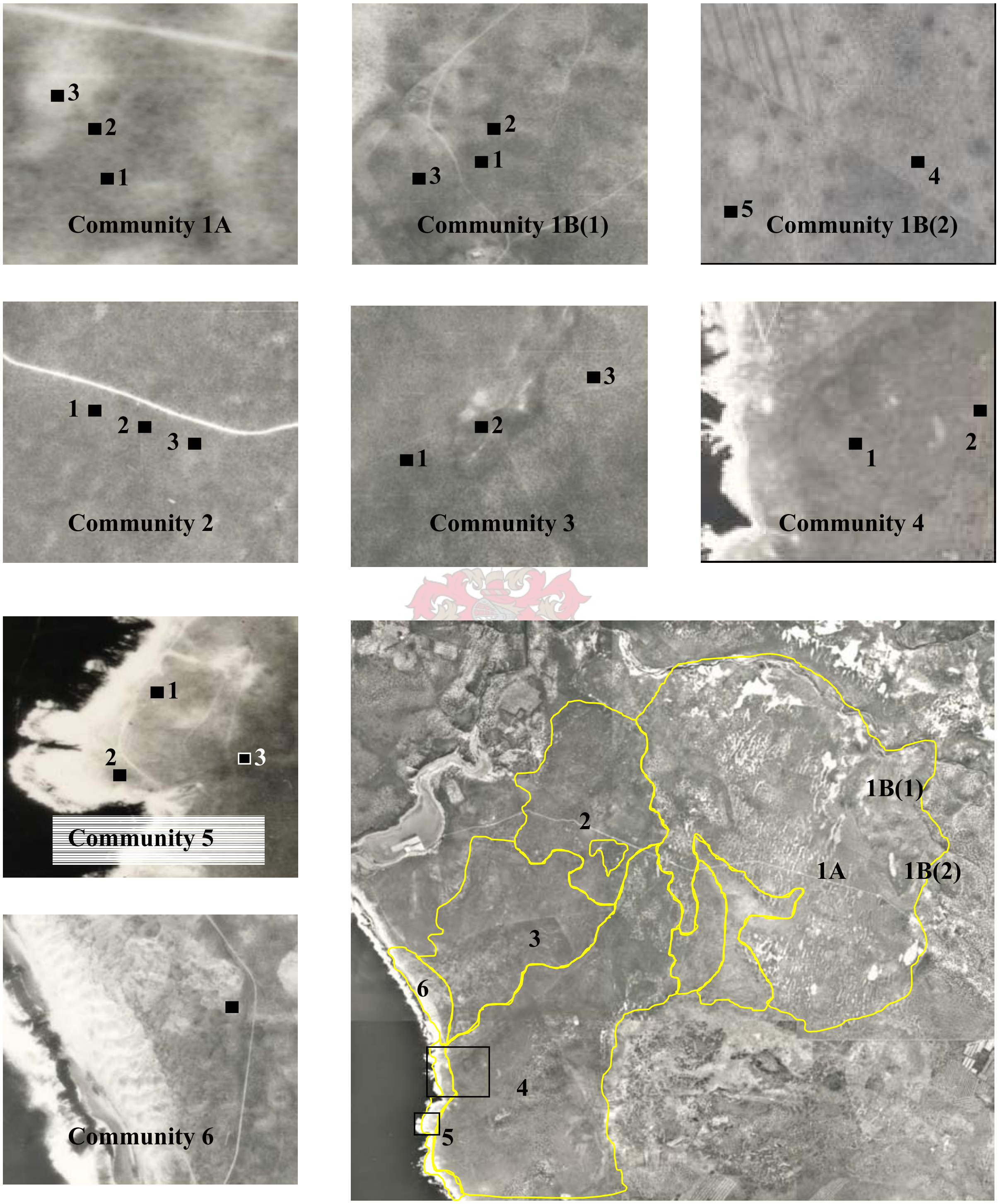


Figure 3.1: Aerial photographs indicating the location of vegetation communities (adapted from De Villiers 2000) and soil profiles (Small photos are located on the larger photo as marked)

Table 3.1 Criteria for neocutanic B-I and neocutanic II horizons

Horizon sequence	**Horizon**	**Abbreviation**
Orthic A or E	Neocutanic B-I	ne I
Orthic A / yellow brown B, red apedal B or neocutanic B-I / gleyed sand	Neocutanic II	ne II

Table 3.2 Criteria for dorbank I and dorbank II horizons

Horizon criteria	**Horizon**	**Abbreviation**
Yellow-brown or red matrix; Not effervescing with 10 % HCl Homogenous matrix colour	Dorbank I	db I
Slightly effervescing with 10 % HCl Light brown matrix with white layers Very high density and consistence	Dorbank II	db II

3.2.2 Chemical, physical and mineralogical analysis

All the non-cemented horizon samples were chemically analysed. Analysis included electrical conductivity (EC) of 1:5 soil-water suspensions, pH of 1:2.5 soil-water suspensions and 1:2.5 soil-0.1M (KCl) suspensions. Selected soil samples were analysed for extractable iron with the citrate-bicarbonate-dithionite (CBD) extraction method (Mehra & Jackson 1960) and organic carbon content with a carbon combustion technique. Selected soil samples were analysed for bulk density with clod method and clay by sedimentation. A simple wet-sieving method was used to determine the clay plus silt content (>53 micron fraction). Scanning electron microscopy (SEM) and X-ray diffraction (XRD) patterns were done on selected soil materials. A modified computer-controlled Philips 1410-diffractometer at the Stellenbosch University with Cu Kα radiation was used in the identification procedure of minerals in selected material. Clay smears on glass slides were examined after Mg or K saturated treatments and various heat treatments. Imaging of the run products and analysis of the phase compositions was accomplished using a Leo® 1430VP Scanning Electron Microscope at the Stellenbosch University. Phases were identified according to crystal form and relative greyscale in backscattered electron (BSE) images, and phase compositions quantified by EDS analysis using an Oxford Instruments® 133KeV detector and Link Semquant software. Beam conditions during the analyses were 20 KV and 1.5 nA, with a working distance of 13 mm. Despite the relatively low energy of the beam, X-ray counts with the set-up used were typically ~ 5000 cps. The counting time was 50 s live-time. Natural mineral standards were used for standardization and verification of the analyses. Pure Co, as well as Ti and Fe in ilmenite were used periodically to correct for detector drift.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Description of study area

Soil classification

Seven soil forms and eleven soil horizons or material were found in the study area (Table 3.3). Soil profiles were classified into both forms and families. Five soil horizons occurred having a transitional nature between two diagnostic horizons. Explanations for horizon abbreviations are given in Table 3.4. A combination of the horizon symbols indicates soil horizons that were transitional in character. Classification of the soil profiles according to the FAO-WRB classification system (2001), revealed the presence of 3 Reference Soil Groups and 14 Soil Units (Table 3.5).

Soil chemistry

The soils tend to be neutral to alkaline with pH values in water mostly between 6 and 8 (Table 3.6). Although most of the samples had relatively low salinity levels, the value range was high with a high standard deviation (Table 3.6).

Soil colour

The dunes along the northern section of the coast are generally pale in colour, becoming progressively more yellow and red further away from the coast (De Villiers et al. 1999).

Table 3.3: Soil forms and families (Soil Classification Working Group 1991) identified in vegetation communities

Vegetation community	**Profile No**	**Soil form**	**Soil form abbreviation + family number**	**Horizon sequence** (Table 3.4 for abbreviations)
1A	1	Pinedene	Pn 1100	ot, ye, gs, ne-II, db-I
	2	Pinedene	Pn 1100	ot, ye, gs, ne-II, db-I
	3	Clovelly	Cv 2100	ot, ye
1B	4	Oudtshoorn	Ou 2210	ot, ne-a, ne-I/gs, db-I
	5	Bloemdal	Pn 2100	ot, ye, gs, ne-II, db-I
	6	Oudtshoorn	Ou 2210	ot, ne-I, db-I, R
	7	Bloemdal	Bd 2100	ot, re/gs, re, re/gs, ne-II, db-I
	8	Bloemdal	Bd 2100	ot, re, gs, ne-II, db-I
2	9	Bloemdal	Bd 2100	ot, re, gs, ne-II, db-I
	10	Bloemdal	Bd 2100	ot, re, gs, ne-II, db-I
	11	Bloemdal	2100	ot, re, gs, ne-II, db-I
3	12	Pinedene	Pn2100	ot, ye, gs
	13	Oudtshoorn	Ou 2110	ot, ne-a, db-II
	14	Pinedene	Pn 2100	ot, ye, gs
4	15	Bloemdal	Bd 2100	ot, re, gs, ne-II, sc
	16	Bloemdal	Bd 2100	ot, re, gs, ne-II, re
5	17	Garies	Ga 1000	ot, re/gs, re/ne-I, dn/ne-II, db-II
	18	Tukulu	Tu 1100	ot, ne-I, gc, hc, sc
	19	Garies	Ga 1000	ot, re/gs, re/ne-I, dn/ne-II, db-I
6	20	Namib	Nb 1200	ot, rs

Table 3.4 Horizon abbreviations

Horizon/material	**Abbreviation**
Orthic A	ot
Neocutanic B-I	ne-I
Neocutanic II	ne-II
Red apedal B	re
Yellow-brown apedal B	ye
Regic sand	rs
Gleyed sand	gs
Gleyed clay	gc
Dorbank I	db-I
Dorbank II	db-II
Soft carbonate	sc
Hardpan carbonate	hk
Durinodes	dn
Hard rock	R

Table 3.5: Soils identified in vegetation communities (according to FAO-WRB 2001)

	Profile no.	Soil unit
1 A	1	Abruptic Aridic Cambisol (endostagnic)
	2	Abruptic Aridic Cambisol (endostagnic)
	3	Eutric Chromic Arenosol
1 B	4	Arenic Aridic Durisol (endostagnic)
	5	Arenic Aridic Cambisol (endostagnic bathyduric)
	6	Arenic Aridic Durisol (bathyduric)
	7	Rubic Aridic Arenosol (endostagnic bathyduric)
	8	Rubic Aridic Arenosol (endostagnic bathyduric)
2	9	Rubic Aridic Arenosol (endostagnic bathyduric)
	10	Rubic Aridic Arenosol (endostagnic)
	11	Rubic Aridic Arenosol (endostagnic)
3	12	Chromic Aridic Arenosol (bathystagnic)
	13	Arenic Aridic Durisol
	14	Chromic Aridic Arenosol (bathystagnic)
4	15	Rubic Aridic Arenosol (bathycalcic endostagnic)
	16	Rubic Aridic Arenosol (endostagnic)
5	17	Rubic Aridic Arenosol (bathyduric buthicalcic)
	18	Arenic Aridic Cambisol (bathycalcic)
	19	Rubic Aridic Arenosol (bathyduric endostagnic)
6	20	Protic Aridic Arenosol

Table 3.6: Statistical summary of EC and pH values of horizon/materials

	N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
EC (mS.cm-1)	92	0.26	0.43	0.10	0.01	2.12
pH (H_2O)	92	7.0	0.9	6.9	5.0	9.3
pH (KCl)	92	5.9	1.1	5.8	3.9	8.9

Soil texture

According to De Villiers (2000) the soils of the study area are characterised by the presence of single-grained aeolian sediments that vary in depth and colour (Environment Evaluation Unit 1990). Textural properties vary significantly between soil horizons ranging from 0.1 to 20.9 % silt plus clay content (Appendix 1: Table 2, 7, 9, 10). The textural transition between gleyed sand and more clayey (loamy sand to sandy loam) neocutanic-II horizons is abrupt.

Soil structure

Most of the surface and middle horizons in profiles of the study area are single grained and weakly structured or structureless. Firm more clayey subsurface horizons above the dorbank show some signs of structural development.

Bulk density

High bulk densities of the soils in this region reflect the presence of heavy minerals. Significant amounts of heavy minerals sometimes give a false indication of bulk density as an indicator of soil compaction (Appendix 1: Table 6).

Mineralogy

The pale grey dune sands consist of unconsolidated quartz-rich materials in contrast to the more feldspathic sand of the red terrestrial deposits (Ellis 1988). These terrestrial deposits are characterised by heavy a mineral enrichment that includes ilmenite, rutile, leucoxene, zircon and monazite (Environmental Evaluation Unit 1990). The author's field observation indicates that only the white aeolian sand of vegetation community 6 contains calcareous material.

Soil consistence and permeability

A hard layer of variable thickness of pedocrete or duripan (cemented silica, iron oxide and calcium carbonate), known as dorbank, extends over most of the study area and occurs at various depths between 0.3 and 5 m (Environment Evaluation Unit 1990). A dense neocutanic horizon of varying thickness overlies most of the upper surface of the dorbank and is characterised by the presence of overlying gleyed sand, indicating the presence of an intermittent pearched water table. A soft water-repellent surface horizon, underlain by soft water-absorbent, permeable sand, is common throughout the whole study area.

Soil hydrology

Coarse textured soils contain a greater proportion of available water at low suctions than finer soils. Due to the high percentage of macropores in sandy soils, much of the retained moisture is lost at low suction values (Hillel 1998). This phenomenon enables plants to extract all the available water. The combination of a low field water capacity and high saturated hydraulic conductivity results in deep water penetration during rapid and large rainfall events. It is also well documented that water infiltrates sandy soil along preferential flow paths called fingers (Kawamoto et al. 2003; Ritsema et al. 1997). According to Esler et al. (1999), low intensity rainfall events favour the development of shallow-rooted plant species occurring in the Succulent Karoo. Field observation of a profile, after approximately 20 mm of rain, revealed the formation of a water finger reaching 1 m in depth (Chapter 5). The hydrophobic topsoil of this area has an enormous influence on the hydrology of these sandy soils. Soil surface hydrophobicity promotes fingered water infiltration. The presence of water-repellent topsoil would also result in restricting evaporation losses due to the reduced water-holding capacity of such topsoil (Mellouli et al. 1998; Mellouli et al. 2000). This phenomenon would result in the entrapment of water below an evaporation restriction layer and above a dense more clayey or a cemented horizon.

3.3.2 Site and profile characteristics

Description of soils is given according to the occurrence within vegetation communities, as identified and described by De Villiers (1999).

Vegetation community (VC) 1: (*Ruschia tumidula—Tetragonia virgata* Tall Shrub Strandveld)

Site description

This community is situated furthest inland and consists of small dune systems. The four variants of this community are classified according to the vegetation composition on and between dune systems (De Villiers 1999). This area receives the least amount of fog and salt spray and is the driest of the communities in the study area (De Villiers

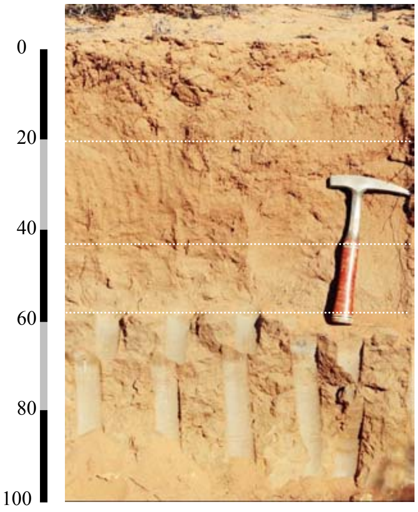
1999). The soils in this area are characterised by a wide range in depth and with Munsell colours occurring mostly within the yellow-brown and red range. The mining process will destroy a large part of this community. The most eastern part of this community contains ‘heuweltjies’, and was investigated as a separate subgroup. The two sites investigated were on the small dune systems, community 1 A, and on the heuweltjie landscape, community 1 B (Figure 3.1).

VC 1A

Profile description

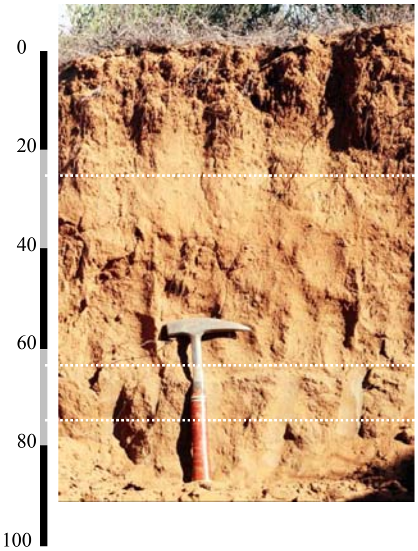
The three profiles of community 1 A are characterised by the presence of an orthic A and yellow-brown B horizon. Topsoil horizons have a tendency to repel water in the dry state (see 3.3.3). A highly permeable yellow-brown B horizon underlies the water-repellent A horizon. Shallower profiles 1 and 2 contain firm sandy loam neocutanic horizons on indurated dorbank layers. This firm more clayey horizon is overlain by gleyed sand, indicating an intermittent, perched water table. The transition to bottom horizons of these two profiles is abrupt. The absence of an E horizon in profile 1 can be attributed to the absence of a neocutanic horizon that would act as a barrier, blocking water infiltration. A less permeable subsoil horizon occurring in combination with a water-repellent topsoil horizon could have implications for profile hydrology. This phenomenon will be described in more detail in Chapter 5. The main difference between these three profiles was in their depth of high permeability and the salinity (Table 3.10). EC values of soil samples from profiles 1 and 2 indicated an increase in salinity with depth.

Table 3.7: Profile 1: Pinedene 1110 in VC 1A



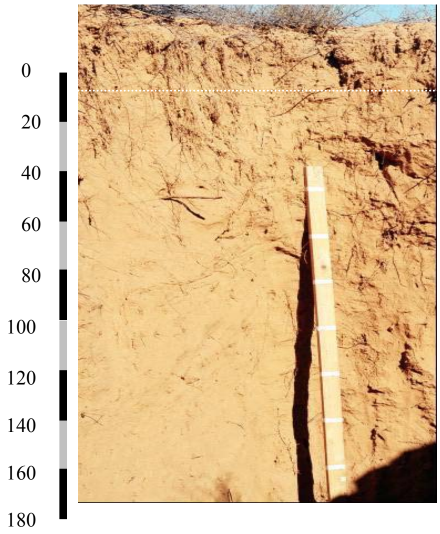
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/4	soft/ pure sand	5	dry
Yellow-brown apedal B	7.5YR4/4	soft/ pure sand	2.5	dry
Gleyed sand	7.5YR5/4	soft/ pure sand	1	dry
Neocutanic-II	7.5YR3/4	firm/ sandy loam	0.5	dry
Dorbank I	nd	cemented	0	dry

Table 3.8: Profile 2: Pinedene 1110 in VC 1A



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/4	soft/ pure sand	5	dry
Yellow-brown apedal B	7.5YR4/4	soft/ pure sand	2.5	dry
Gleyed sand	7.5YR5/4	soft/ pure sand	1	dry
Neocutanic-II	7.5YR3/4	firm/ sandy loam	0.5	dry
Dorbank I		cemented	0	dry

Table 3.9: Selected properties of profile 3: Clovelly 2100 in VC 1A



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/6	soft/ pure sand	3.5	dry
Yellow-brown apedal B	7.5YR4/6	soft/ pure sand	2	dry
Yellow-brown apedal B	7.5YR4/6	soft/ pure sand	1	dry

Table 3.10: Selected properties of soil sampled in VC 1A

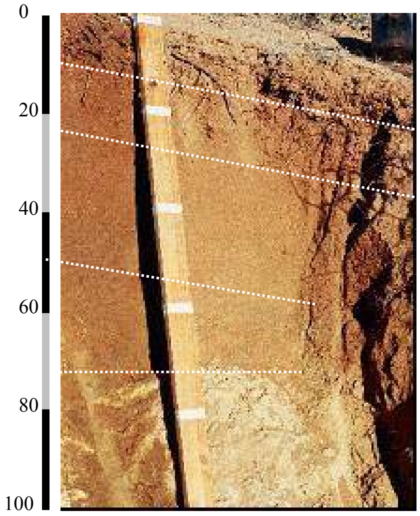
Profile no., form family (position)	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) ($mS.cm^{-1}$)		pH (1:2.5)	
				horizon	profile	(H_2O)	(KCl)
1, Pn 2100 (between dunes)	60	ot	0-20	0.02	248	6.1	4.8
		ye	20-40	0.08		6.0	5.2
		gs	40-60	0.08		6.4	5.1
		ne-II	60-110	0.57		7.3	5.8
		db1	>110	nd		nd	nd
2, Pn 2100 (dune slope)	45	ot	0-20	0.02	82	6.8	5.1
		ye	20-50	0.03		6.2	5.2
		gs	50-60	0.03		6.5	5.5
		ne-II	60-90	0.24		7.9	5.7
		db-I	>90	nd		nd	nd
3, Cv 2100 (dune crest)	<260	ot	0-20	0.02	26	6.2	4.6
		ye	20-140	0.01		6.8	4.6
		ye	>140	0.04		6.0	4.9

VC 1B

Profile description

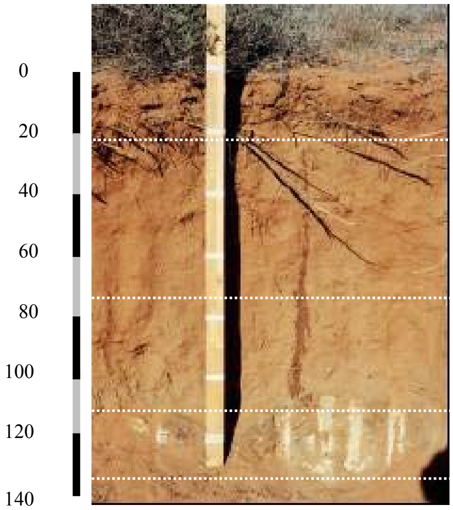
VC 1B is situated in the most eastern part of the study site. Heuweltjies are a common feature in this VC (Figure 3.1). The five profiles dug in this area revealed the existence of two soil types and seven horizons. The profiles on the heuweltjies contained lighter coloured, water absorbent-surface horizons and neocutanic B-I subsurface horizons, in comparison to red, water-repellent surface horizons and red apedal B and neocutanic II subsurface horizons of the profiles between heuweltjies. Red apedal B horizons indicate a well drained oxidised environment (Felix-Henningsen 2000) off the heuweltjies, in comparison to a neocutanic B-I character that indicates soil formation processes, in unconsolidated material on heuweltjies that are still in an early stage of development. If the assumption is made that the heuweltjies are formed due to termite activity, the soil differences can be indicative of the aggregation and clay stabilisation effect of termite action (Mando & Miedema 1997). The presence of gleyed sand on a firm more clayey horizon with a water-repellent topsoil horizon indicates similar hydrological properties as in profiles 1 and 2 in VC 1A. The depth of high permeability is almost the same for all the profiles and the profile ECs, except for profile 3 that is located on a heuweltjie, are not significantly different. Salinity was highest in the horizon above the dorbank layer (Table 3. 16). Profiles 5, 7 and 8 reveal the same physical, chemical and morphological properties, except for the presence of some gleying properties of the B1 horizon of profile 4. The colour difference between the sand of communities 1A and 1B can be explained by one or more factors such as inherited parent material (variation in ferrous iron reserve) differences in environmental gradients, residence time or transport energy (Walden & White 1997).

