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Assessment of Soils and Geomorphology in central Namibia

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Foreword

The preparation of the present project and the field work in Namibia was carried out by Carl Magnus Broman and Silke Bertram. Unfortunately, Carl Magnus Broman could not participate in the analysis and writing part of this study due to illness. This work was done by the undersigned alone.

Silke Bertram

Abstract

Providing the foundation of every agrarian economy, the soil can be considered one of the most important resources in Namibia. Contemporary problems of land degradation therefore demand major emphasis on sustainable treatment, based on careful land use planning. This is especially true for sensitive ecosystems such as those found in central Namibia, location of the study area. The present study aimed at evaluating approaches for the investigation of soils and geomorphology in order to provide a basis for further land capability classification. This was achieved by literature reviews, remote sensing, geomorphological and pedological field work including sampling of material, and analysis and evaluation of the results obtained. The theoretical framework was provided by the land system approach and the catena concept, the soil classification was based on the FAO Soil Classification System. The results showed a strong influence of the denudation history and the complex landscape evolution on the character of the study area. Three different land systems with four comparable land facets could be identified. The land system approach was shown to be very helpful for recording the nature of extensive and initially unknown land over a short period of time. Simultaneously, understanding of the entire ecosystem increased. The catena concept proved not to be applicable in an environment affected by long-term denudation. Soil surveys should therefore be based on the land systems and thereby linked to the entire landscape. The two major soil groupings found were Regosols and Leptosols. The FAO soil classification system provided correct but insufficient information about the soils in the context of land use planning. It is desirable to develop regionally applicable subgroups. Furthermore, the use of soil classification systems evolved in similar environmental conditions might be of advantage, and local knowledge should be taken into account.

Keywords: Namibia, semi-arid environment, land capability, land system approach, catena concept, FAO soil classification system, landscape evolution, denudation.

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1. Introduction

1.1. Background

The soil is probably one of the most important natural resources in Africa since it forms the basis of the essential agrarian economy of most countries. Assessment of past and present land degradation in order to plan for a sustainable use of the soil resources has since long been a key issue which received considerable attention. The Southern African countries have long co-operated on these matters through organizations such as SARCCUS[1] and more recently through SADC-ELMS[2]. Yet, the overall knowledge of the soils is still rather scanty; there is a dearth of detailed studies as reflected in the paucity of large-scale soil maps. In Namibia, in particular, interdisciplinary projects such as Agro-ecological Zoning and Erosion Hazard Mapping at the Ministry of Agriculture, Water and Rural Development are aimed to address the necessity in these fields, and the present study hopefully can make a contribution.

During the 20th century, the land use in Namibia became increasingly intensified, except in the Namib and some nature reserves. This, combined with the fact that Namibia is one of the poorest countries in the world (SIDA, 1991), results in a risk that it will be unable to feed even half of its population in the future (Stocking, 1993). Thus, the government has underlined the importance of improvements in the agricultural sector. The limiting factor in Namibian agriculture is water, and in most parts of the country semi-arid conditions limit agricultural activities to grazing and browsing. As known from areas with similar conditions, problems of land degradation like overgrazing, bush encroachment and soil compaction take place (Kempf, 1994). This demands main emphasis on sustainable treatment, which in turn requires careful land use planning.

Namibia's landscape balance reacts very sensitively to external influences because of its weak equilibrium and poor resilience. The environmental conditions are extremely variable and as a consequence of this high degree of complexity, environmental dynamics do not react homogeneously to uniform cultural systems. This makes it difficult to apply a zonation concept of Namibia's natural landscapes, so instead surveys should regard the small-scale environmental changes. The main reasons for the high variability in ecological conditions are found to be the primary physical factors climate and geology. They influence the landscape balance by mineral composition, weathering form and intensity, sediment supply, hydrodynamics, relief energy, soil formation, transport of material and energy balance. These factors influence each other as well, which makes it difficult to model their effect and intensity. Slight variations of the basic physical factors as climate or geology may result in very different processes, which in turn lead to different formations of ecosystems. Consequently, defining "normal" conditions as a basis for land use planning involves great difficulties (Kempf, 1997).

In addition, even the stability of ecosystems depends heavily on the variability of the environmental conditions, especially precipitation and available soil water capacity. Because of the extreme rainfall variability in Namibia, most of the ecosystems are regarded as unstable since they are characterized by a low regeneration capacity. This exacerbates the degradation hazard. The Khomas and Windhoek highlands, where the study area is situated, belong to the most susceptible regions of Namibia in terms of soil erosion and bush encroachment. Thus, this region experiences very severe damages and land degradation.

[1] Southern African Regional Commission for Conservation and Utilization of Soils
[2] Southern African Development Community - Environment and Land Management Sector

1.2. Aim

Sensitive ecosystems demand major emphasis on sustainable treatment, which in turn requires careful land use planning. One of the bases for this is a rapid appraisal of the land capability. Therefore, the aim of this study is to develop and evaluate a practical approach to provide a basis for further land capability classification, founded on investigations of land conditions in terms of past and present process activity of geomorphology and soils. This is achieved by literature reviews, remote sensing, field visits, soil sampling and analysis of key soil parameters, and with the theoretical framework of two common approaches, namely the land system and the catena approach (Cooke and Doornkamp, 1990; Gerrard, 1992; Strömquist and Larsson, 1991).

2. Study area

2.1. Location

The study area is situated east of Windhoek (22°25' S, 17°08' E - 22°35' S, 17°25' E; approximate location in UTM 75 19 000 N, 7 19 500 E - 75 01 000 N, 7 48 500 E; see Figure 1), covering about 55 000 ha. The main investigations were carried out on three of the indicated farms, namely Bergvlug, Neudamm and Bellerode, together representing one-third (17 500 ha) of the total area size, while the sampling on farm Hoffnung was done more sparsely. These four farms were assessed to be representative of the whole study area and had the advantage of comparatively easy access.

Figure 1

Figure 1: The location of the study area.

2.2. Climate

Knowledge of the climate affecting a certain area is important for studies on ecosystems in relation to human activities. This is because climatological factors such as rainfall and temperature determine geomorphology, weathering and soil formation, transport of material, flora and fauna, and the use of natural resources. Overall, the climate in Namibia is influenced by two factors; the distance from the humid tropics and the Namib desert. The distance from the humid tropics results in a northern-southern gradual change of the climate, where the Tropic of Capricorn (situated in the central part of the country) can be seen as the boundary between the tropics and the subtropics. The Namib desert, located near the coast, modifies this zonation, especially regarding the rainfall, to a south-western - north-eastern one.

The main circulation over southern Africa is anticyclonic throughout the year above the surface layer (Tyson, 1986). Subtropical fields of high pressure over the southern Atlantic are responsible for the summer rains, which are brought by thunderstorms of the continental convectional type (Giess and Tinley, 1968). The regional climates respond distinctively to changes in tropospheric pressure fields over the subcontinent; wetter conditions are associated with lowered pressure over the subcontinent and increased pressure over the Gough Island region of the Atlantic ocean, while the reverse applies during drier conditions (Tyson, 1986).

The study area belongs to the part of central and northern Namibia, which is, according to Köppen (1923), classified as semi-arid hot steppe climate with summer rains (BShw). A more detailed classification of the regional climate is provided by the FAO[3] through the Agroclimatological Station in Windhoek. The mean annual temperature is 19.0°C, with January as the warmest month (23.3°C) and July as the coldest (12.8°C). The mean annual rainfall lies around 360 mm. The rains are markedly seasonal and occur during summer, from January to March, with an erratic distribution within the rainy season, while there is often no precipitation at all during winter (see Figure 2). The growing season is determined by the rainy season and extends from the middle of January until the first days in April. Average crop water requirements are never fully covered, because the potential evapotranspiration is always more than the precipitation. The high mean annual evapotranspiration (1311 mm according to FAO, other sources indicate about 2500 mm and more (Ganssen, 1963; Dept. of Water Affairs, 1992)) also influences surface runoff and capillary rise of soil water leading to crust formation and salinization (FAO, 1984; see Appendix I for more detailed figures).

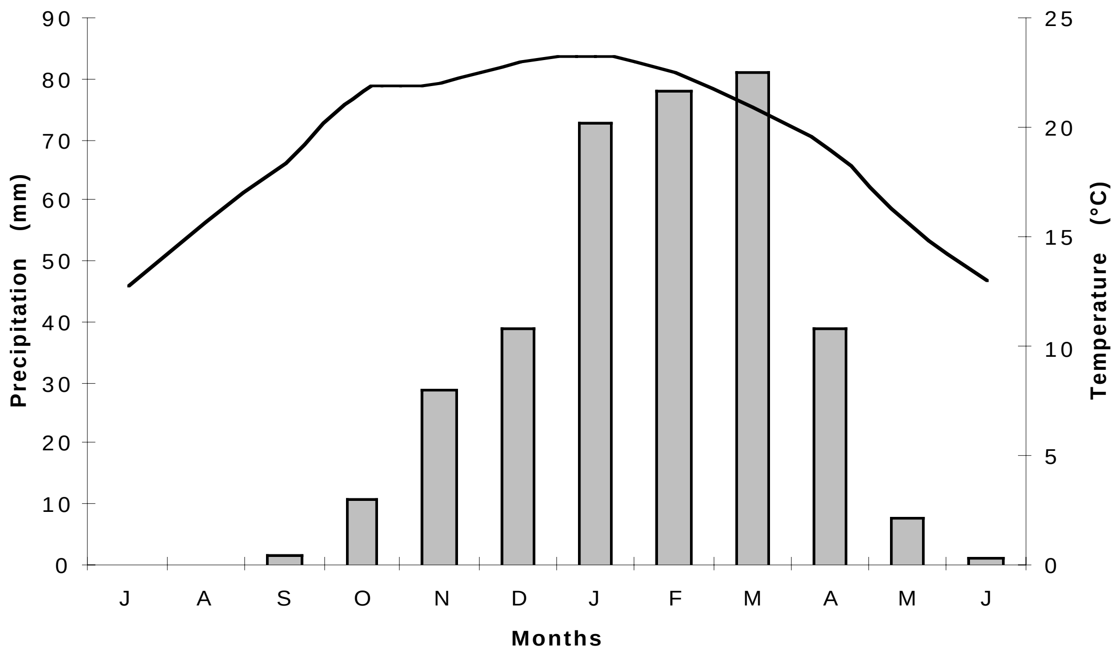

Figure 2: The distribution of temperature and precipitation over the year. Windhoek. Mean values for 49 years between 1921 and 1980 (Source: FAO, 1984).

The main characteristic of the precipitation in Namibia (as well as in the whole of southern Africa) is its high variability, including spatial, temporal and quantitative variations. On a daily scale, the rainfall variability is a function of three factors; (1) atmospheric moisture content and thermal instability, (2) mesoscale forcing and cumulus convection, and (3) larger-scale

[3] Food and Agriculture Organization of the United Nations

synoptic forcing (Tyson, 1986). The dimensions of the rainfall variability are shown by the quotient of the standard deviation over the average annual precipitation, which in Windhoek is 189% (Kempf, 1994). Looking at shorter periods than a year, the variability increases. The mean monthly precipitation, for example, varies noticeably more than the annual (see Figure 3), which means that the course of the rainy season is not uniform at all (Kempf, 1994). This variability, combined with the mainly small amounts of rainfall, results in severe problems for agriculture in terms of limited cultivation opportunities. Such problems require careful planning of both crops and pasture.

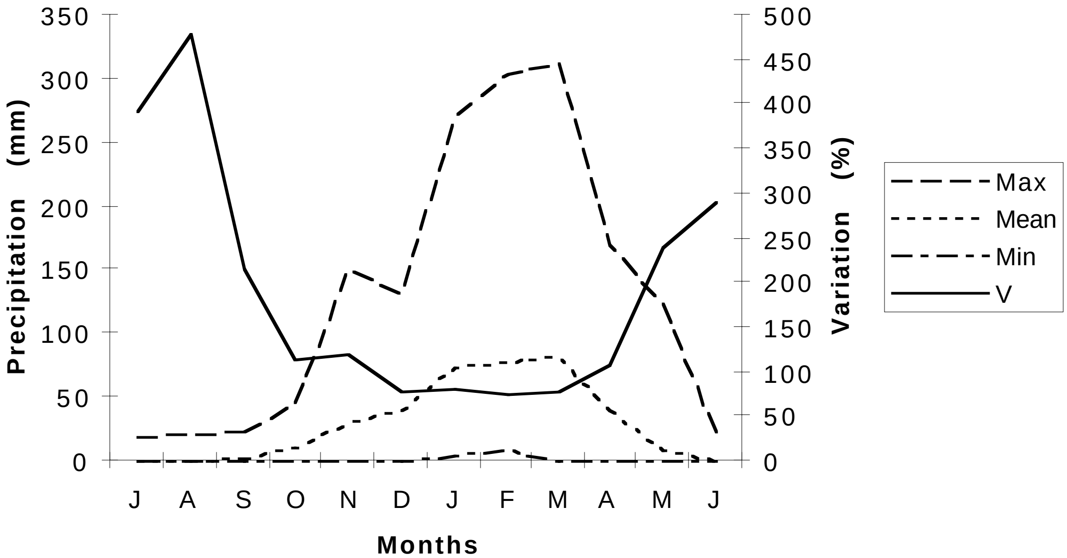

Figure 3: Rainfall variability on a monthly basis for 49 years. Windhoek. Max: absolute monthly maximum of precipitation; Mean: arithmetic monthly mean of precipitation; Min: absolute monthly minimum of precipitation; V: coefficient of variation, representing the quotient of the standard deviation over the average monthly precipitation (Source: FAO, 1984).