Table 3.11: Selected properties of profile 4 (on heuweltjie): Oudtshoorn 2210 in VC 1B



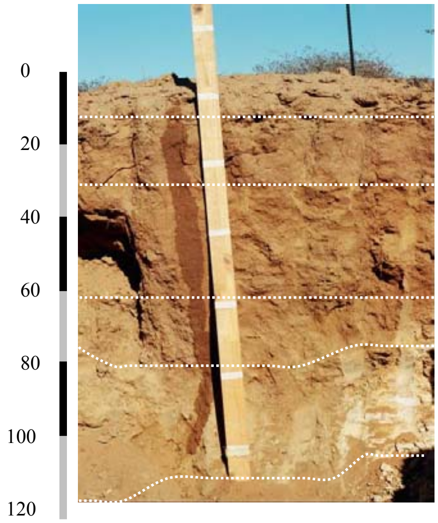
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/4	soft/ sand	4	moist
Neocutanic B-I	5YR4/6	soft/ sand	5	dry
Neocutanic B-I	5YR4/6	soft/ sand	1	dry
Neocutanic B-I/ Gleyed sand	7.5YR4/6	soft/ sand	1	moist
Dorbank I		cemented	0	dry
Hard rock			0	dry

Table 3.12: Selected properties of profile 5 (between heuweltjie): Bloemdal 2100 VC 1B



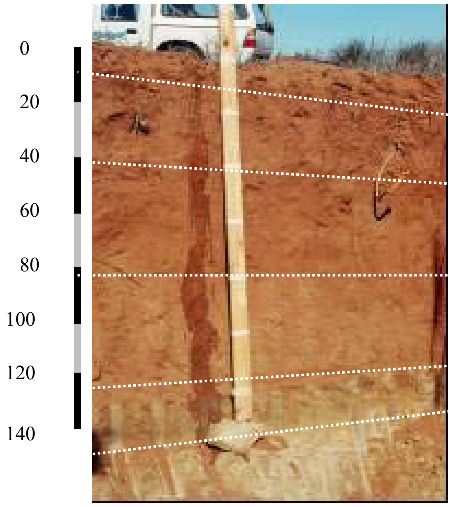
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/6	soft/ pure sand	1	dry
Gleyed sand	5YR3/3	soft/ sand	1	dry
Neocutanic II	5YR4/6	firm/ loamy sand	0	dry
Dorbank II	nd	cemented	0	dry

Table 3.13: Selected properties of profile 6 (on heuweltjie): Oudtshoorn 2210 in VC 1B



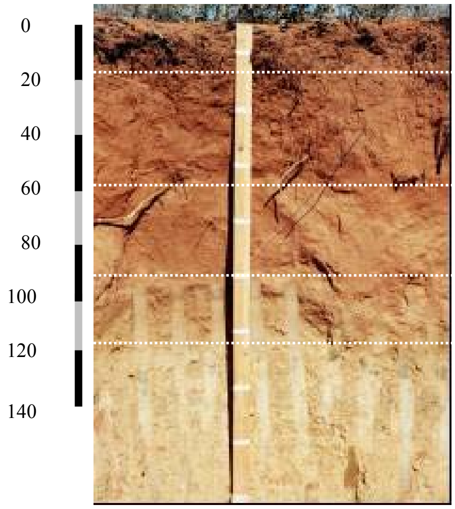
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ sand	3	dry
Neocutanic B-I	5YR4/6	soft/ sand	1	dry
Neocutanic B-I	5YR3/3	soft/ sand	1	moist
Neocutanic B-I	5YR4/6	soft/sand	1	moist
Dorbank I	nd	cemented	0	dry
Hard rock	nd		0	dry

Table 3.14: Selected properties of profile 7: Bloemdal 2110 in VC 1B



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR3/4	soft/ pure sand	5	dry
Red apedal B /gleyed sand	5YR4/4	soft/ pure sand	3	dry
Red apedal B	5YR4/6	soft/ pure sand	2	dry
Gleyed sand / Red apedal B	5YR4/6	soft/ pure sand	1	dry
Neocutanic II	5YR3/4	firm/loamy sand	0	dry
Dorbank I	nd	cemented	0	dry

Table 3.15: Selected properties of profile 8: Bloemdal 2110 in VC 1B



Horizon	Munsell colour (dry)	Consistence/ texture class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/6	soft/ pure sand	3	dry
Gleyed sand / Red apedal	5YR4/6	soft/ pure sand	1	dry
Neocutanic II	5YR3/4	firm/loamy sand	1	dry
Dorbank I	nd	cemented	0	dry

VC 2: (*Eriocephalus africanus—Asparagus fasciculatus* Tall Shrub Strandveld)

Site description

This community is found on small, stabilised dune systems (Figure 3.1). The two community variants are respectively situated on the dunes and in the dune valleys. This area receives more fog and salt spray in relation to community 1, but the intensity is still less than the communities closer to the sea. Soils from the variants on the dunes are deeper than the soils in the dune valleys (De Villiers 1999). Soils from this area have Munsell colours that qualify as red. Only a small part of this area will be subjected to heavy mineral mining.

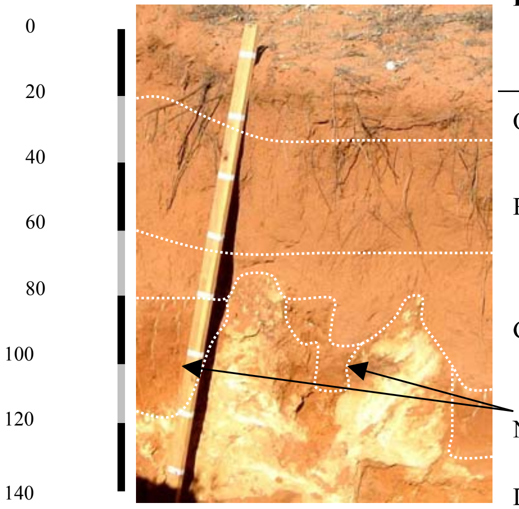
Profile description

Three profiles dug in this community revealed the presence of one soil form and five horizons. Soils in this area have water-repellent orthic A horizons underlain by highly porous red apedal B subsurface horizons. The three opened pits indicated the presence of deep gleyed pure sand on firm, less permeable loamy sand above a dorbank layer. The transition between these two horizons is abrupt. This sequence of horizons can result in hydrological properties similar to those of soils in VC 1. The dorbank layer in profile 9 differed from profiles 10 and 11 due to its tonguing appearance with durinode (silica cemented) inclusions. The durinodules are integrated within a neocutanic II horizon indicating cementation of this horizon. Soils from this community tend to have a higher pH than those from community 1 and EC values indicate higher salinity levels in the neocutanic II horizons in comparison to over lying materials (Table 3.20).

Table 3.16: Selected properties of soil sampled in VC 1B

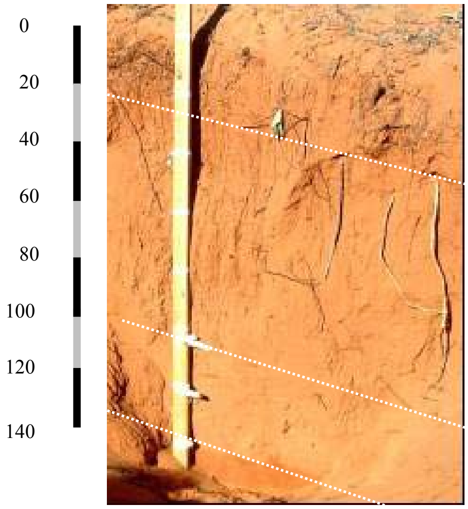
Profile no., form family (position)	**Depth of high permeability (cm)**	**Horizon sequence**	**Horizon depth (cm)**	**EC (1:5) ($mS.cm^{-1}$)**		**pH (1:2.5)**	
				horizon	**profile** (depth weighted)	**(H_2O)**	**(KCl)**
4, Ou 2210 (on heuweltjie)	100	ot	0-5	0.05	0.06	6.3	5.5
		ne-I	5-20	0.02		6.5	5.4
		ne-I	20-40	0.02		7.2	5.5
		ne-I/gs	40-60	0.14		6.5	5.7
		db-I	60-100	nd		nd	nd
		R	>140	nd		nd	nd
5, Bd 2100 (between heuweltjie)	110	ot	0-20	0.04	0.06	6.3	4.9
		re	20-70	0.06		6.2	4.8
		gs	70-110	0.04		6.0	5.1
		ne-II	110-120	0.22		6.6	4.1
		db-I	>130	nd		nd	nd
6, Ou 2210 (on heuweltjie)	100	ot	0-10	0.12	0.55	8.7	7.7
		ne-I	10-30	0.03		6.4	5.8
		ne-I	30-60	0.20		6.8	5.9
		ne-I	60-80	0.72		6.1	5.8
		db-I	80-110	nd		nd	nd
		R	>130	nd		nd	nd
7, Bd 2100 (no variation)	120	ot	0-10	0.05	0.08	6.4	5.0
		re/ gs	10-40	0.05		5.9	3.9
		re	40-80	0.05		6.4	4.0
		gs /re	80-120	0.05		6.4	5.2
		ne-II	120-135	0.30		6.3	5.1
		db-I	>150	nd		nd	nd
8, Bd 2100 (no variation)	95	ot	0-30	0.05	0.1	7.0	5.0
		re	30-60	0.05		6.3	4.9
		gs / re	60-95	0.06		6.0	5.1
		ne-II	95-120	0.37		7.2	5.8
		db-I	>180	nd		nd	nd

Table 3.17: Properties of profile 9: Bloemdal 2100 in VC 2



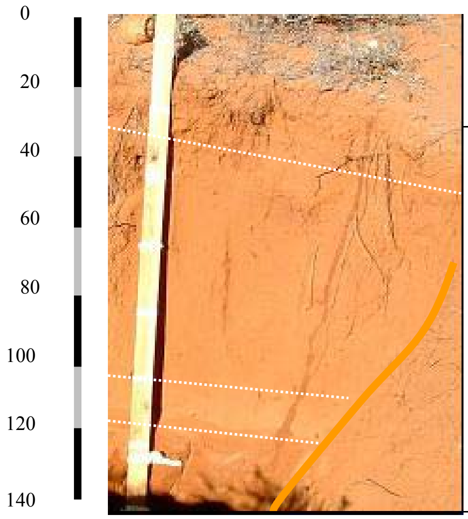
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/6	soft/ pure sand	2	dry
Gleyed sand	5YR5/6	soft/ pure sand	1	dry
Neocutanic II	2.5YR3/6	firm/loamy sand	0	dry
Dorbank I	nd	cemented	0	dry

Table 3.18: Properties of profile 10: Bloemdal 2100 in VC 2



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/6	soft/ pure sandy	3	dry
Gleyed sand	5YR5/6	soft/ pure sandy	2	dry
Neocutanic II	2.5YR3/6	firm/loamy sand	1	dry

Table 3.19: Properties of profile 11: Bloemdal 2100 in VC 2



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/6	soft/ pure sandy	2.5	dry
Gleyed sand	5YR5/6	soft/ pure sandy	1	dry
Neocutanic II	2.5YR3/6	firm/ loamy sand	1	dry

Table 3.20: Selected properties of soil sampled in VC 2

Profile no., form family (position)	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) (mS.cm-1)		pH (1:2.5)	
				horizon	profile (depth weighted)	(H_2O)	(KCl)
9, Bd 2100 (between dune)	80/100	ot	0-20	0.04	0.08	7.5	6.9
		re	20-60	0.04		7.1	6.0
		gs	60-80/100	0.04		8.3	5.9
		ne-II	80/100-80/130	0.18		7.9	6.2
		db-I	>130	nd		nd	nd
10, Bd 2100 (dune midslope)	130	ot	0-20	0.03	0.05	7.6	5.8
		re	20-100	0.04		6.8	6
		gs	100-130	0.03		7.9	6
		ne-II	130-160	0.13		8.6	6.2
		db-I	>160	nd		nd	nd
11Bd 2100 (between dune)	120	ot	0-30	0.03	0.09	7.8	6.2
		re	30-100	0.04		7.1	5.8
		gs	100-120	0.06		7.8	5.5
		ne-II	120-140	0.34		7.5	5.9
		db-I	>140	nd		nd	nd

VC 3: (*Salvia africana-lutea—Ballota africana* Tall Shrub Strandveld)

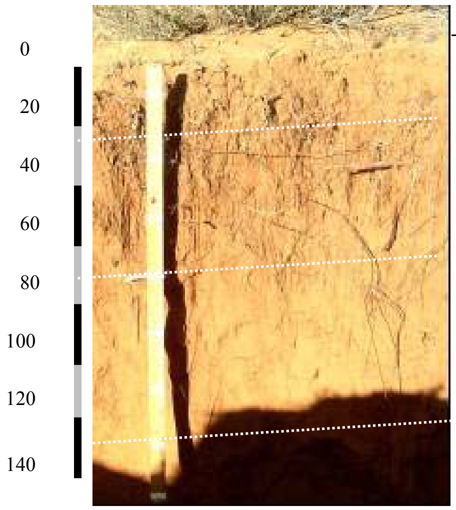
Site description

This community occurs mainly on a large sand dune called Graauwduinen (Figure 3.1). The vegetation is taller than that in the surrounding communities (De Villiers 1999). The soils are characterised by deep yellow sands. Nearly 40% of this community is included in the area to be mined. This area receives more fog and salt spray than community 1 does but less than communities 4, 5 and 6 (De Villiers 1999). A slight depression on the top of the sand dune shows a change in vegetation composition and physiognomy. The soil of the depression area contains a higher clay content than the soil on the nearby hill/dune and is characterised by the occurrence of a shallow dorbank.

Profile description

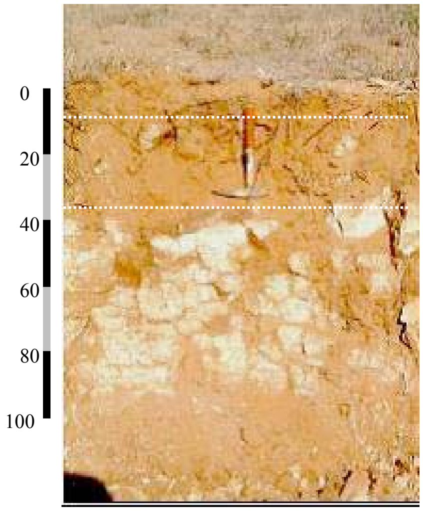
Three profile pits in community 3 revealed two soil forms and five diagnostic horizons. Profiles 1 and 3 have a water-repellent orthic A horizon with a highly porous, yellow-brown apedal B horizon, with a gradual transition to a paler, mottled yellow and grey horizon. This gleyed sand signifies the presence of intermittent perched water. Profile 13 lies in a depression between profiles 12 and 14 with contrasting vegetation in relative to the surrounding vegetation. The different vegetation composition reflects a considerable change in the solum characteristics. Profile 13 comprises a very shallow, bleached orthic A and neocutanic B-I horizon above a dorbank II layer. The properties of this dorbank horizon differ significantly from other dorbank horizons in the study area. This phenomenon suggests an influence of soil depth on vegetation physiognomy and composition in this arid environment. The shallower soil depth, higher salinity and finer texture of profile 13 result in lower water availability in relation to the surrounding environment. There is no indication that EC values change with soil depth but there is a tendency for higher pH in the deepest horizon (Table 3.24). The EC and pH value range of soil samples is similar to that of VC 1.

Table 3.21: Selected properties of profile 12: Pinedene 2100 in VC 3



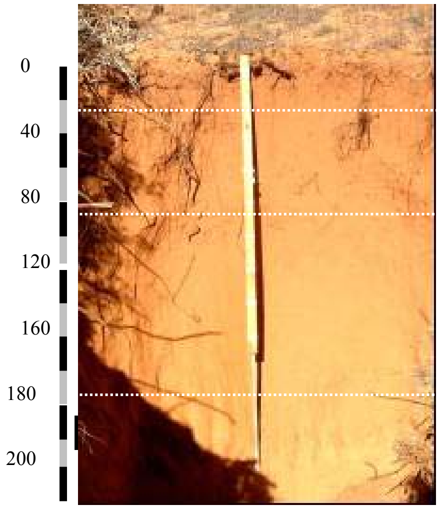
Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/6	soft/ pure sand	5	dry
Yellow-brown apedal B	7.5YR4/4	soft/ pure sand	2	dry
Yellow-brown apedal B	7.5YR4/6	soft/ pure sand	1	dry
Gleyed sand	10YR5/8	soft/ pure sand	0	moist

Table 3.22: Selected properties of profile 13: Oudtshoorn 2110 in VC 3



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/6	soft/ sand	5	moist
Neocutanic B-I	7.5YR4/6	soft/ sand	5	dry
Dorbank II	nd	cemented	1	dry

Table 3.23: Selected properties of profile 14: Pinedene 2100 in VC 3



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	7.5YR4/6	soft/ pure sand	5	dry
Yellow-brown apedal B	7.5YR4/4	soft/ pure sand	2	dry
Yellow-brown apedal B	7.5YR4/6	soft/ pure sand	1	dry
Gleyed sand	10YR5/8	soft/ pure sand	0	moist

Table 3.24: Selected properties of soil sampled in VC 3

Profile no., form family (position)	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) (mS.cm-1)		pH (1:2.5)	
				horizon	profile (depth weighted)	(H_2O)	(KCl)
12, Pn 2100 (dune crest)	>260	ot	0-25	0.05	0.05	6.7	5.9
		ye	25-70	0.04		6.9	6.1
		ye	70-130	0.04		6.4	5.9
		gs	>130	0.07		7.7	6.3
13, Ou 2110 (depression)	30	ot	0-10	0.21	0.17	7.0	6.9
		ne-I	10-30	0.16		7.1	6.4
		db-II	>30	nd		nd	nd
14, Pn 2100 (dune crest)	>260	ot	0-30	0.08	0.09	6.4	6.0
		ye	30-85	0.05		6.7	6.6
		ye	85-180	0.15		6.4	6.3
		gs	>180	0.08		8.2	6.7

VC 4: (*Ruschia versicolor—Odyssea paucinervis* Dwarf Shrub Strandveld)

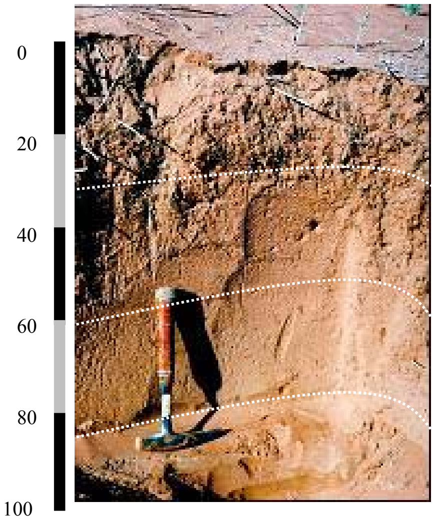
Site description

Community 4 is found in the southern part of the survey area and incorporates most of the area to be mined. This area receives more fog and salt spray than communities 1, 2 and 3, but less than communities 5 and 6 (De Villiers 1999). The soils from this area change from a firm, dark red sand in the east to loose yellow sand in the west. This VC comprises three variants that are located in the central, eastern and southern part of the dwarf shrub Strandveld (De Villiers 1999). The soil investigation was conducted on the mine face in the central variant.

Profile description

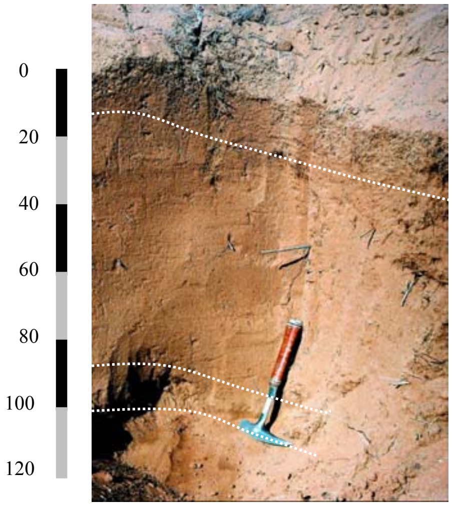
A soil investigation on profiles on the western side of this mine face revealed the presence of a Bloemdal 2100 soil form and five horizons. Except for the calcite accumulation in the lower part of the neocutanic II horizon in profile 15, these two profiles showed the same horizon sequence as that of community 2. Although dorbank was not reached in this profile, previous surveys and mining activities revealed the presence of a dorbank horizon throughout this community. This soil form indicates that these soils experiences similar hydrological processes to those of the soils in communities 1 and 2. Although the pH levels of soil samples agree with communities 1 and 2, the high EC values indicate that soils from these profiles have significantly higher salinity levels (Table 3.27). This confirms the data presented by De Villiers 1999, that this community receives more salt spray than communities 1, 2 and 3 do. The salinity levels also increased significantly with depth.