The importance of the rainfall variability has led to many studies into this phenomenon. For example, on the big scale, Tyson (1986) presents an 18-year oscillation, common throughout southern Africa (9 dry years, 9 wet years). This pattern can be overlaid by shorter oscillations, where Namibia, for example, is subject to a 6-year oscillation. These patterns, however, are not simple, as stressed by Dryer and Marker (1978) and Kempf (1994), who refer to a considerably higher complexity, especially regarding Namibia.

Rainfall diagrams over the last 80 years (cf. Kempf, 1997) show clearly that drier years are more common than wetter ones, compared with the mean annual precipitation over the same period. This plays an important role regarding erosion processes, which goes beyond the already existing hazard by the distinct erosivity of the rainfalls. A dry year provides good conditions for wind erosion, with processes like outblow of material, transportation and sedimentation, while in wet years, which thus are intensively wet, fluvial erosion is favoured.

2.3. Geology

A considerable part of Namibia is made up of schists, quartzites, granites, metamorphic limestones, dolomites, conglomerates and other rocks belonging to formations of the proterozoic Damara Sequence. Interspersed is the archaic Mokolian Complex of the Kalahari and Kongo Cratons (gneisses and other highly metamorphic rocks) in the north-west, centre, south-east and south. Karoo-Volcanics occur at intervals in the north-western, central and north-eastern areas (SACS, 1980).

The study area belongs to the southern and south central zones of the precambrian Damara Orogen, which is about ± 700 to ± 1100 million years of age (SACS, 1980; Geological Survey, 1996 (map)). The main part of the area lies in the Onyati-Mountains Schist Belt, which is part of the tectonostratigraphic Khomas Terrane (Kasch, 1988). The Khomas subgroup is the youngest of the Damara Sequence and consists of metamorphic rocks like mica schist, traversed by micaceous quartzite, subordinate calcareous schist and impure marble, and amphibole schist (Geological Survey, 1996 and unpublished maps). Especially in the south-eastern half of the study area, many south-west - north-east striking faults occur due to intense precambrian folding (Krenkel, 1928). Younger faults result in extremely small-scale changes of rock types in the direction of the tilting. The rocks are partly of higher age (mainly Auas formation), but of similar type as in the Khomas subgroup. Different forms of mica schist also dominate here, but the interbedded quartzite occurs more extensively (Geological Survey, 1996 and unpublished maps). Deposits of economic interest are found in the Otjihase Mine a few kilometers north of the study area, where stratiform massive sulphide orebodies occur with the Matchless greenstone (Amphibolite) (Geological Survey, 1982).

2.4. Geomorphology

2.4.1. The geomorphological development of southern Africa at the macro-scale

The present landscape of southern Africa is largely a product of the breakup of Gondwanaland and the tectonic processes associated with this event. The other major influence since the creation of Africa as a distinct continental block has been continuing episodes of uplift, rifting, volcanism, warping, and subsequent denudation and erosion due to the creation of new base levels. These processes have formed certain specific characteristics of present-day Africa such as the series of broad upwarps which run parallel to the coastline in several areas. These are flanked on their seaward side by a sharp topographic discontinuity in the form of a major escarpment, separating the interior plateau from the coastal regions (Summerfield, 1996).

Although the major processes forming the macrogeomorphology of southern Africa are fairly well known, the landscape still remains highly controversial, and there is debate regarding the genesis of the land (or planation) surfaces and their ages (Dardis and Moon, 1988). Different numbers of surfaces comprising the southern African landscape have been recognized at different times. The different interpretations arise from the problems of correlating erosion surfaces across the Great Escarpment, the difficulties inherent in determining the ages of the surfaces, and the structural control that has affected the progress of the major planations (Moon and Dardis, 1988). A summary of present-day knowledge about the geomorphic development of southern Africa is presented by Partridge and Maud (1987) (Table 1).

Partridge and Maud show that the development of the landscape at the macro-scale has occurred in discrete stages. The existence of the surfaces related to these stages in the present landscape is evidence of landscape development progressing through backwearing, but the

Table 1: Stages in the geomorphic development of southern Africa (after Partridge and Maud, 1987)

Date	**Event**	**Geomorphology**
Late Pliocene to Holocene	Climatic fluctuations, sea level changes, small-scale tectonism	Marine benches, coastal dunes, river terraces
Late Pliocene to Holocene	Post-African II erosion	Post-African II surface formed, incision of gorges
Late Pliocene (ca. 2.5 Ma BP)	Major uplift (up to 900 m)	Asymmetric uplift of continent, westward tilting
Early mid-Miocene to late Pliocene (ca. 2.5 Ma BP)	Post-African I erosion	Post-African I erosion surface formed (imperfectly planed, major deposits in Kalahari basin)
End of early Miocene (ca. 18 Ma BP)	Moderate uplift (200 - 300 m)	Interruption of African erosional phase, westward tilting of African surface
Late Jurassic/early Tertiary to end of early Miocene	African erosion	Large-scale planation of African surface (at different levels above and below escarpment), deep weathering on erosion surface
Late Jurassic/ early Cretaceous	Fragmentation of Gondwana-land, initiation of Great Escarpment	New base levels formed, rapid erosion

variants of the African surface attest to landscape development by downwearing as well. The modern landscape is not static, in that the existing surfaces will continue to develop at the expense of higher lying areas, and lowering and incision will continue (Moon and Dardis, 1988).

2.4.2. The geomorphology around Windhoek

The region around Windhoek is part of the south-west African plateaux (Bridges, 1990) and characterized by extreme ruggedness (see Figure 4). Near Windhoek, an east-west axis of uparching transverse to the Great Escarpment has generated the Khomas highlands at an elevation of 1900 m. Inselbergs and ranges on the Khomas plain all show a summit level around 2300 m, decreasing in elevation eastwards more rapidly than the Khomas surface and indicating an early warp (King, 1951). According to King (1963), the smooth ridge crests of the Khomas highlands are assignable to the "Gondwana" land surface, originated during the Jurassic, with extensive "post-Gondwana" valley systems between them, which correspond to an early stage of the "African erosion" of Partridge and Maud (1987).

Next page:

Figure 4: Topography of the study area (after the 1 : 250 000 Topographical Sheet 2216 Windhoek, Government Printer, 1975).

Figure 4

Some kilometers south of Windhoek a further dissected plateau makes the transverse range of the Auas Mountains, a great barrier averaging over 2000 m in height and attaining 2484 m in the Moltkeblick. Many rivers take their rise here, some flowing transversely to the ranges. The Windhoek Valley, formed during the Cretaceous (King, 1963) by erosion through the Otjihavera and Usib rivers, appears as a depression about 350 m below the plateau crest and maintains a width of 10 to 15 km for a distance of 65 km.

In contrast to this interpretation, Kempf (1999, in print) refers to some radiometrically dated Oligocene volcanic plugs and intrusive dykes near Windhoek, which are saprolised and peneplanated in both the Khomas and Windhoek niveaus. The peneplanation is also evidenced by relicts of fossil ferralitic soils on the highlands, which are proposed to be of post-oligocene to miocene age. Following this interpretation, the Windhoek valley forms an intramontane basin associated to a tectonic stressfield with numerous rupture fissures induced by upwarping, where not fluvial incision but peneplanation was the dominant process until the end of the Miocene.

The country east of the valley, the Windhoek or Neudamm highlands, forms a counterpart of the Khomas highlands, also comprising of residuals of older cyclic landscapes upon the "African" cyclic surface (King, 1963). It is a gently sloping planation surface with inselbergs and ranges. Towards the east, the highlands submerge gradually into the Kalahari sands in the intramontane plain of Seeis, probably of Early Tertiary age (King, 1967). The mountainous complex on this plain in the north-western corner of the farm Neudamm with peaks around 2000 m belongs genetically to the planation surface in the west. An important divide is found in the area: In the north-western part the Swakop takes it rise, while the south-eastern part belongs to the drainage of the Nossob-Auob-system. Although characterized by ephemeral drainage, these rivers are of important value for Namibia (Kempf, 1994; King, 1951, 1963, 1967; Wellington, 1955).

Figure 5 shows the land types (or land systems) of the study area according to the classification carried out by the FAO (1991; with the present authors' own interpretation due to the small scale). The division of the study area into two parts again becomes obvious: (1) The north-western part (A and B) belongs to the central high mountains of the highlands of the plateau country. In the west (A), long and steep slopes occur, which show a moderate cover of grasses and herbs, interspersed with bare rock surfaces. Land type B is characterized by hills with pointed ridges and steep, concave slopes, which either appear as bare rock or are permanently covered with green vegetation including trees and some shrubs and grasses. Even the so-called Bismarck Mountains in the south-eastern corner of the study area belong to this land type. (2) The eastern part of the study area (C) is classified as east-central plateau with ridges in the plateau country. The plateau region is characterized as nearly level upland with a moderate cover of grasses and herbs.

Figure 5

Figure 5: Land types of the study area (after FAO, 1991).

2.5. Soils

Soil formation is determined by climate, flora and fauna, topography and parent material, i.e. bedrock or unconsolidated sediment. Because of the long time required for a soil to form, it is important not only to be restricted to a synoptical view of the present situation but also to take past environmental conditions into consideration. The bedrock in central Namibia is of high age, deeply weathered and therefore not a good basis for soil development, partly because old bedrock provides limited leaching of minerals. Instead, the soils are generally rich in material derived from physical weathering (Scholz, 1973). They contain little organic matter (C often < 1%) because of low litter supply and rapid mineralization. This results in a decrease of the water-holding capacity. Furthermore, the soils are shallow and also often skeletic, especially on slopes, where they can turn into blockfields and bare bedrock (Ganssen, 1963). Duricrusts like calcrete, silcrete and ferricrete are common compounds in the soils. These accumulations are often polygenetically developed and not necessarily genetically related to the host sediment. This is true especially in the case of calcretes, where a descending development through the soil profile is possible (Blümel, 1991).

There is no modern soil map of Namibia. Apart from some minor local studies there is only the FAO/Unesco[4] Soil Map of the World (1974), the scale of which (1 : 5 000 000) is far too small to be useful for planning purposes. According to this FAO map, about one-third of Namibia is covered by extremely erodible Leptosols, soils on which the majority of the commercial farmland is situated.

The soils of the study area consist of two soil units; Xk - 2ab and I - X - c, i.e. calcic Xerosols and Lithosols/Xerosols, further defined by particular characteristics. Calcic Xerosols are soils occurring under an aridic moisture regime (gr. *xeros* = dry), having a week ochric A horizon, and a distinct calcium carbonate enrichment within 125 cm of the surface (Fitzpatrick, 1980). The calcic Xerosols in this case are medium textured with a stony phase and occur in levelled to undulating areas (0 - 30% slope). They also include cromic Luvisols and cambic Arenosols and are associated with calcic Cambisols and Lithosols. The other mapping unit of the study area consists of Lithosols/Xerosols, which are actually two major soil groupings. Lithosols are soils limited in depth by continuous hard rock within 10 cm of the surface (gr. *lithos* =stone) and develop mainly in mountainous areas (Fitzpatrick, 1980). The Lithosols/Xerosols of the area are characterized by a phreatic phase, referring to the occurrence of a groundwater table within 5 m of the surface without being reflected in the morphology of the soil (FAO, 1988). The relief is steeply dissected to mountainous (> 30% slope) and rock debris/desert detritus is defined as a miscellaneous land unit. In the Revised Legends of the Soil Map of the World (FAO, 1988), the major soil groupings Lithosols and Xerosols are not in use any longer. Instead, Lithosols are classified as lithic Leptosols, while Xerosols are completely deleted and instead grouped into other units. Nevertheless, the characteristics of the soils remain.

A typical soil profile in the study area often shows a cut or very thin A horizon. This is because the horizons near the surface contain much coarse silt and fine to medium grained sand, which are easily blown out. If the surfaces are already eroded in this way, a pavement remains, which may have a stabilizing function if not destroyed by the trampling of, mostly domestic, animals (Kempf, 1997). The eroded material from these processes, mainly occurring on upper and middle slopes, is transported downslope and builds up the colluvial soils found in the valley floors.

These colluvial soils, partly even of alluvial character, are frequently distinguished by a heterogenetic development; palaeosoils and fossile erosion surfaces can be found in the profiles. In older colluvials these features can indicate climate changes during the Holocene, and in younger soils they may be explained by changes in land use. Another important characteristic is the concentration of exchangeable cations, i.e. K^+, Na^+, Ca^{2+} and Mg^{2+}, which is often higher in the colluvial soils than in the areas from which the sediments originated. This fact has important implications for fluvial erosion, with regards to sheet, rill, and gully erosion. Not only are the highlands especially susceptible to this kind of erosion due to the high relief energy, but also because of the presence of soils with a high sodium content. That means that these soils are very hard when dry, but the cohesion is drastically reduced as soon as they get wet, and thus the fine material can be washed away. Because of the duplex-character of many colluvials (differences in grain size in different horizons due to clay movement), it is often the subsoil that is affected, while the topsoil caves in. Triggers for this kind of donga formation (erosional gully system) are processes making the subsoil susceptible to wetting, like the holes of warthogs or the trampling of domestic and wild animals (Kempf, 1997).

[4] Food and Agriculture Org. of the United Nations/United Nations Educational, Scientific and Cultural Organization

Although dongas have been part of the landscape for at least many decades (Hentie Knouwds, personal communication), if not longer (cf. Eriksson, 1998), their development seems to have become aggrevated recently. The erosion energy in the dongas is extremely high, even bedrock, including especially strongly weathered material like saprolite, can be eroded, and the formation of badlands is not unusual. Altogether, the processes and effects of soil erosion are regarded as very degrading and there is not much hope for improvement in the near future. Many soils are already irreversibly damaged (Kempf, 1997).