Table 3.25: Properties of profile 15: Bloemdal 2100 in VC 4



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	2.5YR4/6	soft/ pure sand	4	dry
Red apedal B/ Neocutanic B-I	2.5YR4/6	soft/ pure sand	2	dry
Gleyed sand	5YR4/6	soft/ pure sand	1	dry
Neocutanic II	5YR4/6	firm/loamy sand	0	dry
Soft carbonate	5YR4/6	slightly cemented	0	moist

Table 3.26: Properties of profile 16: Bloemdal 2100 in VC 4



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR4/6	soft/ pure sand	5	dry
Red apedal B	5YR4/4	soft/ pure sand	2.	dry
Gleyed sand	5YR4/6	soft/ pure sand	1	dry
Neocutanic II	5YR5/8	firm/loamy sand	0	dry
Neocutanic II	5YR4/6	soft /loamy sand	0	moist

Table 3.27: Selected properties of soil sampled in VC 4

Profile no., form family	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) (mS.cm-1)		pH (1:2.5)	
				horizon	profile (depth weighted)	(H_2O)	(KCl)
15, Bd 2100	85	ot		0.06	0.84	6.4	6.1
		re	30-60	0.09		6.1	5.9
		gs	60-85	0.68		6.7	5.7
		ne-II	85-110	1.66		8.7	8.6
		sc	>110	nd		nd	nd
16, Bd 2100	100	ot	0-20	0.08	0.32	5.8	5.1
		re	20-85	0.10		7.2	5.6
		gs	85-100	0.53		7.5	5.7
		ne-II	100-115	0.53		6.7	5.5
		ne-II	>115	nd		nd	nd

VC 5: (*Cephalophyllum spongiosum—Odyssea paucinervis* Coastal Strandveld)

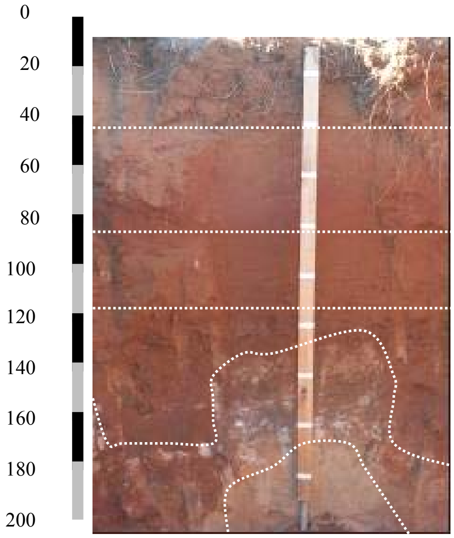
Site description

This VC is situated on a narrow footslope before the terrain rises steeply to the coastal plain. It stretches along the southern coast of the study area with a wave-cut rocky platform (Figure 3.1). The soils from this community consist of a deep yellowish sand (De Villiers 1999). Mining activities will not directly influence this community.

Profile description

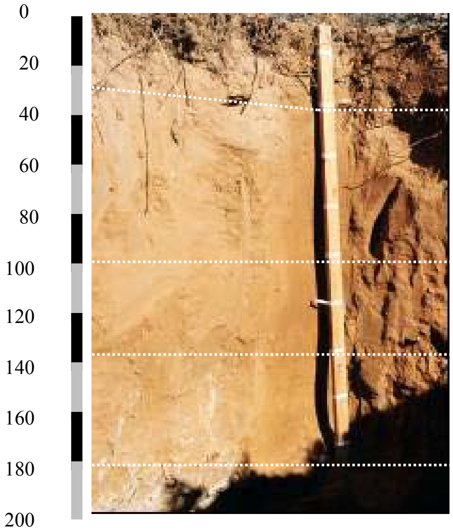
Due to the special distribution of this community, only profile 18 out of the three profiles dug, was situated within the boundaries of the unit. This group of profiles was situated within 300 m from the coast. The main differences between the profiles were the absence of a dorbank, the yellowish colour and high water infiltration rate of the orthic A horizon in profile 18. All the profiles exhibited a gradual increase in silt and clay with depth. Gleying of the sandy loam above the hardpan carbonate layer indicates intermittent saturation with water. The subsurface horizons of profile 18 had a finer textural class compared to all the other profiles, except for profile 4 and 6 in community 1B. The absence of a horizon sequence: gleyed sand on a firm neocutanic II horizon with an abrupt textural change, differentiates the profiles in this community from profiles in communities 1, 2 and 4. The pH of other soil samples in this community did not differ much from those of samples in the other communities, except for rs2 in community 6. Soil samples from all three profiles contained much higher salinity levels in comparison to soil samples from the other communities. EC values also indicated an increase in salinity with depth (Table 3.31).

Table 3.28: Profile 17: Garies 1000 in VC



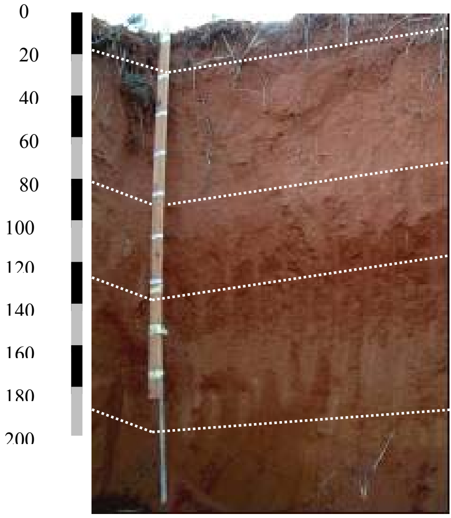
Horizon material	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	5YR3/4	soft/sand	5	moist
Red apedal B	5YR4/6	soft/sand	2	moist
Red apedal B	7.5YR4/6	soft/loamy sand	1	moist
Durinodes/ Neocutanic II	5YR3/4	cemented	0	dry
Dorbank I	nd	cemented	0	dry
Soft carbonate	nd		0	dry

Table 3.29: Profile 18: Tukulu 1110 in VC 5



Horizon material	**Munsell colour (dry)**	**Consistence/ textural class**	**Root density index**	**Moisture status**
Orthic A	7.5YR5/4	soft/sand	5	moist
Neocutanic B-I	7.5YR4/6	soft/sand	2	moist
Neocutanic B-I	7.5YR5/6	soft/loamy sand	1	moist
Gleyed loam	10YR5/8	soft/sandy loam	0	moist
Hardpan carbonate	nd	cemented	0	dry
Soft carbonate	nd		0	dry

Table 3.30: Profile 19: Gr 1000



Horizon material	**Munsell colour (dry)**	**Consistence/ textural class**	**Root density index**	**Moisture status**
Orthic A	5YR3/4	soft/ pure sand	5	moist
Red apedal B/ gleyed sand	5YR4/6	soft/ pure sand	2	moist
Red apedal B/ neocutanic B-I	2.5YR4/4	soft/ sand	1	moist
Neocutanic II/ Durinodes	2.5YR5/6	firm/loamy sand/cemented	0	dry
Dorbank I	nd	cemented	0	dry

Table 3.31: Some properties of soils sampled in VC 5

Profile no., form family	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) (mS.cm-1)		pH (1:2.5)	
				horizon	profile (depth weighted)	(H_2O)	(KCl)
1, Gr 1000	150	ot	0-40	0.56	1.11	6.5	6.4
		re/gs	40-80	0.53		6.9	6.1
		re/ne-I	80-120	1.09		7.4	6.2
		dn	120-130/170	2.12		8.6	8.5
		db-II	130-170	nd		nd	nd
		sc	>170	nd		nd	nd
2, Tu 1100	170	ot	0-30	0.17	0.93	6.4	4.7
		ne-I	30-100	0.17		7.3	5.8
		ne-I	100-140	1.58		9.2	7.8
		gc	140-180	2.08		9.3	8.8
		hc	140-190	nd		nd	nd
		sc	>190	nd		nd	nd
3, Gr 1000	220	ot	0-20	0.15	0.59	7.4	6.4
		re/gs	20-80	0.08		7.1	6.0
		re/ne-I	80-130	0.34		8.0	6.3
		dn/ne-II	130-220	0.12		6.6	5.9
		db-b	>220	nd		nd	nd

VC 6 (*Cladoraphis cyperoides—Lebeckia multiflora* Coastal Strandveld)

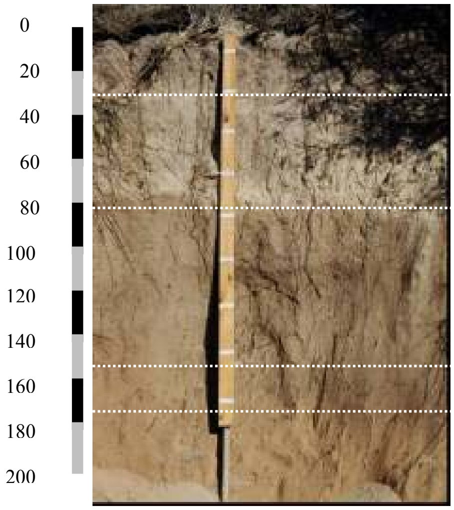
Site description

This community is found on a white coastal dune system next to a beach in the northern part of the study area. This white dune Strandveld community (Boucher & Le Roux 1989) is often associated with river estuaries and is easily disturbed, leading to dune movement. Soil formation in these dune fields is incipient.

Profile description

Only one profile was dug in this area (Table 3.32). The soil of this profile has a very loose consistence. It had a grey matrix colour and sand grains effervesced with 10% HCl probably indicating comminuted shell fragments. A water-repellent orthic horizon covered four layers of regic sand horizons, indicating differential aeolian deposition. The four top horizons had tints of grey while the bottom horizon was light yellow. The rs3 horizon showed a considerable increase in salinity (Table 3.33). The other horizons had relatively low EC values. Horizon rs2 had a significantly higher pH value compared to the other horizons. The soil samples had a clay content below 1% (Appendix 1).

Table 3.32: Selected soil properties of profile 20: Namib 1200 in VC 6



Horizon	Munsell colour (dry)	Consistence/ textural class	Root density index	Moisture status
Orthic A	2.5Y5/2	soft/ pure sandy	3	dry
Regic sand 1	10YR6/2	soft/ pure sandy	3	dry
Regic sand 2	10YR7/2	soft/ pure sandy	3	dry
Regic sand 3	2.5Y4/4	soft/pure sandy	2	moist
Regic sand 4	10YR5/4	soft/pure sandy	1	moist

Table 3.33: Selected properties of soil sampled in VC 6

Profile no., form family (position)	Depth of high permeability (cm)	Horizon sequence	Horizon depth (cm)	EC (1:5) (mS.cm-1)		pH (1:2.5)	
				horizon	profile (depth weighted)	(H_2O)	(KCl)
1, Nb 1200 (dune footslope)	>220	ot	0-30	0.05	0.09	6.8	6.2
		rs1	30-80	0.05		6.8	6.6
		rs2	80-150	0.06		9.1	8.9
		rs3	150-180	0.23		7.7	7.9
		rs4	>180	0.08		8.8	8.7

3.3.3 Horizon descriptions

Topsoil horizons

Orthic A horizons are classified as topsoil horizons that lack the diagnostic properties of an organic, humic, vertic or melanic topsoils due to the absence of high a organic carbon content, swelling, dark colour and/or high base status (Soil Classification Working Group 1991). Orthic A horizons can thus have a wide range of chemical, physical and morphological properties.

Selected soil samples from orthic A horizons in all the communities had very low organic carbon contents and showed very few signs of organic matter accumulation (Appendix 1: Tables 1 and 5). Previous studies by Ellis (1988) indicated low to very low organic carbon content of soil in the Hutton and Clovelly soils of the northern West Coast. This is not an unusual phenomenon and aridisols worldwide are characterised by very low organic carbon contents.

Hydrophobic characteristics are caused by a range of hydrophobic organic materials (King 1981). They can be due to the presence of fungal hyphae (Bond & Harris 1964) or particulate organic matter that acts as a carrier and reservoir of hydrophobic waxes (Franco et al. 1995). These waxes can diffuse out and coat the sand grain surfaces inducing hydrophobicity. Hydrophobic topsoil will induce fingered infiltration patterns in these sandy soils (Chapter 5). This phenomenon has been described in a study done by Ritsema et al. (1997*).*

Crusting of the soil surface (0 – 3 mm depth) occurs widely throughout the whole study area. Two types of crusts, a salt crust and a biological crust, are found. A salt crust is the dominant crust form and occurs mostly within the drip zone of the vegetation cover. A salt crust underneath a shrub in VC 2 had an EC value of 0.62 $mS.cm^{-1}$. The soil directly underneath the crust had an EC value of 0.24 $mS.cm^{-1}$. These crusts can be very hard and can act as erosion prevention layers in an area that is exposed to high wind erosion. Biological crusts play an important role in arid ecosystems. Various studies have indicated that these crusts can result in either an increase or decrease in water infiltration rate, depending on composition and moisture status of the crust (Seyfried 1991; Bond 1964; Graetz & Tongway 1986). These crusts are mixtures of lichens, mosses, cyanobacteria and green algae that retain soil moisture, fix nitrogen and protect these ecosystems by preceding vascular plant growth and preventing erosion.

Middle horizons

Yellow-brown and red apedal B horizons

These horizons are characterised by a soil matrix with uniform colours, lacking well formed peds other than porous micro-aggregates (Soil Classification Working Group 1991). Microscopically weakly structured or structureless materials indicate that soil formation takes place in a well-drained oxidising environment to produce coatings of iron oxides on individual soil particles. The formation of these horizons occurs under the full range of climatic conditions in South Africa. The Soil Classification Working Group (1991) set out criteria for colour classification according to Munsell colour. Due to the low clay and silt content of these soils (Appendix 1: Table 2), very little iron oxide coating is needed for the soil matrix to appear yellow or red. The extractable iron content of selected samples averaged 4 $g.kg^{-1}$ (Appendix 1: Table 4). Permeable characteristics of these apedal sands result in rapid drainage. As described above, the porous nature of the subsoil in conjunction with a hydrophobic topsoil results in drainage fingers down to considerable depths, wetting lower soil horizons.

Neocutanic B horizons

A horizon is classified as a neocutanic B horizon when unconsolidated material, usually transported material, has undergone pedogenesis to such an extent that it is excludes from being stratified alluvium, regic sand or man-made deposit (Soil Classification Working Group 1991). Pedogenesis has nevertheless been insufficient for the horizon to be classified as any other horizon (Soil Classification Working Group 1991). Pedogenic processes, like clay illuviation in aeolian-derived neocutanic sands of the study area, can transform these horizons into red or yellow-brown apedal B horizons. The two types of neocutanic horizons, as described in the methodology, probably differ in the intensity of pedogenesis. Profiles with a neocutanic II horizon can be the outcome of pedogenesis in profiles with a neocutanic B-I. The significant higher clay content of neocutanic B-I horizons (Appendix 1: Tables 9 and 10), in relation to red or yellow apedal horizons, can be indicative of retarded clay illuviation of soils on heuweltjies due to the stabilisation and bioturbation effect of termite action (Black & Olwakol 1997).

Regic sand

Recent aeolian deposits show little evidence of pedogenesis, except for the darkening of the topsoil by organic matter (Soil Classification Working Group 1991). Regic sands are characteristic of a young environment of cover sands where little or no profile development has taken place. The colour of the sands can vary between red, yellow-brown or pale grey, depending on the source of origin (Soil Classification Working Group 1991). The texture is usually not finer than pure sand. The low clay content, loose consistence and water-repellent topsoil of this soil in the study area can result in the same soil hydrological processes such as water fingering, as described for the apedal horizons. Due to the presence of calcitic sand grains, probably derived from shell fragments, and the low buffer capacity, the pH values are mostly above seven. Absence of stabilising factors such as soil aggregates and organic matter makes these horizons susceptible to wind erosion when disturbed.

Lower horizons

Gleyed sand

Gleying of soil material takes place when it has been subjected to intense reduction due to prolonged saturation with water (Soil Classification Working Group 1991). These zones can be recognised by the grey, blue and green colours that predominate, but stains of ferric and manganese oxides and hydrates (yellow, brown, red and black) may be present in localised areas of better aeration (Van der Watt & Van Rooyen 1995). Bleached or grey horizons, such as the gleyed sand found in the study area, are formed due to the reduction and removal of ferric and manganese oxides through lateral flow of a perched water table (Blume et al. 1987) on an impermeable layer (Washer & Collins 1988). Although the classification of soils with redomorphic conditions requires Munsell colours with chromas less than 2 (Soil Survey Staff 1992), Daniels et al. (1967) found that redomorphic conditions can also exists in soils with higher chromas. Lower CBD (Citrate-Bicarbonate-Dithionite) extractable iron content between the gleyed sand and the overlying horizons support the indication of redomorphic conditions due to the presence of a bleached sandy (Appendix 1: Table

4) horizon in the Pinedene and Bloemdal soil forms. A decrease in the fine fraction (clay + silt) of the gleyed sand in relation to the overlying horizon indicates possible removal of colloidal matter such as silicate clay, iron oxides or organic matter. Redox reactions in soil are dependent on microbiological reactions and the availability of organic matter (Smith & Dowdell 1974). The low organic matter of these soils (Appendix 1: Table 3) will limit reduction processes, lengthening the formation period of gleyed sand. The presence of gleyed sand in this region is the sign of prolonged periods of water saturation on an impermeable layer.

Gleyed loam

Many of the same processes as described in the previous paragraph account for the formation of gleyed clay. The only difference observed is that the net removal of colloidal matter did not take place. Redistribution of iron and manganese oxides is controlled by a redox gradient present in the soil matrix (Le Roux 1996). This will result in the formation of mottles due to zonal iron and manganese accumulation. The higher clay content of this horizon will also inhibit the removal of colloidal matter through lateral water movement (Appendix 1: Table 2).

Neocutanic horizon

The same criteria presented for the description of the neocutanic B-I (ne-I) horizon account for the neocutanic II (ne-II) horizon. In spite of these criteria, the ne-II horizon has distinct differences in chemical and physical properties. Field and laboratory observations revealed that the ne-II horizon had a definite higher consistence and significantly higher clay content (Appendix1 : Table 2, 9 and 10) in relation to the ne-I horizon. The significantly higher EC values of the neocutanic II horizons in relation to the above-lying apedal horizons indicate the accumulation of salts in the neocutanic II horizons. The abrupt textural change of these horizons will induce a water-impermeable horizon contact resulting in the formation of a perched water table during deep water infiltration. The presence of gleyed sand above these horizons confirms this statement.

Cemented horizon (pedocrete)

Horizons that are partly or completely cemented occupy a large area of the subsurface soil environment. Slaking tests with strong acid (2M HCl) and strong alkali (4M

NaOH) indicated that most of the hardpan horizons are cemented by silica (Table 3. 34). The Soil Classification Working Group (1991) classifies these hardpan horizons as dorbank. This horizon is related to the duripan of other classification systems (Ellis 1988) and is characteristic of arid regions of the world. Ellis (1988) has reviewed the occurrence of dorbank in this region. Dorbank occupied 71.4% of the deeper-lying material, occurring mostly on well drained sandy soils originating from transported material. Desilification of preweathered inland material, occurring underneath silcretes, as well as the overlying aeolian A and B horizons, could have provided the silica needed for dorbank formation (F. Ellis personal communication, 2003). The lateral and horizontal influx of silica-rich soil water from alkaline parent material could have provided enough silica for cementation to take place. Due to the low rainfall in this area, total leaching of silica through the soil profile is inhibited (Ellis 1988). Accumulation and cementation take place at the depth to which water infiltration takes place regularly (F. Ellis, personal communication, 2003). Scanning electron microscopy (SEM) indicated cementation of rounded aeolian material by amorphous silica bands (Figure 3.3). Low rainfall conditions, characterised by limited leaching, will result in the potential formation of a cemented horizon sequence of dorbank at a shallow depth, followed by calcite cementation (hardpan calcrete) deeper down in the profile with gypsum cementation or accumulation the deepest due the solubility variation (Ellis 1988).

Two types of dorbank were found in this area. The first one (db-I) is as described above. The second type (db-II) has a whitish colour and is characterised by a very hard consistence. XRD and SEM analysis revealed a strong presence of sepiolite, and calcite was only present in the cracks of the cemented layer (Figures 3.2 and 3.3). This horizon was found on the top of Graauwduinen. The genesis behind this horizon is still unclear and needs further investigation.

Silica cemented nodules (durinodes) were found in profiles 10, 17 and 19 above a dorbank horizon. The genesis behind this horizon is still unclear and needs further investigation.

The only other calcium cemented horizons were found in profiles 4, 15, 17and 18. These horizons slaked in strong acid (Table 3.34) indicating cementation by calcium and/or calcium-magnesium carbonates. These horizons are classified as hardpan carbonate horizons according to the South African classification system (Soil Classification Working Group 1991). XRD and SEM analysis of this horizon also revealed the presence of sepiolite (Figures 3.2 and 3.3).

Table 3.34: Results of slaking test. Solution: A = 2M HCl; B = 2 M NaOH; C = 4M NaOH; D = 4M NaOH heated; E = 4M NaOH / 2M HCL heated alternatively.