2.6. Vegetation

2.6.1. Characteristic vegetation types

In the central highlands, elements of both the Sudano-Zambezian Flora and the Namib-Karoo Flora can be found, depending on small-scale environmental factors (Kempf, 1994). In a map of vegetation zones, Giess (1998) classifies the central mountainous area of Namibia as Highland Savanna, but also emphasizes the importance of azonal elements like differences in hydrology and pedology, which can cause many subgroups. Having this in mind, the observation of two more vegetation types, Thornbush Savanna and Camelthorn Savanna, during field work is not surprising. The three occurring vegetation types show typical characteristics regarding tree and grass species (cf. Müller, 1984).

(1) *The Highland Savanna*
The Highland Savanna is characterized by trees like *Combretum apiculatum*, *Acacia hereroensis*, *A. reficiens* ssp. *reficiens* and *A. erubescens* among others. The undisturbed grass cover consists of climax grasses such as *Anthephora pubescens*, *Brachiaria nigropedata*, *Digitaria eriantha* and many other good pasture grasses. A decline in these valuable grasses can be attributed to selective grazing and overgrazing.

(2) *The Thornbush Savanna*
In the Thornbush Savanna, the grass cover varies more depending on the soil type, but the species composition is similar to that of the Highland Savanna. Other characteristic species are *Schmidtia pappophoroides*, *Stipagrostis* spp (especially *S. uniplumis*) and *Schmidtia kalahariensis*, the latter showing a clear sign of deterioration in the veld. The grassveld is interspersed with trees and large shrubs like *Boscia albitrunca*. *Acacia* species often dominate, and bush encroachment by *Acacia mellifera* ssp. *detinens* may cause problems.

(3) *The Camelthorn Savanna*
(3) The Camelthorn Savanna is an open savanna on deep sandy soils with good grass cover, where the camelthorn (*Acacia erioloba*) is dominating among other trees and shrubs. In this vegetation type, hard and unpalatable grasses such as species of *Eragrostis* (especially *E. pallens*) and *Aristida stipitata* can be found.

Additional grass species found in the study area are *Aristida* sp. and *Cenchrus ciliaris*. *Aristida meridionalis* and *Fingerhuthia africana* are very common on slopes in the eastern part, while *Stipagrostis namaquensis* and *Themeda triandra*, the latter mostly in small colonies, are observed mainly on valley floors. The occurrence of bigger trees is also connected with the valley floors in the form of so-called gallery forest. This means that, despite the drying up of the rivers during most of the year, there is flowing water at least during parts of the rainy season and the ground water table lies higher.

2.6.2. Reflections on savanna ecology

There is no generally accepted definition of the term "savanna", and there is no savanna *per se*. "Savanna" describes various forms of vegetation, which depend on different ecological factors at the specific location. Nevertheless, some general characteristics can be outlined. Savannas show a very distinct appearance during the year; in the rainy season the biomass production is high and the shrubs and trees are covered with fresh new leaves, while during the dry season, which lasts between three and ten months, many of the woody species shed their leaves and the part of the grasses above ground die (Leser, 1992). Due to differences in water household conditions and root systems, there is antagonism between grasses and woody species in these types of ecosystems.

The variety of vegetation formations cannot only be explained by patterns of zonality (as for example in Walter and Breckle, 1984). Firstly, each ecological determinant in Namibia is extremely spatially variable, and secondly, vegetation formations may differ markedly even in areas with comparable physical and anthropological conditions. This clearly shows the inner dynamics and reactions having a main influence. These processes may vary distinctively and are very difficult to model, which makes it almost impossible to predict the qualitative and quantitative effects of any kind of change. Besides, Namibian ecosystems are often very sensitive with low resilience. Strong impacts involving degrading processes such as pasture, reaping, clearing, or burning may, therefore, result in irreversible damage (Kempf, 1997).

One effect of an ecological imbalance between woody species and grasses induced by human impact can be seen in bush encroachment, where the spreading of bushes is much more intense than under undisturbed conditions. This process leads not only to a quantitative loss of grazing land, but also to a change in pasture quality due to "genetic erosion", which means reduced biodiversity, mainly regarding perennial grasses (Kempf, 1997).

2.7. Land use

2.7.1. Farming

Water is the most important limiting factor in Namibian agriculture. Rainfed cultivation is only possible in the north of the country, where mainly maize, sorghum and millet are cropped. On the main part of the agricultural utilizable land, commercial big-scale livestock farming is taking place. In the north, farmers keep mostly cattle on farms of 5 000 - 10 000 hectares, while farm size increases southwards (about 15 000 - 20 000 ha) due to decreasing rainfall, and the animal-keeping concentrates on sheep and goats. The study area in the central part of the country is located in the transitional zone, and therefore the livestock consists of both small and large stock.

The livestock are kept in camps with a regulated change of pasture land by driving the animals. A mixed pasture after a rotation scheme where grazers are followed by browsers is favourable. The camp practice is meant to have two effects; (1) intensification of production, and (2) preservation of pasture land. Unfortunately, the latter is not attained very often; in many cases land use in the camps is very intensive, leading to bush encroachment and more or less severe degradation. This happens because the dimensions of the camps are often chosen according to access of water supply and regular and manageable division of the farmland, and seldom according to land capability and number of livestock, at least not for dry-year conditions. An illustration for the latter issue is the fact that 80% of the livestock in Namibia had to be slaughtered during the last drought (1995 - 1996).

A short description of the farms, where the main part of the field work was carried out, is given below:

(1) *Bergvlug*
Bergvlug is a governmental farm, run by the Directorate of Veterinary Services within the Ministry of Agriculture, Water and Rural Development. The farm serves as Veterinary Research and Quarantine Station. It covers an area of approximately 5 000 ha and keeps a mixed livestock of cattle, sheep and goats. The usual number of cattle amounts to 300, but due to the drought the number was reduced to 180 in October 1996. Compared with the figure mentioned above, the reduction in livestock numbers is not quite as extreme, which may be explained by a relatively small stock during "normal" years.

(2) *Neudamm*
Also Neudamm is government-owned and also houses the Agricultural College. The farm has six divisions; training, large stock, small stock, dairy, agriculture and general. The training division includes 64 students attending agricultural education. The area of slightly more than 10 000 ha is divided into 9 blocks and 210 camps. 200 ha are used for experimental growing of vegetables and maize. The large stock (Oct. 1996) consists of Afrikander Cattle (270), dairy cows (40) and horses (40), kept for twice weekly counting of the whole stock. Different breeds of sheep and goats (for example Boerbok, Damara- and Karakul sheep) make up the small stock totally amounting to 1 200 animals. These are kept on about 60% of the area, mainly in lower parts where bushes make browsing suitable. If practicable, the quality of the grass is decisive for planning. The water supply is provided by 9 boreholes, some reaching down to 110 m, and 19 dams.