Vegetation Unit	Profile	Cemented horizon	Slaking solution	Cementation material	Diagnostic horizon
1A. Tall Shrub Strandveld	1	db I	C	Silica	Dorbank
	2	db I	C	Silica	Dorbank
	3	none	*	*	*
1B. Tall Shrub Strandveld. Occasional heuweltjie occurrence	4	db I	E	Silica	Dorbank
		hk	A	Calcite	Calcrete
	5	db I	D	Silica	Dorbank
		db I	C	Silica	Dorbank
	6	db I	B	Silica	Dorbank
		db I	D	Silica	Dorbank
	7	db I	C	Silica	Dorbank
	8	db I	B	Silica	Dorbank
2. Tall Shrub Strandveld	9	db I	B	Silica	Dorbank
	10	db I	B	Silica	Dorbank
	11	db I	B	Silica	Dorbank
3. Tall Shrub Strandveld	12	none	*	*	*
	13	db II	E	Silica/Calcite	Dorbank
	14	none	*	*	*
4. Dwarf Shrub Strandveld	15	sc	A	Calcite	Soft Calcrete
	16	none	*	*	*
5. Coastal Strandveld	17	dn	B	Silica	Durinodes
		hk	A	Calcite	H-Calcrete
		sc	*	*	S-Calcrete
	18	dn	B	Silica	Durinodes
		hk	A	Calcite	H-Calcrete
	19	dn	B	Silica	Durinodes
		db II	*	*	Dorbank

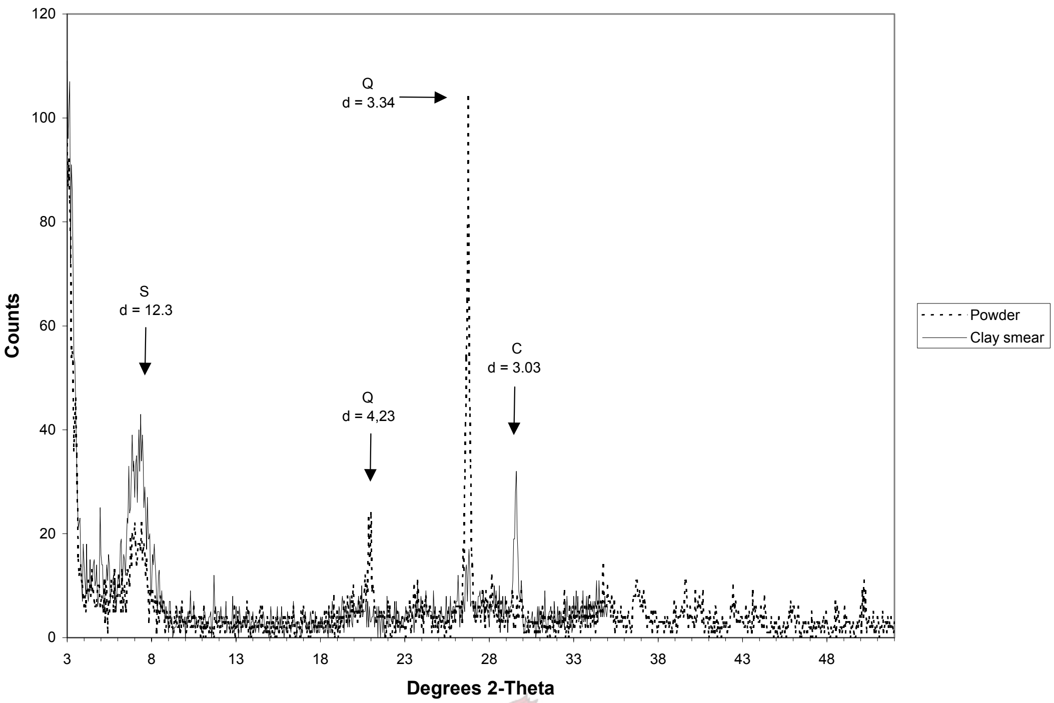


Figure 3.2: XRD analyses of clay smear and powder from a dorbank II horizon. Q = quartz, C = calcite, S = sepiolite; d = d-spacing (Å)

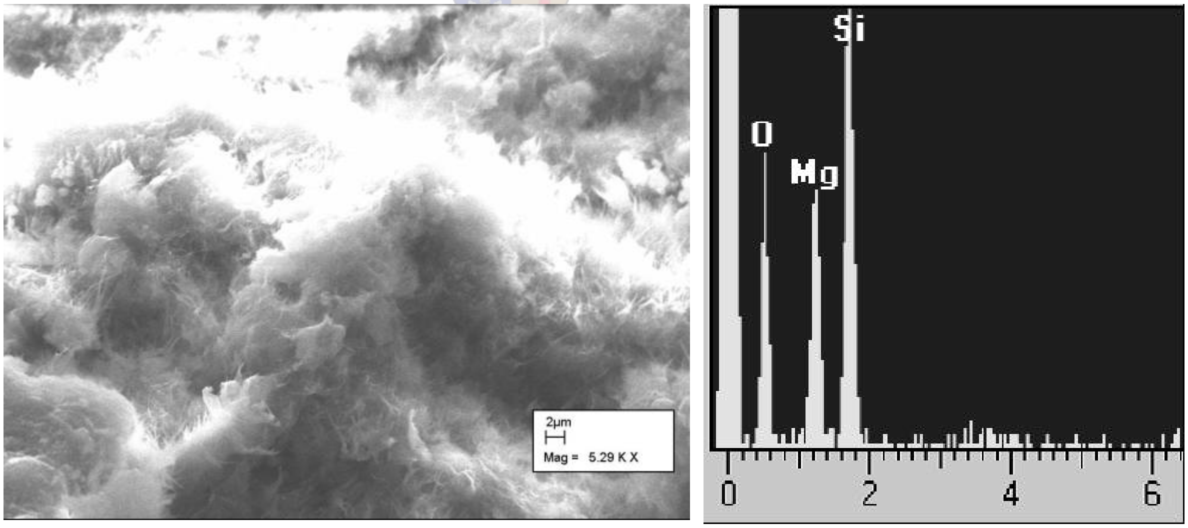


Figure 3.3: SEM and XRD analysis of a dorbank II horizon indicating the presence of magnesium (Mg) and silica (Si)

3.4 CONCLUSIONS

The investigation of 20 soil profiles revealed that significant chemical, physical and morphological differences exist within soils of the study area. Soil differences and similarities confirm most of the variation described by De Villiers (2000) through the positioning of abiotic characteristics found in plant communities on an ordination diagram, with axes representing gradients in soil colour, salt spray, fog intensity and sand depth.

An investigation of pedological processes can be used to give a reflection of the environmental conditions at a specific location. Observed differences in properties reflecting soil forming processes suggest variation in both past and present environmental conditions.

Pedological features such as water repellency, permeable subsurface apedal horizons, subsurface impediments such as cemented (calcrete or dorbank) hardpans and significant more clayey (cutanic, luvic) horizons were identified. Cemented hardpans indicate that this area experiences a low precipitation and high evaporation levels contributing to a high pH resulting in silica becoming soluble. The low rainfall prevented sufficient leaching of silica, resulting in cementation as a dorbank horizon at a specific depth. Cemented horizons then act as impermeable barriers, preventing further illuviation of dispersed clay and leached salts. The abrupt textural change induces the formation of a perched aquifer. This stagnant water results in the formation of gleyed sand, above the dense more clayey horizon. The reason why shallow-rooted plants do not directly utilize the deep-water aquifer needs to be investigated.

The dynamics of soil genesis play an important interactive role in terrestrial ecosystem functioning. Homogenisation of soils due to mining activities would thus permanently alter ecosystem functioning.

CHAPTER 4

CHANGES IN THE SOIL MANTLE BROUGHT ABOUT BY MINING AND RESTORATION

4.1 INTRODUCTION

The Succulent Karoo biome is known for its exceptionally high floristic diversity and endemism, contains a contrasting low level of growth form diversity (Esler et al. 1999). The processes that have produced this unique ecosystem through the interaction of plants, micro-organisms, animals, climate and soil are still not well understood (Milton & Dean 1999).

Strip-mining for titanium, diamonds, gypsum, silver and other minerals is destroying thousands of hectares in this biologically diverse environment (Milton 2001). Bradshaw (1983) states that strip-mining is a violent form of ecosystem disturbance that not only destroys vegetation, but also soil in either a pedological or biological sense. Due to the nature of the starting material, revegetation involves a slower process of primary succession rather than the more rapid processes of secondary succession (Bradshaw 1983). Without human assistance and management, the reconstruction of an ecosystem can extend over a considerable longer period. Re-establishing natural processes such as mineral cycling, resource capture, pollination, dispersal and recruitment is essential for achieving sustained rehabilitation success (Milton 2001).

The rehabilitation goal set by Namakwa Sands Pty (Ltd) is to return the vegetation cover and biodiversity of post-mined areas to a state equivalent to pre-mining conditions. A complete Environmental Impact Assessment (EIA) needs to incorporate all sectors of the environment. Milton (2001) reviews the recommendation by Antje Burke (EnviroScience) to analyse landscape processes and patterns in early stages of rehabilitation planning. An important aspect that still needs to be evaluated is the impact of strip-mining and rehabilitation practices on the pedosphere and landscape processes.

One of the objectives of this study, which is addressed in the present chapter, was to compare the end product of mining and rehabilitation practices with the previous natural environment. A comparison was made between rehabilitated land and natural soils in terms of texture, salinity, pH and organic carbon content. The effect of mining and rehabilitation on the natural topography and on soil horizonation was also considered.

4.2 MATERIALS AND METHODS

4.2.1 Study area

The study area included natural land from vegetation communities 1 to 4 as described in chapter 2, that is still to be mined, as well as land that was rehabilitated between 1999 and 2003.

4.2.2 Data collection

Natural land

Soil samples were collected from 0–5 cm and 5–20 cm and analysed for EC (electrical conductivity) of a 1:5 soil-water suspension, pH of a 1:2.5 soil-water suspension and pH of a 1:2.5 soil-1M KCl suspension. Samples were collected to include variation associated with the presence of heuweltjies in the north-eastern part of VC 1 and with small dunes in vegetation communities 1 and 2. Sampling was evenly divided between these contrasting components. Deep soil material of the permeable soil layer in profiles described in Chapter 2 was used for analysis. The EC, pH and silt plus clay content of these deep soil materials were compared with those of deep samples from rehabilitated land. Organic carbon and silt plus clay contents of A and B1 horizons in profiles from communities 1, 2, 3 and 4 described in Chapter 2, were compared with those of the 0–20 cm layer of rehabilitated land.

Rehabilitated land

Soil samples were collected from 0–5, 5–20 and 100–120 cm depths. Three samples were taken at each soil depth in six rehabilitation blocks in the Graauwduinen East mine. These blocks varied in terms of year of rehabilitation, topsoil treatment and mineral separation method (Table 4.1). Samples were collected at sites 100 m apart. Four 100–120 cm samples, one from the 2001 no-topsoil block and three from the 2003 block, contained loamy material from the soil layer below the rehabilitation material and were excluded from the analysis. Three samples were taken from fresh tailings.

Table 4.1: Treatment of rehabilitation blocks situated in the Graauwduinen East mine

Year of rehabilitation	Topsoil treatment	Mineral separation method
1999	No topsoil	Fresh water
2000	No topsoil	Salt water
2001	No topsoil	Salt water
2001	Topsoil	Salt water
2002	Topsoil	Salt water
2003	Topsoil	Salt water

4.2.3 Statistical analysis

An ANOVA (analysis of variance) was used to compare salinity, pH, silt plus clay and organic carbon contents. A Kruskal-Wallis test was conducted on non-parametric data. The ANOVA comparisons were made with STATISTICA software (StatSoft Incorporated 2002).

4.3 RESULTS AND DISCUSSION

4.3.1 Salinity and pH

A statistical evaluation of pH and salinity differences between undisturbed and rehabilitated soil is presented for three soil depths in Tables 4.2. No significant differences were found at any of the depth intervals. There was a consistently larger mean salinity at all three depths in rehabilitated soil but associated with this was a high standard deviation which is probably accounted for by the very high salinity maximum in rehabilitated soil. No significant differences were recognised between the salinity and pH values of the 0–5 cm soil layer of rehabilitated land and the natural soil. The high maximum salinity of the 0–5 cm from the rehabilitated site resulted in the higher average and standard deviation in EC values presented in Table 4.2.

Table 4.2: Statistical analysis of pH and EC values of the 0–5 cm, 5 – 20 and deeper soil layers obtained from the natural soil (N) and rehabilitated land (R). * Indicate Kruskal-Wallis analysis for non-parametric data

		Avg		**Stdev**		**Geomean**		**Min**		**Max**	
0 – 5 cm		**N**	**R**	**N**	**R**	**N**	**R**	**N**	**R**	**N**	**R**
pH(H_2O)	$p > 0.05$	6.9	6.5	0.8	0.4	6.9	6.5	5.6	5.9	8.7	7.3
pH(KCl)	$p > 0.05$	6.1	5.9	0.9	0.3	6.0	5.8	4.6	5.4	7.9	6.5
EC mS.cm^{-1}	$p > 0.05^{*}$	81	141	48	141	70	87	32	23	206	433
5 – 20 cm											
pH(H_2O)	$p > 0.05$	6.7	6.6	0.8	0.4	6.6	6.6	5.5	5.8	8.6	7.9
pH(KCl)	$p > 0.05$	5.7	5.8	0.8	0.2	5.7	5.8	4.3	5.4	7.0	6.3
EC mS.cm^{-1}	$p > 0.05^{*}$	64	104	44	140	53	57	21	16	155	552
Deeper layers											
pH(H_2O)	$p > 0.05$	6.7	6.9	0.7	0.5	6.6	6.9	6.0	6.2	8.3	7.8
pH(KCl)	$p > 0.05$	5.6	5.8	0.5	0.3	5.5	5.8	4.6	5.4	6.3	6.7
EC mS.cm^{-1}	$p > 0.05^{*}$	101	157	169	241	57	69	90	19	719	852

Maximum electrical conductivity values of soil depths from both rehabilitated land and 0–5 cm and deep profiles from natural land exceeded 0.4 mS.m^{-1}, a threshold indicated by Donner & Grossl (2002) as representing saline soils. The average and geometric mean values at all soil depths from both rehabilitated land and natural land fell well beneath 0.4 mS.m^{-1}.

A conversion from EC values of the 1:5 soil water extract to that of a saturated paste extract was done according to White (2003). Trends over time are to be presented in a latter section.

4.3.2 A comparison between organic carbon and texture of soil from natural and rehabilitated land

Total soil organic carbon (OC) was mostly situated in the top 20 cm of soil profiles sampled from the study area, and can be seen in the darkening of this zone (Chapter 2). Organic matter in soil is measured and presented as mass percentage of OC of soil. The OC content of the natural soil was, as can be expected in arid soil, very low with a geometric mean of 0.21%. Statistical analysis revealed a geometric mean value of 0.09% OC for the top 20 cm of the rehabilitated land. The OC content differed significantly between natural and rehabilitated soils (Table 4.3). Both the organic carbon and silt plus clay content of the 0–20 cm soil layer were significantly lower in rehabilitated land than in natural soils while silt plus clay content showed a similar trend in deeper soil layers (Table 4.3). Rehabilitated land has only about a third of the silt plus clay content and about a half of the organic carbon content of the natural soils. Since both these constituents are present in small quantities to begin with, this would be expected to greatly diminish the fertility status with respect to both the reservoir of plant nutrients (reduced CEC and miniralizable organic matter) and to the storage capacity for water.

Table 4.3: Statistical analysis of the organic carbon (OC) and texture of 0–20 cm and deeper soil layer from natural (N) and rehabilitated (N) land. * Indicate Kruskal-Wallis analysis for non-parametric data

0–20 cm		**Avg**		**Stdev**		**Geomean**		**Min**		**Max**	
		N	**R**	**N**	**R**	**N**	**R**	**N**	**R**	**N**	**R**
OC	$p < 0.05$*	0.23	0.10	0.09	0.06	0.21	0.09	0.10	0.06	0.35	0.25
Silt + clay	$p < 0.05$*	4.0	1.2	1.9	0.6	3.5	1.1	0.5	0.6	6.2	2.6
Deeper layers											
Silt + clay	$P < 0.05$	3.3	1.1	2.2	0.5	2.6	1.0	0.6	0.4	9.4	1.7

4.3.3 Changes in Salinity, pH and texture

Cumulative rainfall of 46 mm over a four month period resulted in a more than threefold decrease of salinity from 1500 mS.cm-1 in fresh tailings to levels below 500 mS.cm-1 (Figure 4.1). Cumulative rainfall of 490 mm over a period of 28 months decreased salinity at all three soil depths to mean levels below 200 mS.cm-1 (Figure 4.1). A large rainfall event in month 21 (July 2001) resulted in the most pronounced decrease in salinity. There was no significant difference in the mean pH and silt plus clay content of soil samples taken from rehabilitated land ranging in age from fresh tailings to 52 months after rehabilitation had commenced.

The use of seawater for heavy mineral extraction can result in sufficient salinity to inhibit plant growth in the tailings (Environmental Evaluation Unit 1990). Figure 4.1 suggests that rainfall will result in the leaching of excess salts to achieve salinity levels comparable with those of natural soils. Mahood (2003) also indicates a significant decrease in salinity of tailings within 15 months of rehabilitation. It is accepted that saturated sandy soil conducts water more rapidly than a saturated clayey soil. The opposite is true for unsaturated soil (Hillel 1998). Intense rainfall events such as was experienced during month 21, can potentially leach the whole soil profile of excess salts. The variability of salinity in the rehabilitated land of 21 months and younger could be the result of partial leaching due to preferential flow during smaller rainfall events.

High salinity levels inhibit the seedling emergence and survival of four Namaqualand pioneer species (De Villiers 2000). These results support the conclusions of Seneca (1972) that seed germination is inhibited at salinity levels above the tolerance levels of seedlings. This could be an important survival mechanism but could also delay revegetation.

Another factor likely to affect the rate at which leaching takes place is the absence of a dorbank or clay rich horizon in the rehabilitated soil. While a fast decline in salinity is to be welcomed, it also signifies deep water percolation and the possible removal of soluble nutrients below the main root zone. This especially can be a problem in the Graauwduinen West mine where the dorbank is removed to leave an ore of porous sand up to depths of 40

m. The dorbank in the natural land and the Graauwduinen East mine can thus act as a barrier to prevent deep water infiltration.

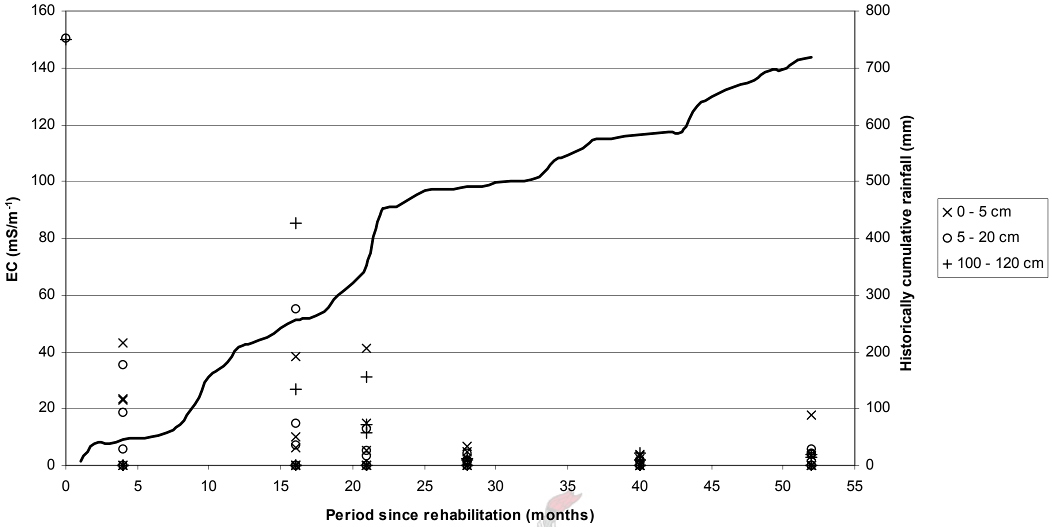


Figure 4.1: Time series graph to indicate the change in mean salinity of 1:5 soil water suspensions from soil samples taken at 0–5 cm and 5–20 cm soil depths of rehabilitated site versus cumulative rainfall over the same period.

4.3.4 A comparison between hydrophobicity of the topsoil in natural and rehabilitated land

A porous matrix of dry, hydrophilic mineral particles normally adsorbs water by capillary attraction. Natural soil mineral surfaces are typically hydrophilic. Hydrophobicity in the surface horizons is a common feature in the undisturbed soils of the study site. Soil samples taken from the natural and rehabilitated land, which received topsoil treatment, included 77% and 73% water-repellent samples, respectively. Only 11% of the samples taken from the 0–20 cm depth of rehabilitated land that did not receive topsoil treatment, displayed hydrophobic characteristics. Ritsema et al. (1997) found that hydrophobicity in the topsoil prevents uniform water infiltration and induces preferential flow paths in the soil. Field observations revealed that hydrophobicity was most severe under the shrub canopy, possibly originating from the large fraction of organic debris. This was also the region that supported the densest root distribution. The dense root zone directly underneath the plant canopy is subjected to the driest conditions but also the least amount of leaching. This phenomenon will be discussed further in Chapter 5.

Loss of hydrophobicity in the soil surface alters the soil water dynamics. This can result in a change that could be a very important ecological process. This again emphasises the importance of retaining the natural topsoil for rehabilitation.

4.3.5 Haploidisation of natural soil materials due to mining and rehabilitation techniques

This study revealed the presence of five soil forms and eight soil materials within the area which can be affected by the mining process. These soil morphological features are the product of pedogenic processes operating over varying periods of time, in response to climate, organisms, relief and parent material (Buol et al. 1997). The mining of soil in this area results in the formation of sand tailings and slimes by-products, originating from the sand and clay fractions from the mined soil. Rehabilitation in the Graauwduinen East region has created homogenous materials consisting of porous sand tailings of varying depth. The rehabilitated sand tailings are underlain by unmined dense sandy loam on top of a dorbank horizon. The deep-mining and rehabilitation process in the Graauwduinen West area results in the formation of a deep homogeneous material containing a crushed dorbank layer on top of a deep, porous sand body. A thin layer of topsoil is spread over both the areas. Rehabilitated land differs from the natural soil in that the porous section of the soil is a by-product of the mining process that homogenises the natural soil and extracts silt plus clay and organic matter. None of the original soil morphological characteristics of the permeable horizon, as described in Chapter 3, are found in the rehabilitated land of Graauwduinen East. Graauwduinen West is subjected to destruction of all morphological features to a considerably greater depth than in Graauwduinen East. Haploidisation of the pedosphere, due to the mining process, results in a loss of many of the features associated with the horizonation described in Chapter 3.

4.3.6 The effect of mining and rehabilitation processes on the natural topography of small dune fields

Mining has affected the natural topography. The mined land is rehabilitated to dovetail with the surrounding topography. The main impact of the mining is thus on micro-relief. Micro-topographical features of the area to be mined include small fixed dunes present in VC 1 (Figure 4.2) and 2 and heuweltjies in the eastern part of VC 1. Figure 4.3 shows the relief compared with the relief of dune systems apparent in VC 1.

Figure 4.2: Rehabilitation in Graauwduinen East mine. Loss of dune relief

De Villiers (1999) describes the presence of two variants of the vegetation communities *Ruschia tumidula—Tetragonia virgata* Tall Shrub Strandveld, and *Eriocephalus africanus—Asparagus fasciculatus* Tall Shrub Strandveld, on the small dunes and in the dune valleys. The small dunes can be seen as features that induce small-scale variation in environmental conditions.

Figure 4.3: Vegetated small dune system of VC

Ridolfi et al. (2003) emphasised the importance of a hillslope on the spatial variation of soil hydrological conditions. Both soil water content and temperature patterns for a bare and vegetated transect in a typical sand dune area indicated heterogeneous transport of soil water after rainfall (Berndtsson et al. 1996). Chapter 5 illustrates soil water infiltration through tonguing after 20 mm of rainfall. Such preferential flow of water (as illustrated later in Figure 5.1) can then also result in preferential movement and leaching of salts through the soil. De Rooij (2000) stated that when fingered flow occurs, the fraction of the soil participating in the flow and the finger radius governs solute transport. Zhenghua et al. (2003) observed a difference in soil profile development, morphology, physiochemical properties, particle size and nutrient accumulation between dune crest and interdune soils after 35 years of sand dune stabilisation. This difference is attributed to the accumulation of fine soil particles in the interdune area due to dustfall and surface water runoff.