(3) *Bellerode*
Bellerode is a private farm of approximately 2 500 ha. The livestock consist mainly of cattle. Because farming on a comparatively small area is getting increasingly difficult, animal keeping is not the only source of income any longer. As common among many other farms in the country, tourism is seen as an alternative by offering, for example, lodgings, hunting and photo-safaris.

(4) *Hoffnung*
Hoffnung is a privatly owned farm of more than 10 000 ha with some cattle and a concentration on keeping wild animals, both serving "experience of the wilderness" for tourists and meat production. An extra income seems to be provided by running a scrap yard.

2.7.2. Reflections on degradation and flexibility

As explained earlier, natural conditions in Namibia are highly sensitive and variable, with low ecosystem stability. Today’s problems can be seen as an inadequate ability of inflexible cultural systems to adapt to the ecosystem conditions. Consequently, areas of highest natural variability and lowest economic flexibility are most severely affected by degradation processes. Therefore, increased flexibility in the land use systems is of vital importance for sustainable land use to be achieved. There is also a need for local investigations adapted to the area, because the natural variability makes it impossible to develop generally applicable strategies (Kempf, 1997). One example of this approach is the "Holistic Resource Management", a pasture management based on Savory (1988). It is a new form of High-Impact-Grazing; intensive pasture on small camps during a very short time with long regeneration periods, resulting in an improvement of pastures by perennial grasses which, in turn, reduce degradation processes.

3. Methods and materials

3.1. Background

3.1.1. The land system approach

The information-gathering process preceding decisions on soil management or land use planning is founded on the investigation of land conditions like characteristics of geomorphology and soils, and related processes. A common approach to this kind of landscape description and assessment is to find the distribution and pattern of physical factors defining the terrain and to delineate units or regions of specific, uniform character. Such studies based on analyses of genesis and processes, as well as directly observable surface attributes, can form part of the basis for decisions about the utilization and management of land. One way to find the units forming the terrain is to apply the physiographic or land system approach (Larsson and Strömquist, 1991). The term "land system" was first defined by Stewart and Perry (1953): "The topography and the soils are dependent on the nature of the underlying rocks (i.e. geology), the erosional and depositional processes that have produced the present topography (i.e. geomorphology), and the climate under which these processes have operated. Thus the land system is a scientific classification of country based on topography, soils and vegetation correlated with geology, geomorphology and climate" (in Cooke and Doornkamp, 1990). Conclusively, the land system is an area with a recurring pattern of topography, soils and vegetation, and with a relatively uniform climate. The land system approach is more about dividing an area into morphological regions rather than defining individual landforms or slope characteristics. Each land system is divisible into smaller components (land facets), which are associated with a defined and uniform set of geological, pedological, vegetational, and sometimes hydrological conditions. The facets within a system are not a random collection of contiguous areas but are often causally linked, by geomorphological processes, origin or groundwater flow (Cooke and Doornkamp, 1990; Larsson and Strömquist, 1991). The land system approach provides an extremely simple, cost-effective, and versatile method for rapidly classifying large areas of relatively unknown territory, even if there are weaknesses in terms of being general and, regarding the selection of criteria, both qualitative and subjective (Cooke and Doornkamp, 1990).

3.1.2. The catena concept

Linked to the land system approach, but having a more soil scientific point of view, is the catena concept. As concluded from the above, the land system and the land facet are, among others, based on the assumed close relationship between slope processes and soil-forming processes and, consequently, soil morphology. The catena concept focusses on just this relationship, assuming that particular slope forms are associated with particular soil sequences (Gerrard, 1992). The properties of the soil that are directly influenced by slope form and angle include drainage, soil depth, texture, stone content, and occurrence of indurated layers or iron concretions. Slope may also influence other properties, including colour, clay mineralogy, humus and nutrient status, and the content of weatherable minerals. The structural stability and, consequently, the risk of soil erosion also vary with slope (Areola, 1996). The soil catena as a taxonomic unit can, therefore, be seen as a "grouping of soils which, while they fall wide apart in a natural system of classification on account of fundamental and morphological differences, are yet linked in their occurrence by conditions of topography and are repeated in the same relationships to each other wherever the same conditions are met with" (Milne, 1935, in Gerrard, 1992).

These two approaches of land systems and catenas provided the theoretical framework for the choice of methods.

3.2. Air photo interpretation

Air photo interpretation was made to get an initial classification of the different land systems and land facets and to choose representative slopes in homogeneous areas for a field survey. The primary classification was made before the field investigations, which then could be checked in the field and compared with reality. The interpretation was based on a set of air photographs in the scale of 1 : 50 000 covering the entire area. Three pictures of the main part of the field investigation were also available in the scale of 1 : 20 000, providing more detailed information.

3.3. Field surveys

3.3.1. Slope profiles

With the aim of characterising slopes and land facets, and investigating soil catenas, 15 slope transects (in this report commonly refered to as "profiles") from the top of a hill to the valley floor and further to the opposite top were made with the help of a pendulum for the levelling and a tape measure. From the resulting figures, the shape and length of the slopes could be calculated. The position of the transects is shown in Figure 6.

Figure 6

Figure 6: The location of the slope transects and the single soil sample points.

3.3.2. Soil samples

To classify the soils of the study area, and to gain information about past and present processes, totally 104 soil samples in 56 soil profiles were collected. The majority of them were taken along the slope transects, but at four places sampling was done without any correlation to a slope transect (for the position of these samples see Figure 6). The overall depth of the soil profiles, dug as deep as possible, was dependent on the hardness of the soil or the depth of the parent material, and varied between 10 and 300 cm. If possible, soil samples of approximately 1 kg were taken at various depths of a single soil profile. The soil profiles were described according to colour (determined for the dry soil, using the revised Munsell Standard Soil Color Chart), root abundance and diameter, stone content, parent material, and moisture (if perceptible) (see FAO Guidelines for soil description, 1990). Different horizons were identified and sampled if present. The labelling of the soil samples was done according to the following system: “Slope profile : Soil profile, Depth in cm”; example: “II:3, 0 - 10”, which is read as: soil sample at the depth of 0 - 10 cm in the third soil profile of the slope profile II.

3.3.3. Surface characteristics and vegetation

For the further characterisation of the land systems and land facets, the surface characteristics of the slopes and the valley floors were determined by walking along every transect with a stick, pointing it randomly on the ground every second step (approximately every 2 m). The surface characteristic at that particular point was classified as vegetation (both dead and alive), fine material (soil matrix) or coarse material (gravel, stones) and then expressed in per cent surface cover.

This “stick method” cannot give a picture about the shrub density as normally the way of easiest accessibility was chosen. The shrub density was estimated, although with difficulty since one was standing *beneath* the canopies. Using air photos for this determination was neglected because of the inactuality of the photos for this kind of investigation.