These processes could explain the variation in soil profile morphology, hydrology, physics and chemistry observed in the profiles situated in small dune fields of communities 1A and 2. The homogenisation of topographically induced environmental variation, due to mining the process, can result in the loss of the environmental niches that support VC variants described by De Villiers (1999). This can lead to the disruption of the ecological facilitation and competition processes that support the communities existing in the small dune fields, resulting in an overall loss of biodiversity.

4.3.7 The effect of mining and rehabilitation processes on the natural topography of heuweltjies

'Heuweltjies' (termite mounds), are a prominent feature of many areas of the biome and support distinctive plant communities. Heuweltjies are found on the seaward side of the escarpment in the western and south-western parts of South Africa. Heuweltjies also occur in the north-eastern part of the study site. The vegetation of this area is classified as Lowland Succulent Karoo (De Villiers 1999).

Ellis (2002) records a striking difference in soils and vegetation cover generally occurring on and between heuweltjies. As revealed in chapter 2, heuweltjies contain a different vegetation structure and composition than the surrounding environment. Soil morphological properties on and off the heuweltjies differ. Ellis (2002) shows a relation between the occurrence of heuweltjies, caused by the harvester termite *Microhodotermes viator,* hardpan (petrocalcic, petrogypsic or petroduric horizons) and the occurrence and gradient of rainfall on the West Coast of South Africa. Mound-building termite species have a significant impact on the distribution and composition of soil mineral and organic matter (Coleman & Crossley 1996). Heuweltjies-related differences were found in pH, silica solubility, salinity, extractable phosphorus and morphology. Soil chemical analysis from heuweltjies in the Kleinsee area, approximately 25 km north of Brand-se-Baai, indicated that soil on the heuweltjies had higher SAR (sodium adsorption ratio) values than soil from between the heuweltjies. The heuweltjies also contained more clay than the surrounding environment.

Ellis (2002) describes these mounds as biological 'cities' where the gathering of plant material in various stages of decomposition results in the build-up of bases (especially C) and silica over time. Heuweltjies can be seen as features that induce small-scale variation due to termite activity. The microtopographical and topsoil properties of the heuweltjies can induce water runoff. This can result in a drier moisture regime on the heuweltjie, compared with the receptor region between heuweltjies (F. Ellis, personal communication, 2003). The mining process will thus eliminate variation in soil properties associated with the occurrence of heuweltjies.

4.4 CONCLUSIONS

Soil morphological features are key ingredients of the space in which an ecosystem functions. Pedogenic features are the result of climate, relief, parent material and organisms interacting over a specific period. The rehabilitation process of mined land has resulted in a more homogeneous soil environment than in the pre-mined soils. Rehabilitated soil has only half of the OC and one third of the silt plus clay of the natural solum Homogenisation of the solum, removal of the dorbank and the dense neocutanic horizon in the west mine area, alteration or loss of hydrophobicity, the lowering of OC and the clay plus silt fraction can all be expected to have detrimental effects on the attempted restoration of this area to its natural condition prior to mining. The high salinity of the freshly rehabilitated tailings is amenable to reduction by natural leaching that may have been accelerated by removal of the fine fraction as slimes and less permeable dorbank and clay layers. Consequently, the new vegetation gets some protection against salinity. This could be "short-changed" with respect to the soils capability to sustain an adequate supply of water and nutrients. The leaching of solutes in the rehabilitated land will need further study to ascertain whether salinity is more homogenous than in to the natural solum.

CHAPTER 5

SOIL WATER DYNAMICS

5.1 INTRODUCTION

Water has the most dominant influence on arid ecosystem form and function. A clear understanding of arid ecosystems demands a thorough knowledge of hydrological processes and patterns (Evans & Thames 1981). It is also essential to understand the method of water distribution and provision in an arid ecosystem before rehabilitation of such an ecosystem can take place. Notwithstanding well documented research on desert hydrology and its importance for the dynamics of vegetation, very little is known about soil water regimes and their controlling factors in semi-arid and arid climates, where long or even medium-term meteorological and hydrological records are often lacking (Cantón et al. 2003).

Soil hydrology of arid ecosystems is influenced by various factors such as varying rainfall intensity, rainfall interception by vegetation, soil relief and topography, retention and detention on the soil surface, infiltration and evaporation at the soil surface, transport of vapour out of the system and runoff (Parsons et al. 1992; Abu-Sharar 1995; Bromley et al. 1997; Gaze et al. 1997; Rao et al. 1998; Cantón et al. 2003; Howes & Abrahams 2003).

The first section of this chapter discusses factors that can influence the hydrology of natural soils in the Strandveld Succulent Karoo. Such factors include soil texture, soil hydrophobicity and plant cover, soil surface sealing of crust formation, relief, and rainfall intensity. These factors are used to describe and discuss hydrological patterns observed in the field as observed and described in Chapters 2 and 3. The second section of this chapter investigates a method of water acquisition by vegetation through water distillation as a possible explanation for the apparent discontinuity between the shallow root zone and deeper lying aquifer.

5.2 IMPORTANT FACTORS THAT CAN INFLUENCE THE HYDROLOGY OF NATURAL SOILS

5.2.1 Soil texture

Coarse textured soils, as found in the study site, are naturally characterised by a high saturated hydraulic conductivity (Hillel 1998). Hillel furthermore states that the opposite is also true for these soils in the unsaturated state. This characteristic of sandy soils, as well as other causes such as air entrapment, microlayering, water repellency and zones initially higher in water content, may cause preferential water infiltration patterns in an apparent homogenous sand (Wang et al. 2003; Ritsema et al. 1997; Berndtsson et al. 1996). Experiments done on water infiltration into uniformly packed coarse sand columns illustrated water infiltration through fingering though the medium was homogenous (Wang et al. 2003). A study done by Berndtsson et al. (1996) revealed the same phenomenon in highly pervious and homogeneous sand along the dune slopes. Along with other characteristics of sandy soils, such as low water-holding capacity (Hillel 1998), water infiltration through preferential zones can hold various advantages for water conservation in arid and semiarid regions. Storage in deeper lying pockets can preserve the scarce supply of water from the high evaporation demand of the hot and dry desert climate. This phenomenon is clearly illustrated in Chapter 3 and will be discussed in this chapter.

5.2.2 Hydrophobicity and plant cover

Hydrophobic characteristics are caused by a range of hydrophobic organic materials (King, 1981). It can be due to the presence of fungal hyphae (Bond & Harris 1964) or the presence of particulate organic matter that acts as a carrier and reservoir of hydrophobic waxes (Franco et al. 1995). These waxes can diffuse out and coat the sand grain surfaces inducing hydrophobicity. Hydrophobic topsoil will induce fingered flow patterns of these sandy soils (Ritsema et al. 1997; Van Dam et al. 1996; Van Ommen et al. 1988. Jaramillo et al. (2000) observed that during precipitation, a water-repellent top layer caused water to infiltrate through a few wet patches and consequently reached relatively great depths. Hillel (1998) reviewed agricultural practices in semi-arid regions where the soil surface was broken and treated to become water repellent. This was done to increase water infiltration through water-repellent clods and decrease evaporation from underlying moist soil. He states that the overall effect of water repellency in the desert seems to enhance water conservation. According to DeBano (2000), Hergenham believes that due to the reduction in capillary rise of water to the soil surface where it can evaporate, hydrophobicity can act as a natural water-saving mechanism. Van Dam et al. (1996) reported that the residence time of nutrients in preferential flow paths is decreased considerably. This phenomenon will thus prevent leaching of nutrients through hydrophobic regions. Runon-runoff relationships in the semiarid patterned vegetation of Niger were also found to have considerable implications for the field nutrient balance, with increased leaching at the runon patches (Gaze et al. 1997). The same can be true for runon-runoff relationships of hydrophobic soils. Field observations revealed that hydrophobicity was most severe under the shrub canopy, possibly originating from the large fraction of organic debris. This also occurs in the region that supports the most dense root distribution. The dense root zone directly underneath the plant canopy is subjected to the driest conditions but also the least amount of leaching. The soil surface beneath shrubs in the Strandveld Succulent Karoo can thus act as water-runoff regions with runon patches between shrubs (Figure 5.1). Jaramillo et al. (2000) indicated a correlation between field water repellency and different shrub and tree species.

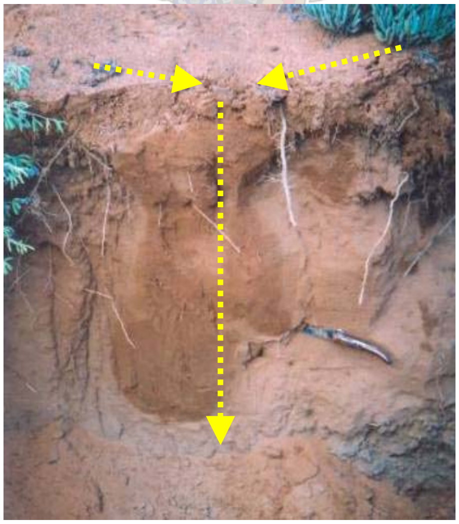


Figure 5.1: Water moves as a tongue through sandy subsoil and is stored above dense more clayey or a hardpan layer.

5.2.3 Soil surface sealing or crust formation

Soil crusting can result in impeded water infiltration, soil air movement and seedling emergence to varying degrees. Various types of soil crusts occur in natural ecosystems. Surface crusts play an integral part in the hydrodynamics of ecosystem functioning. A clear example is the initiation of runoff-runon of rainwater in patterned vegetation was indicated by Bromley et al. (1997).

Biological crusts

Biological soil crusts play a very important role in the functioning of various arid ecosystems (Belnap 2002, Li et al. 2002, Cantón et al. 2003). Microbiotic crusts can form due to the interactions between bacteria, small soil-dwelling animal, algae, fungi, moss and lichen (Schulten 1985, Eldridge & Greene 1994, Li et al, 2002, Cantón et al 2003). A study done by Cantón et al. (2003) revealed the importance of lichen crusts in preserving soil water in arid and semiarid ecosystems. It was found that lichens contributed to the variation observed in the hydrological behaviour of soil. It seemed that low intensity rainfall favoured infiltration and enhanced volumetric water content, while with high intensities it favoured runoff. An investigation conducted by Li et al. (2002) showed that biological crusts on the artificially stabilized desert dunes in Tengger Desert, North China, reduced the amount of rain that infiltrated downward into deeper layers. In contrast, a study by Williams et al. (1999) showed that crusts have little influence on the soil hydrological regime in Australia. Biological soil crust can also be an important source of fixed N in arid and semi-arid soils (Belnap, 2002). Field observations revealed the occurrence of biological crusts in the study region and in the more northern part of the Strandveld Succulent Karoo.

Mineral crust

Soil surface crusting (mineral crust) is the result of physical disintegration of soil aggregates and consequential dispersion and compaction by the kinetic action of raindrops (McIntyre 1958; Agassi et al. 1981; Le Bissonnais & Singer 1992). Raindrop impact and wetting and drying cycles influence the forming process of the surface seal and therefore they have an effect on its hydraulic properties and the levelling and compaction of the surface (Fohrer et al. 1999). In their review Rao et al. (1998) cited findings of El-Swaify et al. that the effect of surface sealing is enhanced by low organic matter content, poor aggregation, and low soil strength under saturated conditions leading to slumping, high bulk density, and loss of surface roughness.

A salt crust commonly occurs throughout the study region (Figure 5.2). The EC value of 1:5 soil water extract of this crust was 0.63 mS.cm-1. The soil underneath the crust had an EC value of 0.32 mS.cm-1. This salty crust can be ascribed to the influx of salt from the sea through frequent fog. Plants can capture this salty mist, resulting in salty drops dripping beneath the drip zone of the shrub canopy. This hypothesis needs to be tested because it may reveal important processes in the functioning of the ecosystem. The critical placement of salts, directly in the root zone of plants, could significantly influence our understanding of this ecosystem.

Figure 5.2: Dark saline crust downslope from shrubs.

5.2.4 Relief

A common feature in desert areas is the occurrence of shrubs on microtopographical mounds a few centimetres high. The development of shrub mounds is attributed to a number of abiotic and biotic processes. Abiotic processes include the deposition of fine aeolian material by wind and differential rain splash. Differential rain splash is the preferential migration of sediment due to raindrop action, from between shrubs to shrub areas, rather than in the reverse direction because shrub canopies dissipate raindrop energy (Parsons et al. 1992).

Howes & Abrahams (2003) state that these microtopographic mounds cause overland flow in the bare inter-shrub areas to concentrate in flow paths around the shrubs in a complex reticular pattern. De Rooij (2000) states that local heterogeneities in the top centimetres of the soil as well as microtopography may determine in which direction water flows, the infiltration of water through fingers and how much water a finger receives. Berndtsson et al. (1996) discovered heterogeneous distribution of soil water content in homogeneous desert sand. Dune top and bottom had on average higher water content than the dune slope sections. These findings were, amongst other things, explained by the effect that millimetre scale sand layering, that follows topography, has on water infiltration. It was concluded that lateral layering of soil material leads infiltrated water to dune bottoms.

5.2.5 Stemflow

Another mechanism that can have a significant influence on the hydrology of soils from arid regions is canalisation of water through stemflow and root channel micro-pores (Devitt & Smith 2002; Martinez-Meza & Withford 1999). According to these experiments, much deeper infiltration depths are possible and water is redirected to the immediate root zone for optimal utilisation. The occurrence of downslope surface salt crust underneath shrub canopies and wet tongues of water between shrubs, discussed in previous chapters and later in this chapter, precludes the functioning of such a mechanism in the study area.

5.2.6 Hydraulic lift

A possible mechanism by which water can be transported from deeper moister horizons to the surface is through hydraulic lift (Caldwell et al. 1998; Wan et al 1993; Caldwell & Richards 1989). Due to the shallow nature of the root architecture of this region, it is doubtful that this mechanism can significantly contribute to water distribution in soils of this region.

5.2.7 Rainfall intensity

Summer thunderstorms of high intensity and short duration in desert ecosystems naturally cause overland flow due to surface crusting and low infiltration rates (Hekman & Berkas 1981). Although surface crusting also reduces infiltration rate during winter frontal storms, low intensity rainfall events limit the number of runoff events. In an experiment conducted by Fohrer et al. (1999), infiltration rate, water content, water suction, bulk density and surface roughness proved to be susceptible to the type of rainfall pattern and initial soil moisture content. The low intensity, frontal winter rainfall pattern of the study site (Desmet & Cowling 1999) will, in combination with the coarsely textured soils, limit extensive overland flow and runoff patterns. A hydrophobic soil surface can, on the other hand, induce runoff.

5.2.8 Impermeable horizons

Soils of the Strandveld Succulent Karoo are characterised by the extensive occurrence of subsurface cemented horizons of variable depth (Ellis 1988). As has been stated in chapter 3, these horizons are also found in the study area and are largely the result of variable cementation by silica and carbonate. Rapid surface infiltration and reduced permeability of a subsurface cemented horizon can cause subsurface water build up and vertical distribution (Blume et al. 1987). The occurrence of a bleached horizon above the water impenetrable dorbank horizons, as indicated in Chapter 2, confirms the existence of this phenomenon in the study area. Palmer et al. (1999) indicated that the taller Strandveld vegetation is associated with deeper sands while short Strandveld vegetation, with a considerable succulent element, occurs predominantly on shallow soils with less soil moisture. These findings indicate that vegetation height and composition can mirror the effect of varying soil depths on water catchment and storage.

5.3 POSSIBLE WATER INFILTRATION AND DISTRIBUTION PATTERNS OF THE STRANDVELD SUCCULENT KAROO

The factors mentioned above that can influence water infiltration and distribution patterns, have led to the formulation of a unique water balance model for the Strandveld Succulent Karoo. In contrast with other desert ecosystems, where the soil surface beneath shrub canopies constitutes as fertile islands that act as a sink for water runon, the hydrophobic soil surface surrounding shrub canopies induce and accelerate water runoff that accumulates and infiltrates between desert shrubs. As mentioned above, subsequent infiltration fingering and deep percolation (Figure 5.1) result in the build-up of an aquifer extending out of reach of shallow-rooted desert shrubs. Water distillation and subsurface dew formation are possible mechanisms that can bridge the apparent discontinuity between the shallow root zone and the deeper-lying water aquifer. A temperature gradient formed by radiative cooling at night can enhance upward vapour movement from deeper-lying warmer and water-saturated soil horizons (Hanks & Woodruff 1958; Hanks et al. 1960; Jury et al. 1981; Krishnaiah & Singh 2003), causing condensation in the surface horizon.

The next section of this chapter investigates this theory as a possible mechanism that can supply the vegetation with water more regularly.

5.4 STUDY AREA

The investigation was conducted in VC 1A as described in Chapter 2, where a one-metre deep profile pit was dug. The topsoil horizon has a tendency to repel water in the dry state. A highly permeable yellow-brown B horizon underlies the water-repellent A horizon. The subsoil contains a firm gleyed more clayey horizon on an extremely hard silica-iron cemented layer. This firm gleyed more clayey horizon is overlain by gleyed sand, indicating stagnant water properties. The transition to bottom horizons of this profile is abrupt.

5.5 MATERIALS AND METHODS

Three ML1 types and one ML2 type ThetaProbe sensors and 12 Copper-Constantan thermocouples (TC) were installed on 14 August 2003. The sensors were installed in the sidewall of a one-metre deep profile pit that was closed soon afterwards. The installation depths for the ThetaProbes are given in Table 1.

Table 5.1: Installation depths of the ML1 and ML2 type ThetaProbe sensors

Depth (mm)	ThetaProbe sensors
95	ML1 - 1
235	ML1 - 2
359	ML1 - 3
900	ML3

Each ThetaProbe sensor has a 112 mm long and 40 mm diameter cylinder housing the electronics. The sampling volume is measured by four 60 mm long sensing rods, with three distributed uniformly around the 26.5 mm circumference and at the centre. Sensors were inserted horizontally at the depths given above. TCs were used to measure the temperature profile up to 900 mm. Twelve TCs were installed over the whole profile at depths of 0, 25, 50, 100, 150, 250, 300, 400, 500, 600, 700 and 900 mm. The reference temperature used for the calculation was the panel temperature of the data logger. The output data had already been converted to the respective profile temperature in degrees Celsius. All sensors were connected to 21x data logger (Campbell Scientific, Logan, Utah) and batteries that remained outside the pit at the surface. A laptop was connected to the data logger to retrieve data. A fifth-order polynomial of the ThetaProbe sensor analogue output voltage V (in volts) was used to estimate the square root of the dielectric constant ($\sqrt{\varepsilon}$) of the soil (Delta-T Devices 1995):

$$\sqrt{\varepsilon}=1 + 6.19V - 9.72V^2 + 24.35V^3 - 30.84V^4 + 14.73V^5$$

Volumetric soil water content θ_v ($m^3.m^{-3}$) is calculated from $\sqrt{\varepsilon}$ using soil calibration constants a_o and a_1:

$$\theta_v = (\sqrt{\varepsilon} - a_o)/ a_1$$

Factory values for a_o and a_1 of 8.4 and 1.6 respectively were used. These values were derived for mineral soils. Field calibration was unsuccessful and soil core samples were removed to be used for laboratory calibration of sensors.

5.6 RESULTS AND DISCUSSION

Measurements of θ indicated extremely dry conditions at all four depths during the observation period (Figure 5.3). Precipitation did not result in any variation of θ measurements at 235 mm, 360 mm and 900 mm depths. θ at 95 mm increased gradually by 1.5% after total precipitation of 29.5 mm over a period of 20 days. Calculations revealed an increase of 1.452 mm water or 0.5% of the total precipitation received to a depth of 95 mm. A percentage of 99.5 of the precipitation water did not infiltrate to this point and 0.5% reached it over a period of 20 days. The small and delayed response questioned the direct influence of precipitation infiltration on the increase of the water content measured at 95 mm. What happened to the precipitation water? Figure 5.1 clearly answers this question. This infiltration pattern resulted from 17.5 mm of precipitation during the previous 5 days. As has been reviewed previously in this chapter, hydrophobic topsoil prevents uniform infiltration and induces preferential flow patterns in the soil (Ritsema et al. 1997). Local heterogeneities in the top few centimetres of the soil as well as microrelief may determine in which direction water flows and induce preferential infiltration of water through fingers (De Rooij 2000). Field observations revealed that hydrophobicity was most severe under the shrub canopy, possibly originating from the large fraction of organic debris that can be the main source of water-repellent substances. This was also the region that supported the most dense root distribution. Jaramillo et al. (2000) show a relationship between soil hydrophobicity and the plant species under which it occurs. The dense root zone, directly underneath the plant canopy, will be subjected to the driest conditions and the least amount of leaching. This phenomenon can explain the extreme dryness and lack in response to precipitation at 95 mm and 235 mm situated directly within the root-zone of a leaf succulent plant.

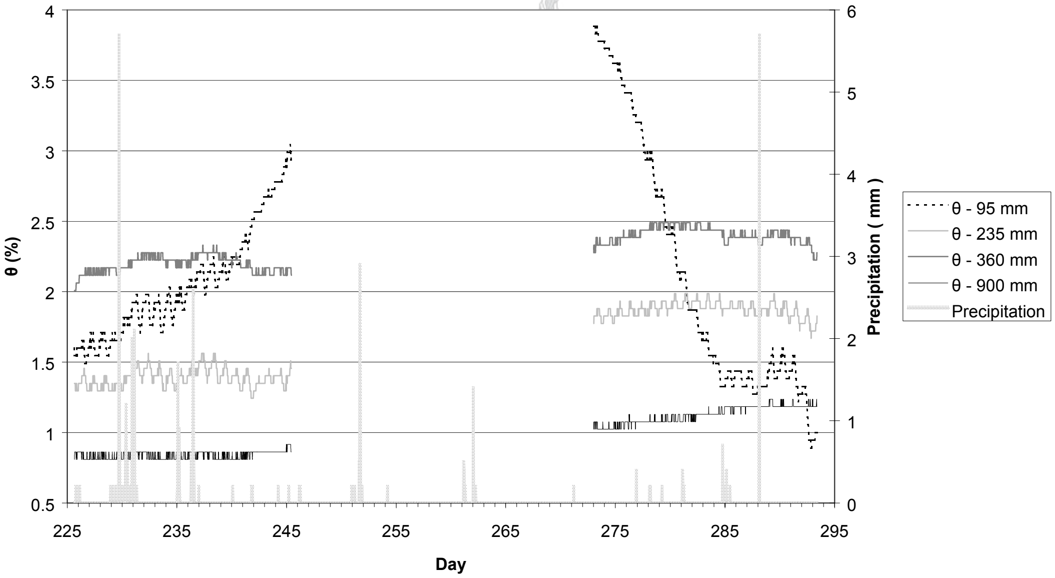


Figure 5.3: Volumetric % soil water content (θ) of four depths in relation to precipitation (mm) over the same period.