3.4. Laboratory analyses

The sieving part of the grain size analysis was carried out in the Agricultural Laboratory of the Ministry of Agriculture, Water and Rural Development in Windhoek. The other analyses of physical and chemical parameters of the material < 2 mm were done in various laboratories of the Department of Earth Sciences, Uppsala University, Sweden. Analyses were carried out according to a laboration manual at the Agricultural Laboratory, based on the Booker Tropical Soil Manual (Landon, 1991) and the Field and Laboratory Handbook for Soils (Stocking, 1983).

3.4.1. Physical parameters

(1) *Grain size analysis*
The soil samples were passed through two sieves of 2 mm and 3.5 mm (no access to other sieves). The grain size distribution for three grain size classes (< 2 mm, 2 - 3.5 mm, > 3.5 mm) could be calculated (in per cent of weight). The grain size distribution of the material < 2 mm was determined by sedimentation, using a hydrometer. The results were then grouped into grain size classes of sand, silt, and clay.

(2) *Particle density*
Particle density was measured with a pyknometer.

3.4.2. Chemical parameters

(1) *pH*
pH was measured in both water and a KCl-solution (ratio soil : fluid as 1:4).

(2) *Cations, acidity, cation exchange capacity, base saturation*
The amounts of K^+, Na^+, Ca^{2+}, and Mg^{2+} were determined by atomic absorbance spectrophotometry, the acidity by titration. The cation exchange capacity (CEC; maximum amount of exchangeable cations that a soil can adsorb) and the base saturation (BS; proportion of the adsorption complex of a soil saturated with exchangeable cations other than hydrogen and aluminium) could be calculated from these results.

(3) *Electrical conductivity*
Measuring of the electrical conductivity (EC) with a conductivity meter (ratio soil : water as 1:4).

(4) *Organic matter*
Organic matter (OM) was determined by loss on ignition.

3.5. Soil classification

The soils were classified according to the Revised Legend of the FAO/Unesco Soil Map of the World (1988), as this system is in use in Namibia. This classification is based on the identification of diagnostic horizons. These soil horizons combine a set of properties which are used for identifying soil units. Since the characteristics of soil horizons are produced by soil-forming processes, the use of diagnostic horizons for separating soil units relates the classification to general principles of soil genesis. Characteristics of horizons or soil materials that cannot be considered as diagnostic horizons are referred to as diagnostic properties. Finally, phases are used for further characterisation of the soil units. They are limiting factors related to surface or subsurface features of the land, not necessarily related to soil formation and generally cutting across boundaries of different soil units.

Thus, the classification of the soil profiles was carried out according to the identification of the following characters: (1) major soil grouping, (2) soil unit, (3) diagnostic properties, and (4) phases. Additional characterising features not fitting into the FAO classification system were indicated separately.

4. Results

4.1. Soil samples

4.1.1. Physical and chemical analyses

The interpretation and rating of the content of the analysed chemical parameters is made with help of the Booker Tropical Soil Manual (Landon, 1991) and the Field and Laboratory Handbook for Soils (Stocking, 1983). Even if the analyses were carried out as carefully and accurately as possible, they should be regarded as providing chiefly “order-of-magnitude” results, capable of interpretation in general terms. Contamination as a source of error is possible, but many extreme values correlate well with other samples from the same soil profile or can be explained with values of a different parameter of the same sample (a very high total acidity, for example, seems to be reliable if the pH is low). Appendix III provides complete tables of the results of all analyses.

(1) *Grain size distribution*
The markedly dominating texture class is sandy loam, followed by loam and silt loam, and loamy sand and sand in single cases. The content of rock fragments (> 2 mm) varies between 0 and 91%, and the absolute clay content is low, around 5%.

(2) *pH*
The pH (in H_2O) intakes values between 4.82 and 8.74. These values can be seen as extreme, as the pH of the majority of the samples lies around the mean pH of 6.38, which is medium acid to neutral (5.5 - 7.0). The pH measured in KCl is commonly lower, on average about 0.8 units.

(3) *Cations*
The total amount of cations is low to medium in most samples, as their mean values (in me/100g soil) show clearly: Na^+ 0.34, K^+ 0.38, Mg^{2+} 1.32 and Ca^{2+} 13.2, even if amounts of cations rated as high or very high occur.

In four samples, the Na^+ content exceeds 15% of the TEB (Total Exchangeable Bases, sum of Na^+, K^+, Mg^{2+} and Ca^{2+}), in eight samples 10%. These soils can be regarded as sodic and therefore as structureless and easily erodable (see Section 2.5). A good and stable structure is provided by a high calcium content and, consequently, the sodium-rich samples contain only little calcium. In three samples, the Ca^{2+} content exceeds 100 me/100g. As also other samples from the same soil profiles show very high contents, it does not have to depend on contamination. Furthermore, an intensive reaction with the extracting agent ammonium acetate was observed, pointing to a high content of alkalinity (possibly $CaCO_3$). As the analysis of exchangeable calcium had to be carried out with high dilution, the margin of error increased.

In the upper 40 cm of the soil profiles the Ca : Mg ratio is ≥ 5 : 1, which means that Mg is increasingly unavailable with increasing Ca. The ratio then decreases with depth. The K : Mg ratio lies in the optimal range from the agricultural point of view.

(4) *Acidity*
The total exchangeable acidity (TA) shows low values around a median of 0.18 me/g. In samples not containing any exchangeable Al^+-ions the TA is made up of H^+-ions alone. The amount of Al^+-ions in the 30 affected samples never reaches dangerous levels. The high presence of Al^+ ions in slope profiles III and IV is striking. The relatively high total acidity in

sample V:1 (1.61 me/g) probably depends on contamination, but on the other hand the very low pH is supporting.

(5) *Cation exchange capacity*
The average cation exchange capacity (CEC) is high with about 33 me/100g soil, but with a broad variation between low and very high values. In most samples, the high value of the CEC can be explained by the high Ca^{2+} content or by the TA. Soils with a high CEC provide good fertility, but if the base saturation is low, most of the CEC is occupied by H^{+}-ions. Such soils are regarded as only potentially fertile.

(6) *Base saturation*
The base saturation (BS) depends on the amount of cations and the total acidity. The values vary between 7 and 98%, which contains the whole spectrum from very low to very high. The average BS lies at 42%, which is medium and slightly dystric. As well as the CEC, the BS is strongly influenced by the high content of Ca^{2+}.

(7) *Organic matter*
The contents of organic matter are rated as very low to low; the values vary between 1.0 and 6.5%, with a mean value of 3.4%. It should be observed that both references rate contents of organic carbon, not of organic matter as a whole as analyzed here. Besides, the obtained values are probably too high, because the samples contained visible, barely mineralized organic matter like parts of roots, that were difficult to remove. Therefore, the content of organic matter in all the soil samples is regarded as very low.

(8) *Electrical conductivity*
The measured values of electrical conductivity (EC) are multiplied by a factor of five to get an assessable EC_e value. With values between 0.2 and 2.2 mS/cm (sample 103 probably contaminated) and a mean of 0.8 mS/cm, the samples can be considered as salt free, the salinity effects are negligible. Especially regarding the fact that the samples are taken from an area used for grazing, there should not be any salinity problems for this type of vegetation.