These findings contradict statements by Eccles (2000), Esler & Rundel (1999), Esler et al. (1999) and Rundel et al. (1998) that shallow root systems of the Strandveld Succulent Karoo will intercept infiltrated water from low intensity winter rainfall events. Findings that microhabitat characteristics underneath shrubs or a shrub patch can act as a water runon sink

(Ludwig et al. 1999) cannot be used to construct and investigate a hydrological model for this region.

As has been described and reviewed in chapter 3, the presence of a gleyed or bleached horizon (Figure 5.4), indicates reduction and removal of ferric and manganese oxides through lateral flow of a perched water table (Blume et al. 1987) on an impermeable layer (Washer & Collins 1988). This indicates that water infiltration in this area is sufficient to reach the depth of the water impenetrable more clayey layer at approximately one metre. At first glance it seems that the vegetation in this area neglects the availability of the deep water source. It is nearly impossible to accept the above statement, knowing that these plants should be adapted to a xeric environment, able to utilise all available water resources with extreme thoroughness and efficiency (Evans & Thames 1981).

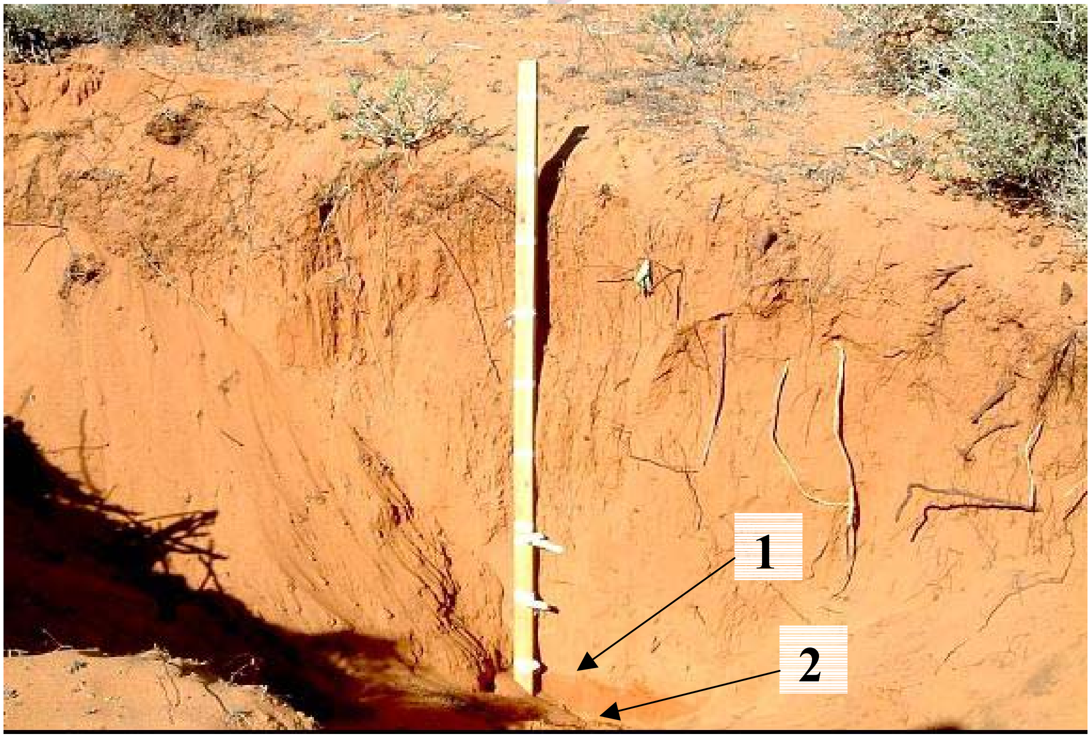


Figure 5.4: Bleached sandy horizon (1) on impermeable more clayey horizon (2) indicating intermittent saturation with water (profile 11; VC 2).

As has been described in Chapter 3, there are very few roots present in the deeper soil horizons. Despite the extreme dryness of this environment, plants in this region do not seem to make direct use of the deep aquifer. A possible method of water uptake is illustrated in Figure 5.3. ThetaProbes inserted in the root zone at 95 mm and 235 mm depths measured fluctuations in water content. Soil water increased with an average of 0.4 mm per night in the first 235 mm of soil surface, over a period that diurnal fluctuations were measured (Table 5.2). Volumetric water content measurements for depth 95 mm from days 240 to 285 were not incorporated into the calculation due to the consistent increase and decrease and lack of fluctuations over this period (Figure 5.3). The difference in diurnal minimum and maximum water content measurements for this period was the result of a constant increase and not of fluctuations. The explanation for this increase cannot be confirmed due to a lack of necessary climatic and soil data. During periods of water stress certain plants possess the ability to induce CAM photosynthesis that would enable them to transpire at night while their stomata are closed at daytime (Bowie 1999). This photosynthetic mechanism enables the plants to utilise the accumulated water source at night.

Table 5.2: Amplitude of diurnal soil water fluctuation in the surface horizon

Depth (mm)	Diurnal amplitude (mm)		
	Min	Max	Average
0–95	0.10	0.42	0.20
95–235	0.07	0.30	0.19
Total	0.18	0.72	0.39

The nocturnal water accumulation in the surface horizon can be explained by isochronic radiative cooling. Figure 5.5 clearly reveals these simultaneous oscillations in temperature and water content. Figures 5.6 and 5.7 show average minimum soil temperatures at 100 mm and 250 mm during four periods from August to October 2003. These figures clearly indicate the existence of thermal gradients with depth as well as a seasonal change in the soil temperature regime. As has been reviewed above, water vapour movement is directed by thermal gradients from colder towards warmer temperatures. The results presented by Figures 5.6 and 5.7 indicate the possible existence of a mechanism where water vapour movement takes place from warm to cold zones within the soil profile. Harris & Campbell (1981) mention the importance of considering a three-dimensional model, incorporating horizontal temperature and moisture gradients for the soil-plant-atmosphere system.

The gradual increase and decrease in soil water content from day 240–245 and day 273-285 respectively and the disappearance of soil water content oscillations during these periods in the 95 mm zone are difficult to explain due to insufficient measurements that in turn can explain the dynamics of soil conditions surrounding this point of measurement.

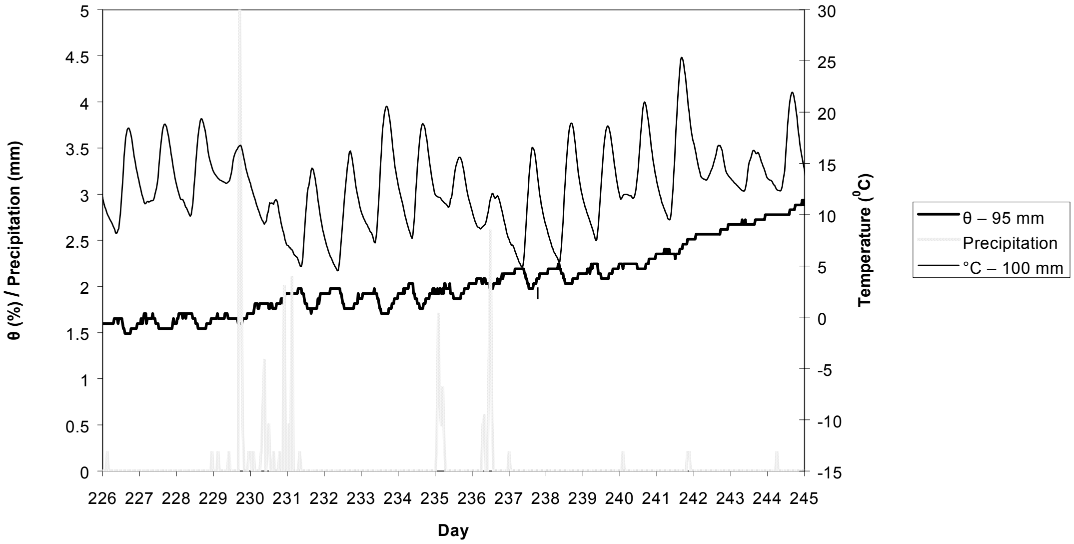


Figure 5.5: Oscillations in volumetric soil water content (θ) and soil temperature at 95 and 100 mm depths respectively.

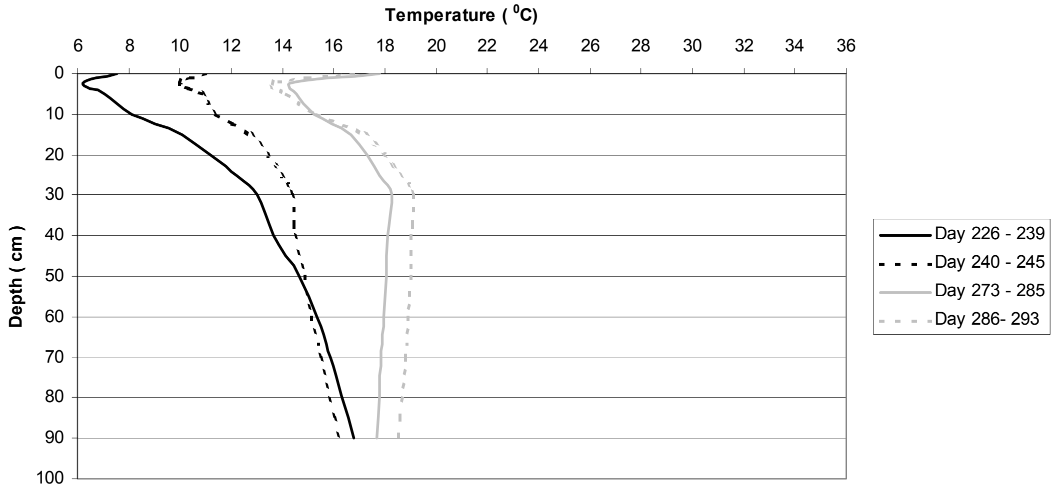


Figure 5.6: Average soil temperature profile coinciding with daily minimum temperature at 100 mm for four periods from August to October.

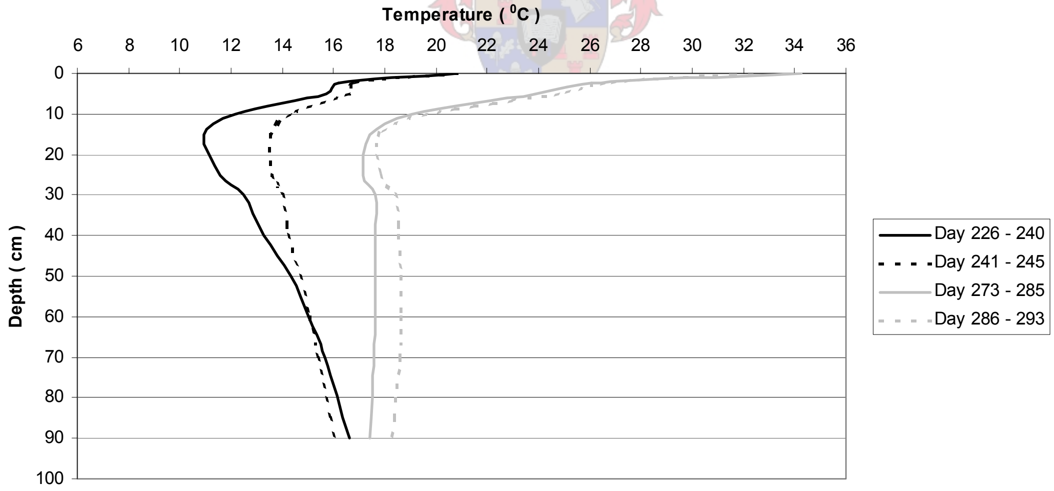


Figure 5.7: Average soil temperature profile coinciding daily minimum temperature at 250 mm for four periods from August to October.

Despite these shortcomings, some interesting observations emerge from Figures 5.6 and 5.7, which could cast some light on the phenomenon:

1. At the time of the minimum temperature at 100 mm depth the average soil temperature regime of days 226–239 and days 240–245 exhibited a positive heat gradient with depth down to 900 mm.
2. Under the same conditions the average soil temperature regime of days 273–285 and days 286–293 exhibited a positive heat gradient down to about 300 mm below which the soil temperature remained constant.
3. Coinciding with the minimum temperature at 250 mm the average soil temperature regime of day 226–239 and day 240–245 exhibited a positive heat gradient nearing the soil surface and with depth down to 900 mm.
4. The average soil temperature regime of day 273–285 and day 286–293 during the minimum temperature at 250 mm depth only exhibited a positive heat gradient nearing the surface.

The diurnal average temperature and water content values, presented in Figure 5.8, indicate that the gradual increase in soil water content at 95 mm, except for day 240–245, coincides with the presence of a positive heat gradient with depth. Measurements from day 273–288 revealed the opposite. During this period the decrease in soil temperature with depth coincides with a gradual decrease in soil water content. From day 289–291 the opposite is true. Could these differences in soil temperature regime explain the gradual increase and decrease in soil water content at 95 mm depth?

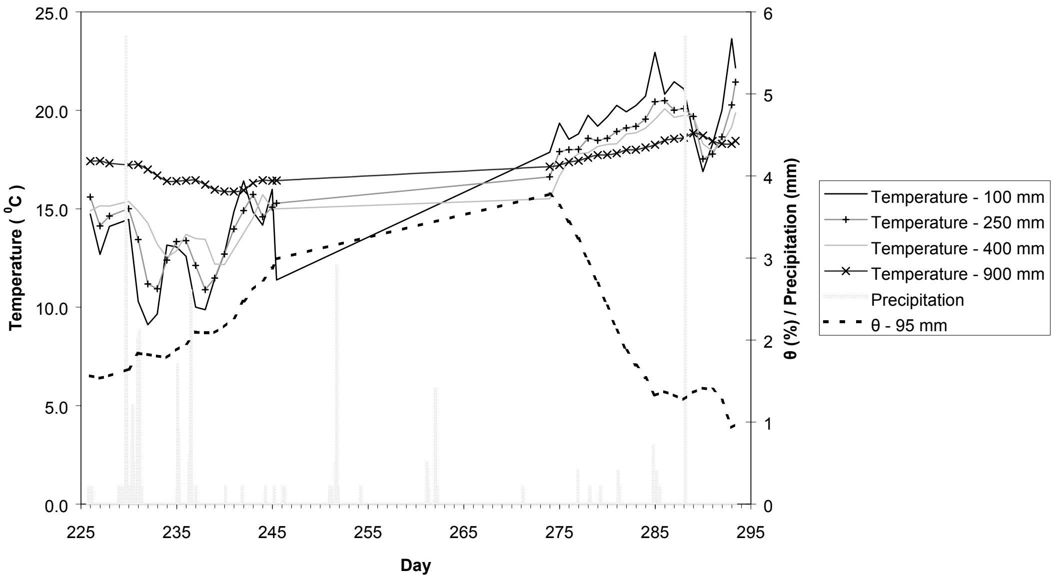


Figure 5.8: Precipitation values and diurnal average soil temperature and percentage volumetric soil water content (θ) of four depths.

The lack of atmospheric measurements, soil water content and temperature measurements in the immediate surroundings of the existing measurements, limits the conclusions that can be drawn from the above observations. Nevertheless, the above results do suggest that the soil temperature regime significantly influences the soil water regime, and may provide a mechanism for shallow-rooted plants to obtain water from greater depths.

5.7 CONCLUSIONS

Field observations indicated that rainwater infiltrated the soil through preferential infiltration zones or tongues. During precipitation, water repellency of the soil surface beneath plants may cause runoff and water to infiltrate through depressions between plants. Consequently, water infiltration can reach relatively great depths. This phenomenon can explain the bleached and mottled subsoil horizons indicating the occurrence of reducing conditions due to periodic waterlogging on less permeable neocutanic or dorbank layers. The water repellent characteristics of the soil surface can also prevent upward capillary movement, capture deep percolated water and prevent its evaporation. As has been shown in Chapter 2 and by various authors, vegetation in the study area is characterised by a predominantly shallow root system within a dry hydrophobic surface horizon. Water content measurements indicated that precipitation did not result in any increase in θ at 235 mm, 360 mm and 900 mm depths. Water content at 95 mm increased gradually by 1.5 % after total precipitation of 29.5 mm over a period of 20 days. Precipitation could thus have resulted in runoff and the wetting of the soil zone between plants with the formation of deep tongues of wetted soil. Considering the shallow root architecture, it seems that plants do not make use of a deep water source. An investigation of the hypothesis that temperature gradients enhance upward movement of water vapour at night, causing condensation in the surface horizons, revealed the occurrence of possible subsurface dew formation. Diurnal volumetric water content fluctuations were measured in the top 95 mm and 235 mm of the soil surface. An average water content increase of 0.4 mm per night was measured in the first 235 mm of soil surface. This amount is a significant source of water that can provide regular supply to shallow-rooted vegetation. Nocturnal radiative cooling of the soil surface results in thermal gradients within the soil profile. Water vapour movement due to temperature gradients can explain the diurnal volumetric water content fluctuations observed. It appears that the ecological functioning of the Strandveld Succulent Karoo may involve a unique hydrological cycle that needs to be considered for rehabilitation after strip-mining.

CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The West Coast of South Africa has seen a dramatic increase in strip-mining for diamonds, titanium, silver and gypsum (Milton 2001). This region contains a remarkable dominance and unique diversity of leaf-succulent shrubs and rich geophyte flora (Esler et al. 1999; Jürgens et al. 1999). The regional diversity is exceptionally high for an arid environment (Cowling et al. 1999) and it hosts the richest floral diversity of any winter rainfall desert. Notwithstanding the extraordinarily high level of endemism, Van Jaarsveld (1987) also determined that 37% of the world's approximately 10 000 succulent species occur in South Africa. Heavy mineral mining in this region poses more challenges for rehabilitation due to the aridity of this environment. Milton (2001) mentions the economic importance of heavy mineral mining in this region but also the consequential damage to a biologically diverse environment where vegetation recruitment is limited due to aridity and nutrient-poor soil.

This study clearly reveals that certain properties of the pedosphere, can be 'key ingredients' in the functioning of this ecosystem. Successful rehabilitation of the pedosphere of the Namakwa Sands heavy mineral mine, in such a manner that the mined environment can sustain land-use practices that preceded mining operations, will largely depends on the ability to create a growth medium with these properties. This chapter summarises the outcomes of this study, discloses soil properties that can be pivotal in the functioning of the ecosystem and recommends actions that should be taken to recreate these functional soil properties as far as possible.

6.1 COMPONENTS OF THE SOIL MANTLE LIKELY TO AFFECT ECOSYSTEM FUNCTIONING

Fey et al. (2002) state that pedological features reveal subtleties of climatic and topographic effects that are key ingredients to ecosystem functioning and that the inability to recognise their significance may doom the rehabilitation effort to failure in the long run. Pedological features such as surface water repellency, permeable subsurface apedal horizons, subsurface impediments such as cemented (calcrete or dorbank) hardpans and significantly more clayey (cutanic, luvic) horizons were identified. These features reveal a hydrologic cycle that could explain the shallow-rooted nature of the flora in this region.

Water repellency and microtopographic mounds are features of the soil surface horizon that cause subsequent infiltration fingering. Permeable subsurface apedal horizons act as a highly permeable medium for deep percolation of water while subsurface impediments such as cemented (calcrete or dorbank) hardpans and significantly more clayey (cutanic, luvic) horizons result in the buildup of an aquifer. The water repellent surface horizon can also serve as a medium to insulate water through breaking the upward movement of capillary water. This can be an important mechanism of natural water conservation in such an arid environment. Nocturnal radiative cooling of the soil surface and subsequent subsurface dew formation can be an indirect method for utilisation of the deeper aquifer by the shallow-rooted vegetation.

Variation of pedological features can be seen as an important contributor to vegetation diversity. De Villiers (2000) points out environmental characteristics specific to vegetation communities through positioning plant communities on an ordination diagram. Gradients on this diagram relate to grass cover, soil colour, salt spray, sand depth and fog intensity. Significant chemical, physical and morphological differences that exist within the solum of the study area can be important determinants of ecological processes that maintain the remarkable diversity of flora in these vegetation communities.

6.2 IMPACT OF MINING ON THE SOIL MANTLE

Mining results in irreversible loss of pedosphere heterogeneity. Heuweltjies, small dune systems, and variation in depth of cemented hardpans and significantly more clayey (cutanic, luvic) horizons are the main features that contribute to pedosphere variation. More studies are still needed to determine the role that spacial variation in soil properties plays in maintaining the unique diversity of flora in this region.

Figure 6.1 summarizes the impact of mining on the soil mantle and suggests possible remedies. Loss of a water infiltration barrier in the Graauwduinen West mine, due to the removal of the dorbank layers, is the main impact that mining has on the soil of this region. It is not possible to quantify the impact that this would have on ecosystem functioning, considering the variation of the dorbank horizon alone. The effect of a water barrier is likely to be considerable, however, in the context of the soil water model as described in chapter 5. Further studies are necessary to determine to what extent the depth of water infiltration influences the capacity of subsurface dew to provide plants with a nocturnal water source. Other impacts include the alteration of surface water repellency, loss of microtopography, lowering of soil organic carbon content, and lowering of silt and clay content.

The mining process in Graauwduinen East results in the removal of sand up to depths of between 1 and 5 m. The dorbank layer and the overlying neocutanic horizon are not excavated in the Graauwduinen East region. Impacts on the pedosphere in this region are likely to include the loss of surface water repellency in areas that did not receive topsoil treatment, loss of microtopography and soil variation induced by dunes and heuweltjies, lowering of soil organic carbon content, and lowering of silt and clay content.

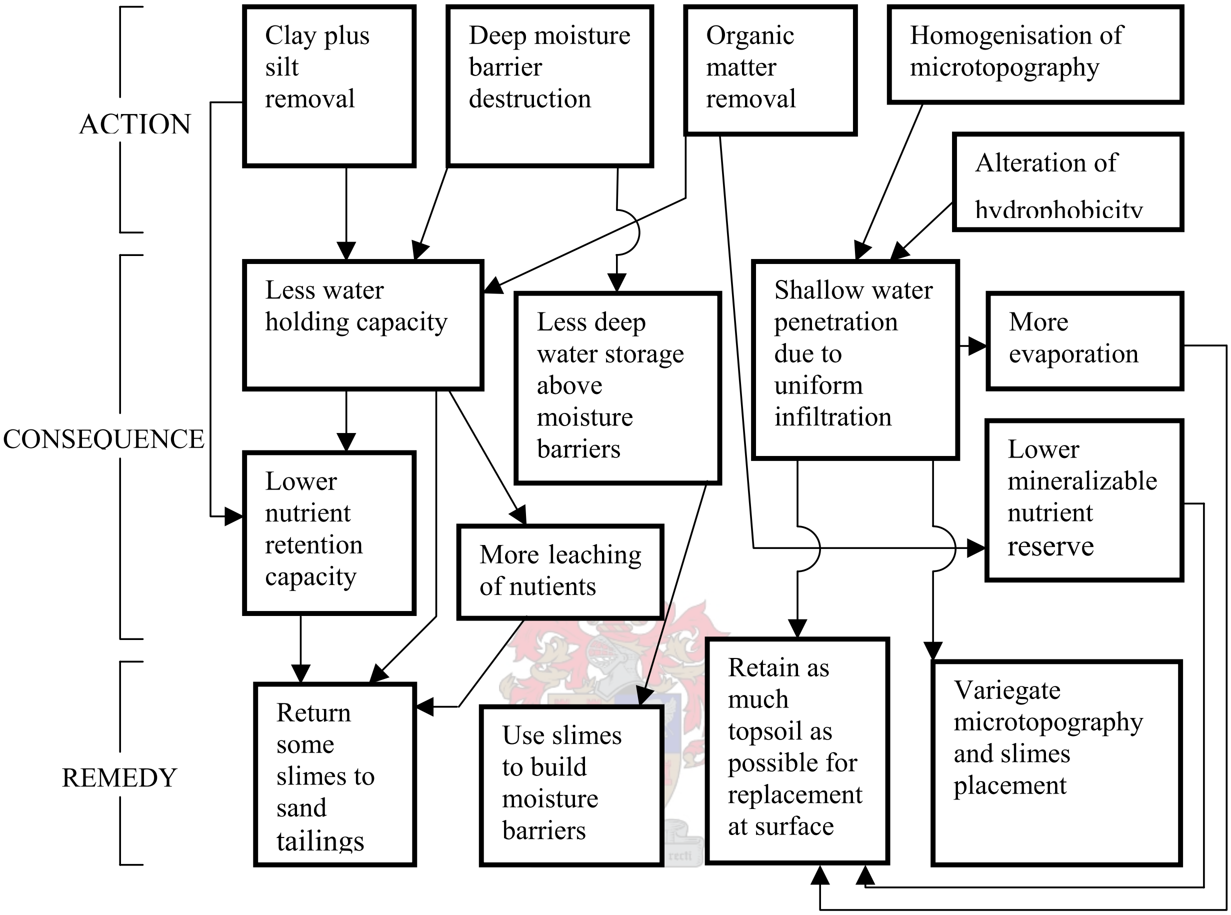


Figure 6.1: Schematic summary of the consequences of mining activities and a suite of proposed remedies that would maximize the opportunity for sustainable rehabilitation.

6.3 RECOMMENDATIONS FOR FUTURE REHABILITATION

No rehabilitation strategy is likely to restore the unique pattern of soil property variation. The trick would be to discover what soil properties are essential in the functioning of this ecosystem and to devise methods to simulate these in the rehabilitation process (Fig 6.1)

Due to the total removal of the dorbank in the Graauwduinen West mine, this region holds the biggest challenges for rehabilitation. Studies by Palta et al. (1972) and Saxena et al.

(1971) evaluated the in situ placement of a continuous asphalt barrier as a technique to reduce deep percolation of water in sandy soils. The placement of this barrier significantly increased water storage resulting in increased crop yields. The value of such techniques to reduce deep percolation of water in this region should not be overlooked. Slimes, as a substitute for asphalt, could be used to build moisture barriers. The possibility of using such a strategy should be evaluated.

Results indicated that hydrophobic soil is present in the areas that received topsoil treatment. It is still uncertain whether this hydrophobicity is sufficient to induce fingered infiltration. Even infiltration in the rehabilitated region could limit rehabilitation success. Further studies should identify the amount of topsoil replacement on the surface needed to induce preferential infiltration.

Removal of organic matter, silt and clay could also seriously impact on the success of the restoration process. Slimes can be incorporated into sand tailings and as much as possible topsoil should be retained for replacement at the surface. The restoration process should also strive to variegate microtopography and depth of slimes placement in order to mimic the natural variation.

While none of these strategies is likely to perfectly simulate the diversity of soil properties that existed prior to mining, when applied in combination they might be expected to significantly enhance the possibility of sustainable revegetation when compared with current practices which destroy potentially critical subsurface features, remove the fine colloidal matter that is essential for the storage of nutrients and water, and which to a large extent homogenise both the regolith and the landscape. This study has demonstrated that such strategies make sense in principle. Their economic viability remains to be tested.

REFERENCES

ABU-SHARAR, T.M. & SALAMEH, A.S. 1995. Reductions in hydraulic conductivity and infiltration rate in relation to aggregate stability and irrigation water turbidity. Agric Water Manag. 29. 53-62.

ACOCKS, J.P.H. 1988. Veld types of South Africa. 3rd edn. Memoirs of the botanical survey of South Africa, 57. 1-146.

AGASSI, M., SHAINBERG, I. & MORIN, J. 1981. Effect of electrolyte concentration and soil sodicity on the infiltration rate and crust formation. Soil Sci. Soc. Am. J. 45. 848-51.

BAILEY, H.P. 1981. Climatic features of deserts. In: Evans, D.D. & Thames, J.L. (eds) Water in desert ecosystems. Dowden, Hutchinson & Ross, Inc. Stroudsburg, Pennsylvania.

BELNAP, J. 2002. Nitrogen fixation in biological soil crusts from southeast Utah, USA. Biol Fertil Soils. 35. 128 – 155.

BERNDTSSON, R., NODOMI, K., YASUDA, H., PERSSON, T., CHEN, H. & JINNO, K. 1996. Soil water and temperature patterns in an arid desert dune sand. J. Hydr. 185:. 221-40

BEZONA, N., HENSLEY D., YOGI, J., TAVARES, J., RAUCH, B F., IWATA, R., KELLISON, M. & WONG, M. 1996. Salt and wind tolerance of landscape plants for Hawaii. Instant Information Series No. 19. Cooperative Extension Service. College of tropical agriculture and human resources, University of Hawaii in Manoa.

BLACK, H.I.J. & OLWAKOL, M.J.N. 1997. Agricultural intensification, soil biodiversity and agro ecosystem function in the tropics: the role of termites. Applied soil ecology. 6. 37-53.

BLUME, H.P., PERKINS, H.F. & HUBBARD, R.Y. 1987. Subsurface water movement in an upland coastal plain soil as influenced by plinthite. Soil Science Society of American Journal. 51. 774-9.

BOND, R.D. & HARRIS, J.R. 1964. The influence of the microflora on physical properties of soils. I. Effects associated with filamentous algae and fungi. Aust. J. Res. 2. 111-22.

BOND, R.D. 1964. The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. Aust. J. Soil Res. 2.123-31.

BOUCHER, C. & LE ROUX, A. 1989. Heavy minerals sand mining project assessment vegetation report. In: Environmental Evaluation Unit: Anglo American Corporation: West Coast heavy mineral sand project Supplementary report. Unpublished report, University of Cape Town, Cape Town.

BOWIE, M.R. 1999. Ecophysiological studies on four selected Succulent Karoo species. PhD thesis. Department of Botany. University of Stellenbosch, Stellenbosch.

BRADSHAW, A.D. 1983. The reconstruction of ecosystems. Presidential address to the British Ecological Society, December 1982. J. App. Ecol. 20. 1-17.

BRADSHAW, A.D. 1984. Ecological principles and land reclamation practice. Landsc. Plan. 11. 35-48.

BRADY, N.C. & WEIL, R.R. 1996. The nature and properties of soil. New Jersey: Prentice-Hall International, Inc.

BROMLEY, J., BROUWER, J., BARKER, A.P., GAZE, S.R. & VALENTIN, C. 1997. The role of surface water redistribution in an arid area of patterned vegetation in semi-arid environment, south-west Niger. J. Hydrl. 198. 1-29.

BUOL, S.W., HOLE, F.D., MCCRACKEN, R.J., & SOUTHARD, R.J. 1997. Soil Genesis and Classification, 4th edn. Iowa State University Press.

CALDWELL, M.M. & RICHARDS, J.H. 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia. 79. 1-5.

CALDWELL, M.M., DAWSON, T.E. & RICHARDS, J.H. 1998. Hydraulic lift: consequences of water efflux from the roots of plants. Oecologia. 113. 151-61.

CAMPBELL, G.S. & HARRIS, G.A. 1981. Modelling Soil-Water-Plant-Atmosphere Systems of Deserts. In: Evans, D.D. & Thames, J.L. (eds) Water in desert ecosystems. Dowden, Hutchinson & Ross, Inc. Stroudsburg, Pennsylvania.

CANTÓN, Y., SOLÉ-BENET, A. & DOMINGO, F. 2003. Temporal and spatial patterns of soil moisture in semiarid badlands of SE Spain. J. Hydr. Article in press.

COLEMAN, D.C. & CROSSLEY, D.A.(JR). 1996. Fundamentals of Soil Ecology. Academic Press, Inc. San Diego, California.

COWLING, R.M., ESLER, K.J. & RUNDELL, P.W. 1994. Plant functional diversity, species diversity and climate in arid and semi-arid southern Africa. Journal of Arid Environments. 27. 141-58.

COWLING, R.M., ESLER, K.J. & RUNDEL, P.W.1999. Namaqualand, South Africa - an overview of a unique winter-rainfall desert ecosystem. Plant. Ecol. 142. 3-21.

DANIELS, R.B., GAMBLE, E.E. & NELSON, L.A. 1967. Relation between A horizon characteristics and drainage in some fine Ultisols. Soil Science. 104. 364-9.

DE ROOIJ, G.H. 2000. Modelling fingered flow of water in soils owing to wetting front instability: a review. Journal of Hydrology: 231-32. 277-94.

DEBANO, L.F. 2000. Water repellency in soils: a historical overview. J. Hydr. 231-2. 4-32.

DELTA-T DEVICES. 1995. ThetaProbe soil moisture sensor. Cambridge, UK.

DENG , Y. & DIXON, J.B. 2002. Soil organic matter and organic-mineral interactions. In: Amonette, J.E., Bleam, W.F., Schulze, D.G. & Chair, J.B.D. (eds). Soil mineralogy with environmental applications. SSSA, Madison, Wisconsin, USA.

DESMET, P.G. & COWLING R.M. 1999. The climate of the Karoo-a functional approach. In: Dean, W.R.J. & Milton, S.J. (eds): The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom.

DE VILLIERS, A.J. 1999. Vegetation Diversity of the Brand-se-Baai Coastal Dune Area, Wet Coast, South Africa: A Pre-mining Benchmark Survey for Rehabilitation. Land Degradation & Development. 10.207-24.

DE VILLIERS, A.J. 2000. Seed bank dynamics of the Strandveld Succulent Karoo. PhD thesis. Department of Botany. University of Pretoria, Pretoria.

DE VILLIERS, A.J., VAN ROOYEN, M.W., THERON, G.K. & VAN ROOYEN, N. 1999. Vegetation diversity of the Brand-se-Baai coastal dune area, West Coast, South Africa: a pre-mining benchmark survey for rehabilitation. Land Degrad. Dev. 10. 207-44.

DEVITT, D.A. & SMITH, S.D. 2002. Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem. J. Arid. Envir. 50. 99-108.

DONNER, H.E. & GROSSL, P.R. 2002. Carbonates and Evaporates. In: Amonette, J.E., Bleam, W.F., Schulze, D.G. & Chair, J.B.D. (eds). Soil mineralogy with environmental applications. SSSA, Madison, Wisconsin, USA.

DUNN DE ARAUJO, D.S. The vegetation and flora of the Cabo Frio Region. Biology InstituteUFRJ. http: // www. reservataua. Com .br / Vegetacao_Flora_Cabo_Frio_in. htm

ECCLES, N.S. 2000. Plant ecology of the Namaqualand Strandveld: Community structure and dynamics in a winter-rainfall desert. PhD thesis. University of Cape Town.

EHLERINGER, J.R. & COOK, C.S. 1987. Leaf hairs in Encelia (Asteraceae). Am J Bot. 74, 1532-40.

ELDRIDGE, D.J. & GREENE, R.S.B. 1994. Microbiotic soil crust: a view of their roles in soil and ecological processes in the rangelands of Australia. Aust J Soil Res. 32. 389 – 415.

ELLIS, F. 1988. Die gronde van die Karoo. PhD thesis. University of Stellenbosch, Stellenbosch.

ELLIS, F. 2002. Contribution of termites to the formation of hardpans in soil of arid and semi-arid regions of South Africa. Paper no. 572 of oral presentation. 17th WCSS 14-21 August 2002, Thailand.

ENVIRONMENT EVALUATION UNIT. 1990. Anglo American Corporation: West Coast heavy mineral sands project. Unpublished report, University of Cape Town.

ESLER, K.J. & RUNDEL, P.W. 1999. Comparative patterns of phenology and growth phonology and growth form diversity in two winter rainfall deserts: the Succulent Karoo and Mojave Desert ecosystems. Plant Ecology. 142. 97-104.

ESLER, K.J., RUNDELL, P.W. & COWLING, R.M. 1999. The Succulent Karoo in a global context: plant structural and functional comparison with North American winter-rainfall deserts. In: Dean, W.R.J. & Milton, S.J. (eds): The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom. 303-13.

EVANS, D.D. & THAMES, J.L. 1981. Desert Hydrologic Systems. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Water in desert ecosystems. Academic Press, Dowden, Hutchinson & Ross Inc. Stroudsburg, Pennsylvania.

FAO 2001. World reference base for soil resources. International Society of Soil Science (ISSS), International Soil Reference and Information Centre (ISRIC) and Food and Agriculture Organization of the United Nations (FAO), Rome.

FELIX-HENNINGSEN, P. 2000. Paleosols on Pleistocene dunes as indicators of paleo-monsoon events in the Sahara of East Niger. Catena. 41. 43-60.

FEY, M.V., O'BRIEN, R.D., MILLS, A.J. 2002. Rehabilitation of waste rock and overburden dumps. Encyclopaedia of Soil Science. Marcel Dekker, Inc. 1115-7.

FOGEL, M.M. 1981. Precipitation in the Desert. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Dowden, Hutchinson & Ross, Inc. Stroudsburg, Pennsylvania.

FOHRER, N., BERKENHAGEN, J., HECKER, J. & RUDOLPH, A. 1999. Changing soil and surface conditions during rainfall Single rainstorm/subsequent rainstorms. Catena. 37. 355-75.

FRANCO, C.M.M., TATE, M.E. & OADES, J.M. 1995. Studies on non-wetting sands. I. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands. Australian Journal of Soil Research. 33. 253-63.

GAY, L.W. 1981. Potential evapotranspiration for Deserts. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Dowden, Hutchinson & Ross, Inc. Stroudsburg, Pennsylvania.

GAZE, S.R., SIMMONDS, L.P., BROUWER, J. & BOUMA, J. 1997. Measurement of surface redistribution of rainfall and modelling its effect on water balance calculations for a millet field on sandy soil in Niger. J. Hydr. 188-9. 267-84

GIBSON, A.C. 1996. Structure-function relations of warm desert plants. In: Adaptations of desert organisms. Cloudsley-Thompson, J.L. (eds). Springer-Verlag, Berlin, Heidelberg.

GRAETZ, R.D. & TONGWAY, D.J. 1986. Influence of grazing management on vegetation, soil structure and nutrient distribution and the infiltration of applied rainfall in a semi arid chenopod shrubland. Australian J. of Ecology 11:347-360.

GRANTZ, D.A. 1990. Plant response to atmospheric humidity. Plant Cell Environ. 13. 667-79.

HAGENMEYER, J. 1997. Salt. In: Prasad, M.N.V. (ed.). Plant Ecophysiology. John Wiley & Sons, Inc. New York.

HANKS, R.J. & WOODRUFF, N.P. 1958. Influence of wind on water vapour transfer through soil, gravel and straw mulches. Soil. Sci. 86. 160-4.

HANKS, R.J., BOWERS, S.A. & BARK, L.D. 1960. Influence of soil surface conditions on net radiation, soil temperature, and evaporation. Soil. Sci. 91. 233-8.

HARRIS, G.A. & CAMPBELL, G.S. 1981. Morphological and physiological characteristics of desert plants. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Academic Press, Dowden, Hutchinson & Ross Inc. Stroudsburg, Pennsylvania.

HEKMAN, L.H. (Jr.), & BERKAS, W.R. 1981. Modelling desert runoff. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Academic Press, Dowden, Hutchinson & Ross Inc. Stroudsburg, Pennsylvania.

HILLEL, D. 1998. Environmental soil physics. Academic Press, New York

HOWES, D.A. &. ABRAHAMS, A.D. 2003. Modelling runoff and runon in a desert shrubland ecosystem, Jornada Basin, New Mexico. Geomorphology 53. 45-73.

JARAMILLO, D.F., DEKKER, L.W. , RITSEMA, C.J. & HENDRICK, J.M.H. 2000. Occurrence of soil water repellency in arid and humid climates. Journal of Hydrology. 105-11. 231-2.

JÜRGENS, N., GOTZMANN, I.H. & COWLING, R.M. 1999. Remarkable medium-term dynamics of leaf succulent Mesembryanthemaceae shrubs in the winter-rainfall desert of northwestern Namaqualand, South Africa. Plant. Ecol. 142, 87-96.

JURY, W.A., LETEY, J. (Jr.) & STOLZY, L.H. 1981. Flow of water and energy under desert conditions. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Academic Press, Dowden, Hutchinson & Ross Inc. Stroudsburg, Pennsylvania.

KAWAMOTO, M., MASHINO, S., ODA, M. & MIYAZAKI, T. 2003. Moisture structures of laterally expanding fingering flows in sandy soils Geoderma, In Press, Corrected Proof.

KENT, M. & COKER, P. 1996. The nature of quantitative plant ecology and vegetation science. 1-22. In: KENT, M. & COKER, P. (eds) Vegetation description and analysis: A practical approach. John Wiley & Sons Inc. Canada.

KING, P.M. 1981. Comparison of methods for measuring the severity of water-repellency of sandy soil and assessment of some factors that affect its measurement. Australian Journal of Soil Research. 19. 275-85.

KOSMAS, C., DANALATOS, N.G., POESEN, J. & VAN WESEMAEL, B. 1998. The effect of water vapour adsorption on soil water content under Mediterranean climatic conditions. Agric. Water Mgmt. 36. 157-68.

KRISHNAIAH, S. & SINGH, D.N. 2003. A methodology to determine soil moisture movement due to thermal gradients. Exp. Therm. Fluid. Sci. 27. 715-25.

LANZ, J. 2003. Specialist study on the impact of the Namakwa Sands mining operation on soil conditions with emphasis on the effect on re-vegetation. Final report.

LE BISSONNAIS, Y. & SINGER, M.J. 1992. Crusting, runoff, and erosion response to soil water content and successive rainfalls. Soil Sci. Soc. Am. J. 56. 1898-903.

LE ROUX, P.A.L. 1996. Die aard, verspreiding en genese van geselekteerde redoksmorfe gronde in Suid Afrika. PhD thesis. University of the Orange Free State, Bloemfontein.

LI, X.-R., WANG, X.-P., LI, T. & ZHANG, J.-G. 2002. Microbiotic soil crust and its effect on vegetation and habitat on artificially stabilized desert dunes in Tengger desert, north China. Biol Fertil Soils. 35. 147 – 154.

LOW, A.B., & REBELO, A.G. 1996. Vegetation of South Africa, Lesotho and Swaziland. Department of Environmental Affairs & Tourism, Pretoria.

LUBKE, R.A. & AVIS, A.M. 1998. A review of the concepts and application of rehabilitation following heavy mineral dune mining. Mar. Poll. Bull. 37. 546?57.

LUDWIG, J.A., TONGWAY, D.J. & MARSDEN, S.G. 1999. Stripes, stands or stipples: modelling the influence of three landscape banding patterns on resource capture and productivity in semi-arid woodlands, Australia. Catena. 37.257-73.

MAHOOD, K. 2003. Strip mining rehabilitation by translocation in arid coastal Namaqualand, South Africa. Unpublished MSc thesis. University of Stellenbosch, Stellenbosch.

MANDO, A. & MIEDEMA, R. 1997. Termite-induced changes in soil structure after mulching degraded (crusted) soil in Sahel. App. Soil Ecol. 6. 241-249.

MARTINEZ-MEZA, E. & WITHFORD, W.G. 1999. Stemflow, throughfall and canalisation of stemflow by roots in three Chihuahuan desert shrugs. J. Arid. Envir. 32. 271-87.

MCINTYRE, D.S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Science. 85. 185-9.

MEHRA, O.P. & JACKSON, M.L. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium carbonate. Clays & Clay Minerals 7. 317-27.

MELLOULI, H.J., HARTMANN, R., GABRIELS, D. & CORNELIS, W.M. 1998. The use of olive mill effluents 'margines' as soil conditioner mulch to reduce evaporation losses, Soil and Tillage Research. 49. 85-91.

MELLOULI, H.J., VAN WESEMAEL, B., POESEN, J. & HARTMANN, R. 2000. Evaporation losses from bare soils as influenced by cultivation techniques in semi arid-regions Agricultural Water Management. 42. 355-69.

MIDGLEY, G.F. & VAN DER HEYDEN, F. 1999. Form and function in perennial plants. In: Dean, W.R.J. & Milton, S.J. (eds): The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom.

MILTON, S.J. 2001. Rethinking ecological rehabilitation in arid and winter rainfall regions of southern Africa. S. Afr. J. Sci. 97. Meeting report.

MILTON, S.J. & DEAN, W.R.J. 1999. The Karoo: past and future. In: Dean, W.R.J. & Milton, S.J. (eds). The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom.

MULROY, T.W. 1997. Spectral properties of heavily glaucous and non-glaucous leaves of a succulent rosette-plant. Oecologia. 38. 349-57.

NAMAKWA FOOTPRINT. 2002. Report on safety, health, environment, quality, sustainable development and community engagement.

PALMER, A.R., NOVELLIE, P.A. & LLOYD, J.W. 1999. Community patterns and dynamics. In: Dean, W.R.J. & Milton, S.J. (eds): The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom.

PALTA, J.P., BLAKE, G.R. & FARREL, D.A. 1972. Water transmission properties of an Asphalt Barrier. Soil Sci. Soc. Amer. Proc. 36. 709 – 714.

PARSONS, A.J., ABRAHAMS, A.D. & SIMANTON, J.R. 1992. Microtopography and soil-surface materials on semi-arid hillslopes, southern Arizona. Journal of Arid Environments. 22. 107-15.

PRENTICE, I.C. & WERGER, M.J.A. 1985. Clump spacing in a dwarf desert shrub community. Vegetatio. 63. 133-139.

PYKE, D.A. & ARCHER, S. 1991. Plant-plant interactions affecting plant establishment and persistence on revegetated rangeland. J. Range. Manage. 44(6). 550-7.

RAO, K.P.C., STEENHUIS, T.S., COGLEC, A.L., SRINIVASAN, S.T., YULE, D.F. & SMITH, G.D. 1998. Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. I. No-till systems. Soil & Till. Res. 48. 51-9.

RIDOLFI, L., ODORICO, P.D., PORPORATO, A. & RODRIGUEZ-ITURBE, I. 2003. Stochastic soil moisture dynamics along a hillslope. J. Hydr. 272. 264-75.

RITSEMA, C.J., DEKKER, L.W. & HEIJS, A.W.J. 1997. Three-dimensional fingered flow patterns in a water repellent sandy field soil. Soil Science. 162(2). 79-90.

RUNDEL, P.W., ESLER, K.J. & MIDGLEY, G.F. 1998. The ecophysiological significance of Mesembryanthemaceae growth forms and demography. Aloe. 35(2). 35-48.

SALISBURY, F.B., & ROSS, C.W. 1992. Plant Physiology. 4th edn., Wadsworth, California.

SAXENA, G.K. HAMMOND, L.C. & LUNDY, H.W. 1971. Effect of an asphalt barrier on soil salinity and yields and water use by tomato and cabbage. K. Amer. Soc. Hort. Sci. 96. 218 – 222:

SCHULTEN, J.A. 1985. Soil aggregation by cryptogams of a sand prairie. Am. J. Bot. 72. 1657 – 1661.

SCHULZE, D.G. 2002. An introduction to soil mineralogy. In: Amonette, J.E., Bleam, W.F., Schulze, D.G. & Chair, J.B.D. (eds). Soil mineralogy with environmental applications. SSSA, Madison, Wisconsin, USA.

SCHULZE, E-D., LANGE, O.L., EVENARI, M., KAPPEN, L. & BUSCHBOM, U. 1974. The role of air humidity and leaf temperature in controlling stomatal resistance of *Prunus armeniaca* L. under desert conditions. I. A simulation of the daily course of stomatal resistance. Oecologia. 17, 159-70.

SENECA, E.D. 1972. Effect of soil and sodicity on seedling growth and mineral composition of *Pongamia pinnata* and *Araucaria cunningamii*. Trop. Ecol. 31. 124-30.

SEYFRIED, M.S. 1991. Infiltration patterns from simulated rainfall on a semiarid soil. Soil Sci. Soc. Am. J. 55(6).1726-1734.

SMITH, R.A. & DOWDELL, R.J. 1974. Field studies of the soil atmosphere. I. Relationships between ethylene, oxygen, soil moisture content and soil temperature. J. Soil Science. 25. 217-30.

SOIL CLASSIFICATION WORKING GROUP. 1991. Soil Classification: A Taxonomic System for South Africa. Mem. Natural Agric. Resources for S.A. No. 15.

SOIL SURVEY STAFF. 1992. Keys to Soil Taxonomy, 5th edn. Pocahontas Press Inc., Blacksburg, Virginia.

SPARKS, D.L. 2003. Environmental soil chemistry. Elsevier Science, USA.

STATSOFT INCORPORATED. 2002. STATISTICA Version 6.0.

TAN, K.H. 1994. Environmental Soil Science. Marcel Dekker, Inc., New York.

THAMES, J.L. & EVANS, D.D. 1981. Desert systems: An overview. In: Evans, D.D. & Thames, J.L. (eds). Water in desert ecosystems. Academic Press, Dowden, Hutchinson & Ross Inc. Stroudsburg, Pennsylvania.

TYLER MILLER, G. (Jr). 2004. Living in the environment. 13th edn. Thomson Learning, Inc.

VAN DAM, J.C., WÖSTEN, J.H.M & NEMES, A. 1996. Unsaturated soil water movement in hysteretic and water repellent field soils. J. Hydr. 184. 153-73.

VAN DER WATT, H.V.H. & VAN ROOYEN, T.H. 1995. A Glossary of Soil Science. 2nd edn. The Soil Science Society of South Africa. Pretoria.

VAN JAARSVELD, E. 1987. The succulent riches of South Africa and Namibia. Aloe. 24. 45-92.

VAN OMMEN, H.C., DEKKER, L.W., DIJKSMA, R., HULSHOF, J. & VAN DER MOLEN, W.H. 1988. A new technique for evaluating the presence of preferential flow paths in nonstructured soil. Soil Science Soc. Am. J. 52. 1192-3.

VAN ROOYEN, S. 2001. A study of the vegetation pattern (degree of clumping clump size, interclump distance) and composition of clumps of the undamaged vegetation of the proposed mining area at Namakwa Sands, near Lutzville. Unpublished student assignment, Department of Conservation Ecology. University of Stellenbosch, Stellenbosch.

WALDEN, J. & WHITE, K. 1997. Investigation on the controls of dune colour in the Namib Sand Sea using mineral magnetic analysis. Earth Plan. Sc. L. 152. 187-201.

WAN, C., SOSEBEE, R.E. & McMICHAEL, B.L. 1993. Does hydraulic lift exist in shallow-rooted species? A quantitative examination with a half-shrub *Guiterrezia sarothrae*. Plant Soil. 153: 11-7.

WANG, Z., TULI, A. & JURY, W.A. 2003. Unstable flow during redistribution in homogeneous soil. Vad. Zone. 2. 52-60.

WASHER, N.E. & COLLINS, M.E. 1988. Genesis of adjacent morphologically distinct soil in Northwest Florida. Soil Science Soc. Am. J. 52. 191-6.

WATKEYS, M.K. 1999. Soils of the arid south-western zone of Africa. In: Dean W.R.J. and Milton, S.J. (eds): The Karoo: Ecological Patterns and Processes. Cambridge University Press, Cambridge, United Kingdom.

WELLS, J.D., VAN MEURS, L.H. & RABIE, M.A. 2000. Terrestrial minerals. In: Fuggle, R.F. & Rabie, M.A. (eds): Environmental management in South Africa. Juta & Co, Ltd. South Africa.

WILLIAMS, J.D., DOBROWOLSKI, J.P. & WEST, N.E. 1999. Microbiotic crust influence on unsaturated hydraulic conductivity. Arid Soil Res. 13. 145 – 154.

WHITE, R.E. 1997. Principles and practice of soil science: The soil as a natural resource. Cambridge: Cambridge University Press.

WHITE, R.E. 2003. Soils for fine wine. New York, Oxford University Press.

ZHENGHUA, D., HONGLANGB, X., XINRONGB, L., ZHIBAOB, D. & GANGC, W. 2003. Evolution of soil properties on stabilized sands in the Tengger Desert, China. Geomorphology. In press.

APPENDICES

APPENDIX 1 (Explanations for abbreviations in appendix 2; table 3.4)

Table 1: Abbreviated description of 20 soil profile pits of the study area

Vegetation community	Profile no.	Depth codes	Form & Family	Subsoil limitations/properties					Topsoil		
				Upper	Middle	Lower 1	Lower 2	Coarse	Coarse	Sand	Clay
1A	1	2468	Pn2100		gs	ne+db	so	1fc	1fc	fi	1
1A	2	2567	Pn2100		gs	ne+db	so	1fc	1fc	fi	1
1A	3	20	Cv2100					1fc	1fc	fi	1
										fi	1
1B	4	12568	Ou2210			db	so	1fc	1fc	fi	1
1B	5	2689	Bd2100		gs	ne+db	db	1fc	1fc	fi	1
1B	6	13678	Ou2210			db	so	1fc	1fc	fi	1
1B	7	14790	Bd2100		gs	ne	db	1fc	1fc	fi	1
1B	8	2689	Bd2100		gs	ne	db	1fc	1fc	fi	1
										fi	1
2	9	26 6/7 7/8	Bd2100		gs	ne	db	1fc	1fc	fi	1
2	10	289	Bd2100		gs	ne	db	1fc	1fc	fi	1
2	11	3890	Bd2100		gs	ne	db	1fc	1fc	fi	1
										fi	1
3	12	269	Pn2100		gs					fi	1
3	13	13	Ou2110					9fa	2fa	fi	2
3	14	37	Pn2100		gs			9fa	2fa	fi	1
										fi	1
4	15	3678	Bd2100		gs	ne	sk			fi	1
4	16	2789	Bd2100		gs	ne				fi	1
										fi	1
5	17	4799	Gr1000			dn	sk			fi	1
5	18	380	Tu1110		gc	hk	sk	2gsh	1gsh	fi	1
5	19	280	Gr1000			dn	db	1fc	1fc	fi	1
										fi	1
6	20	370	Nb1000	U5						fi	1

Table 2: The silt plus clay content of selected soil samples

Vegetation community	Profile	Master horizon	Horizon/ material	% Silt + clay
1A	1	A	ot	5.2
1A	1	B1	ye	4.0
1A	1	B2	gs	3.4
1A	1	B3	neII	20.9
1A	2	A	ot	5.3
1A	2	B1	ye	4.3
1A	2	B2	gs	3.3
1B	7	A	ot	2.7
1B	7	B1	re	2.2
1B	7	B2	re	2.4
1B	7	B3	gs	3.0
2	10	A	ot	2.5
2	10	B1	re	1.8
2	10	B2	gs	2.3
2	10	B3	neII	9.6
3	12	A	ot	2.2
3	12	B1	ye	2.3
3	12	B2	ye	2.8
3	12	B3	gs	1.5
3	13	A	ot	6.2
3	13	B1	neI	6.0
5	18	A	ot	7.5
5	18	B1	neI	8.7
5	18	B1	neI	15.3
5	18	B3	gc	16.4
5	19	B1	re	2.7
6	20	A	ot	0.1
6	20	B1	rs	0.4
6	20	B2	rs	0.2
6	20	B3	rs	1.2
6	20	B4	rs	0.9
EM		B1	ye	1.5
EM		B2	ye	1.3
EM		B3	ye	1.4
EM		B4	gs	1.1
EM		B5	gs	0.6
EM		N	N	5.4
EM		B6	gs	3.8
EM		N	N	5.9
EM		B7	neII	16.7
EM		B8	neII	19.2

N	Mean	Geometric mean	Standard deviation	Minimum	Maximum
41	5.0	2.9	5.3	0.1	20.9

Table 3: The organic carbon content of selected soil samples

Vegetation community	Profile number	Master horizon	Horizon/ material	% Organic carbon
1A	1	A	ot	0.23
1A	1	B1	ye	0.14
1B	6	A	ot	0.32
1B	6	B1	neI	0.22
2	9	A	ot	0.21
2	9	B1	re	0.11
3	12	A	ot	0.29
3	12	B1	ye	0.28
4	15	A	ot	0.35
4	15	B1	re	0.097
6	20	A	ot	0.42
6	20	B1	rs	0.56
5	18	A	ot	0.29

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
13	0.3	0.1	0.2	0.1	0.6

Table 4: CBD extractable iron content of selected samples

Vegetation community	Profile number	Master horizon	Horizon/ material	Fe (g.kg^{-1})	Fe / clay+silt
1A	1	B1	ye	4.3	0.108
1A	1	B2	gs	3.2	0.094
1A	1	B3	neII	7.0	0.033
1B	4	B1	neI	3.7	nd
1B	4	B2	neI	3.6	nd
1B	7	A	ot	3.6	0.133
1B	7	B1	re	3.1	0.141
1B	7	B2	re	3.4	0.142
1B	7	B3	gs	3.5	0.117
2	10	B1	re	3.2	0.178
2	10	B2	gs	3.5	0.152
2	10	B3	neII	5.0	0.052
3	12	B2	ye	3.1	0.111
3	12	C	gs	1.9	0.127
4	16	B1	re	5.0	nd
4	16	B2	gs	5.5	nd
4	16	B3	neII	8.8	0.101
5	19	A	ot	4.6	0.030
5	19	B1	re	5.1	0.031
5	19	B2	re	5.8	0.215

	N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
(g.kg^{-1})	20	4.3	1.6	4.1	1.9	8.8
Fe / clay+silt	16	0.11	0.05	0.09	0.03	0.21

Table 5: Organic carbon content of selected soil samples

Vegetation community	Profile number	% Organic carbon	
		Master horizon	
		A	B1/C
1A	1	0.23	0.14
1B	6	0.32	0.22
2	9	0.21	0.11
3	12	0.29	0.28
4	15	0.35	0.10
5	18	0.29	nd

	Mean	Standard deviation	Geometric mean	Minimum	Maximum
A	0.28	0.05	0.28	0.21	0.32
B1	0.17	0.08	0.16	0.10	0.28

Table 6: Bulk density of selected soil samples

Vegetation community	Profile number	Horizon/ material	Bulk density (g.cm^{-3})
1B	3	ye	1.8
3	12	ye	1.5
3	12	ye	1.5
3	14	ye	1.7
3	14	ye	1.6
EM		ye	1.6
EM		ye	1.7
EM		ye	1.7
2	9	re	1.6
2	10	re	1.5
2	11	re	1.5
5	17	re	1.7
5	17	re	1.7
5	19	re	1.6
5	19	re	1.5

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
15	1.6	0.1	1.6	1.5	1.8

Table 7: Silt plus clay content of apedal horizons

Vegetation community	Profile number	Horizon/ material	% Silt + Clay
1A	1	ye	4.0
1A	2	ye	4.3
3	12	ye	2.3
3	12	ye	2.8
EM		ye	1.5
EM		ye	1.3
EM		ye	1.4
1B	7	re	2.2
1B	7	re	2.4
2	10	re	1.8
5	19	re	2.7

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
15	2.4	1.0	2.2	1.3	4.3

Table 8: CBD extractable iron oxide of apedal horizons

Vegetation community	Profile number	Horizon/ material	Fe*(g.kg^{-1-})
1B	3	re	3.1
1B	4	re	3.4
2	10	re	3.2
4	16	re	5.0
5	19	re	5.1
5	19	re	5.8
1A	1	ye	4.3
3	12	ye	3.1

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
15	4.1	1.1	4.0	3.1	5.8

Table 9: Silt plus clay content of ne-I horizons

Vegetation community	Profile number	Horizon/ material	% Silt + clay
1B	6	neI	6.0
1B	6	neI	9.4
1B	3	neI	6.2
4	16	neI	6.0
5	18	neI	8.7
5	18	neI	15.3

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
6	8.6	3.6	8.1	6	15.3

Table 10: Silt plus clay content of ne-II horizons

Vegetation community	Profile no.	Horizon	% Silt + Clay
1A	1	neII	20.9
2	10	neII	9.6
EM		neII	16.7
EM		neII	19.2

N	Mean	Standard deviation	Geometric mean	Minimum	Maximum
4	16.6	5.0	15.9	9.6	20.9

Table 11: Silt plus clay content of apedal horizons

Vegetation community	Profile number.	Horizon/ material	% Clay + silt content	
			Master horizon	
			B	C1
1A	1	ye	4.0	3.4
1A	2	ye	4.3	3.3
2	10	re	1.6	1.4
3	12	ye	2.8	1.5

Table 12: CBD extractable iron oxide of apedal horizons

Vegetation community	Profile no.	Horizon	Fe (g.kg^{-1})	
			Master horizon	
			B	C1
1A	1	ye	4.3	3.2
1B	7	re	3.4	3.5
2	10	re	3.2	3.5
3	11	ye	3.1	1.9
4	15	re	5.0	5.5

APPENDIX 2

CLASSES AND SYMBOLS FOR SOIL PROPERTIES

Horizon and/or effective depths

The depths of diagnostic and non-diagnostic horizons and/or materials are coded with a number symbol in front of the soil form symbol. Depth classes ~d symbols used are:

Depth class (cm)	Symbol
0–15	1
15–25	2
25–35	3
35–45	4
45–55	5
55–75	6
75–95	7
95–115	8
115–135	9
135–155	10
>155	no symbol

Depth symbols for diagnostic horizons or materials specified in a particular soil form are arranged from shallow (topsoil transition) to deep (subsoil transition) before the form symbol. Depth symbols for subsoil limitations or properties (arranged from shallow to deep) appear between the depth symbols for diagnostic horizon transitions and the form symbol. The same material that occurs within two depth symbols is given in brackets.

Soil Form

The soil forms that were identified, as well as the abbreviations used in the code are explained in the methodology.

Soil family

The soil family is coded by means of a four-digit symbol directly after the form symbol.

Subsoil limitations and properties

Several soil materials and factors determine the depth of soil utilised by plant roots. In those forms where the limiting horizon is part of the defined sequence of horizons, which are diagnostic of the soil form, the symbol for the limiting material or horizon is not coded. If the limiting horizon or material is not included in the sequence of diagnostic horizons, the symbol for the horizon or material must be specified after the family number in the code symbol. The depth symbol for such horizons is written between the depth symbol for diagnostic horizons and the soil form symbol

The more important materials that may affect root penetration and water infiltration to a greater or lesser extent is one or more of the following:

Non-diagnostic hardpans; irreversibly cemented

This is soil material cemented by one or more compounds to such an extent that it does not soften in water.

db:
Dorbank: cemented by silica. Calcium carbonate and iron oxide are permissible as secondary cementing agents.

hk:
Calcrete: cemented by calcium and/or magnesium carbonate. It meets the requirements of a hardpan carbonate horizon.

The degree of cementation is distinguished in terms of the intensity and continuity of cementation.

Numerous vertical fracture planes, or vesicular; moderate degree of cementation; more than 25% of the layer is accessible and penetrable to roots; sufficient fracture planes for free drainage through the pan under normal conditions.

Platy and/or massive with occasional vertical fracture planes; moderate to high degree of cementation; predominantly impenetrable to roots locally (<25% over a horizontal section) soft enough for root penetration; sporadic accumulation of free water on the pan.

Massive and/or continuously platy with no fracture planes in which root development can occur; under normal conditions impermeable to water; regular accumulation of free water on the pan.

Weaker than moderately structured, non-diagnostic unconsolidated materials without signs of wetness.

ne:
Non-calcareous unconsolidated material with signs of soil formation, e.g. aggregation, clay illuviation and/or disappearance of original stratification. It largely meets the requirements of a neocutanic II horizon. Its colour must not qualify for diagnostic red or yellow-brown.

re:
Red, non-calcareous soil material with a structure weaker than moderate blocky or prismatic. It largely meets the requirements of a red apedal B horizon.

rs:
Sandy material, which largely meets the requirements of diagnostic regic sand.

sk:

Calcareous material, which largely meets the requirements of a soft carbonate horizon.

ye:

Brown or yellow-brown, non-calcareous soil material with a structure weaker than moderate blocky or prismatic. It largely meets the requirements of a yellow-brown apedal B horizon.

Non-diagnostic unconsolidated materials with signs of wetness; predominantly gleyed

gc:

Gleyed clay, usually with a firm or firmer consistency; it is firmer than the overlying horizon. If the structure is prismatic or columnar, it is usually weakly developed.

gs:

Gleyed, coarsely textured materials, usually friable, non-sticky and non-plastic.

Textural stratification in diagnostic and non-diagnostic unconsolidated materials

Depending on the mode of transport and deposition, certain unconsolidated materials can be texturally stratified. With time soil development results in the disappearance of the stratification. However, in certain young soils stratification can still be detected. Since textural stratification is an important characteristic in soil use, it has to be indicated in the code in the following way:

U5:

Textural stratification non-prominent or absent; highly bleached material, usually sandy.

Predominantly gravelly, stony, or bouldery diagnostic and non-diagnostic horizons or materials

Coarse fragments (>2 mm) can occur in varying quantities either in a part of or throughout a horizon or layer. Such coarse material can seriously affect root development, water infiltration and water-holding capacity and must be indicated in the soil code in terms of size, quantity (volume percentage) and shape.

The predominant size classes and symbols for coarse fragments used in the code are as follows:

Class name	Size	Symbol
Fine gravel	2–25 mm	f
Coarse gravel	25–75 mm	g

Volume per cent of coarse fragment size classes is qualified by the following numerals:

Volume %	Symbol	Volume %	Symbol
0–10	1	10–20	2
20–30	3	30–40	4
40–50	5	50–60	6
60–70	7	70–80	8
80–90	9	90–100	10

The general form of the coarse fragments can be coded as follows:

Type and description	Symbol
Angular stones	a
Cobblestones	c
Shells	sh

Non-diagnostic materials with signs of weathering residual rock

Material in different stages of weathering which varies from hard rock to fully homogenised soil with cutanic properties in the form of tongues of prominent variegation because of residual soil formation and illuviation. There are no signs of wetness. It largely meets the requirements of a non-hard lithocutanic B horizon or saprolite.

Ro

Hard rock without signs of wetness.

Coarse fragments in topsoil horizon and outcrops

The presence of coarse fragments (>2 mm) in the topsoil horizon or rock outcrops has an important effect on several physical (e.g. water-holding capacity) and chemical (e.g. exchangeable cation content) properties, and on tillage and land use. The size, quantity, and form of coarse fragments in the topsoil horizon (or plough layer) are indicated with the same symbols as those used to describe such materials as subsoil limitations or properties.

Texture of topsoil horizon

The texture of the upper part (usually to a depth of 200 to 300 mm) of the profile is coded in terms of:

i) the sand grade for soils with less than 20% clay and
ii) the clay content (percentage)

Classes and abbreviations for sand grade, texture class and clay and silt content are the following:

Sand grade	
Size	Symbol
fine	fi
Clay content	
0–5%	1
5–20%	2

Phenomena on the A horizon

rs:

Recent aeolian material on the A horizon.

cr:

Surface crust refers to the tendency of some soils to puddle at the surface during rain or irrigation and to form a dense, compact crust when dry. Such crusts are unfavourable for water infiltration, air exchange and germination and emergence of seedlings. This phenomenon also occurs in untilled soils with a natural veld cover.