(9) *Colour*
Brown is the dominating colour and can be considered as the characteristic colour, together with yellowish brown, bright brown, and dull yellowish brown. Other colours present, although more uncommon, are olive brown, dull yellow orange, reddish brown, and dark olive brown.

4.1.2. Variations with depth, slope position, and land system

For better interpretation of the characteristics of the soils and the variability of the physical and chemical parameters, the samples were grouped into different classes according to depth and to position in the slope transects and the land systems (see Table 2). The position in the slope profiles was determined by dividing the transects drawn on paper into classes of upper, middle and lower slope, and valley floor according to subjective criteria. In the slope classes, only the first four depth classes were analysed, because samples > 50 cm were exclusively taken on lower slopes and valley floors. The division of the samples according to their position in the different land systems becomes obvious by comparing Figures 5 and 6. Land systems A and B are grouped together as they represent the mountainous area, while the relief energy in land system C is much lower.

Table 2: Grouping parameters

Depth class	Depth	Slope class	Slope position	Land system class
1	0 - 15 cm	US	Upper slope	A+B
2	10 - 30 cm	MS	Middle slope	C
3	25 - 40 cm	LS	Lower slope	
4	35 - 55 cm	VF	Valley floor	
5	50 - 100 cm			
6	100 - 200 cm			
7	200 - 300 cm			

2 samples classified as both class 1 and 2.
6 samples classified as both LS and VF, 3 as both US and MS.

Tables 3 and 4 show the variation of grain size with depth and slope position. Tables 5, 6, 7 and 8 show the changes of the chemical parameters in relation to depth, slope position, and land system, and between the soil groupings.

Table 3: Variation of grain size in relation to depth

	% of fine earth fraction			% of whole sample
Depth class	**Clay**	**Silt**	**Sand**	**> 2 mm**
1	6.5	32.8	61.5	40.2
2	9.3	33.8	56.9	23.1
3	9.3	40.9	49.8	34.2
4+5	9.5	36.7	53.9	20.0
6+7	10.1	37.2	52.8	20.4

Table 4: Variation of grain size in relation to slope position

	% of fine earth fraction			% of whole sample
Depth class	**Clay**	**Silt**	**Sand**	**> 2 mm**
US	7.7	36.3	57.9	54.5
MS	8.4	33.0	58.7	51.0
LS	10.7	32.3	58.0	26.3
VF	7.6	37.2	55.2	7.1 [1]

[1] 4 of 31 samples on VF contain high amounts of material > 2 mm. If they are excluded from the calculations, the mean value of material > 2 mm decreases to 1.2%.

It is important to bear in mind that the tables show mean values, from which the divergence of single samples may sometimes be extreme. This is illustrated very clearly by Figures 7 - 17. These box plot diagrams are graphs for displaying the 10th, 25th, 50th (median), 75th and 90th percentiles of a variable (horizontal lines). All values for the variable above the 90th percentile and below the 10th percentile are plotted separately to indicate outliers (Abacus Concepts, 1996). The box plots illustrate the variation between the slope classes, according to the idea of the catena concept (see Section 3.1).

Figures 7 to 13 show the variation of the different grain sizes. The absolute content of material > 2 mm increases markedly upslope. The valley floors contain only a very small amount of coarse material, and the spreading is relatively small as well. Due to the extreme increase of coarse material upslope, the absolute amount of the fine earth fraction (< 2 mm) decreases. The absolute clay content of the lower slopes, which is higher than in the valley floors, is interesting. Even relatively, the lower slopes have the highest clay content, but at the same time the lowest content of silt. Otherwise, the differences in the relatively fine earth fractions between the slope classes are rather small. This is supported by the result that sandy loam is the predominating texture class, with only a slight tendency of finer texture classes downslope.

Table 5

Figure 7

Figure 7: Boxplot diagram showing the distribution of material > 2 mm according to slope class.

Figure 8

Figure 9

Figure 8: Boxplot diagram showing the distribution of the absolute clay content according to slope class.

Figure 9: Boxplot diagram showing the distribution of the relative clay content according to slope class.

Figure 10

Figure 11

Figure 10: Boxplot diagram showing the distribution of the absolute silt content according to slope class.

Figure 11: Boxplot diagram showing the distribution of the relative silt content according to slope class.

Figure 12

Figure 13

Figure 12: Boxplot diagram showing the distribution of the absolute sand content according to slope class.

Figure 13: Boxplot diagram showing the distribution of the relative sand content according to slope class.

With regard to the chemical parameters, whose distribution is shown in the Figures 14 - 17, it can be stated that the variations *in* the slope classes themselves always are superior to the variations *between* the slope classes. No chemical parameter increases or decreases continuously from upper slope to valley floor. The lower slope always modifies the pattern by having lower or higher values than the valley floor, in most cases even being the part of the slope having the highest or the lowest (median) values. However, continuous changes can be seen from lower slopes to upper slopes. In some cases, these straight relationships between lower, middle and upper slope are somewhat modified by the middle slope. Therefore, the most pronounced differences between the parameters can be found between the lower and the middle slopes.

Figure 14

Figure 15

Figure 14: Boxplot diagram showing the disbution of pH according to slope class.

Figure 15: Boxplot diagram showing the distribution of the base saturation according to slope class.

Figure 16

Figure 17

Figure 16: Boxplot diagram showing the distribution of the K^+ content according to slope class.

Figure 17: Boxplot diagram showing the distribution of the Mg^{2+} content according to slope class.

Certain interesting relationships are worth while mentioning in greater detail. The pH increases downslope with the highest mean value on the lower slopes, where the total acidity is lowest. Both the highest and lowest extremes of the pH are found on upper slopes, but even on the valley floors the spreading is remarkable. The variation in the content of cations between the slope classes is similar for each element. Their content is highest on lower slopes, where even the spreading is most pronounced.

4.2. Soil classification

As the FAO soil classification (1988) is based on diagnostic horizons (see Section 3.5), efforts were foremost made to identify these horizons. However, in the field it was impossible in most cases to identify any horizons at all. Often it was even hard to divide the profiles clearly into master horizons (like A, B and C horizons), for reasons of lacking accumulation of organic matter or strong weathered bedrock, etc., which eliminated the border between soil and parent material. After the physical and chemical soil analyses had been conducted, still no layers fulfilling the criteria of certain diagnostic horizons could be found in any soil profile. Diagnostic properties are present in four profiles as sodic properties (refering to a saturation in the exchange complex of 15% or more of exchangeable sodium or of 50% or more exchangeable sodium plus magnesium).

Because of the lack of diagnostic horizons and the scarcity of diagnostic properties, the classification of the major soil groupings was difficult and had to be based on other criteria. The first major soil grouping identified was Leptosols (LP), soils limited in depth by continuous hard rock within 30 cm from the surface or having less than 20% of fine earth over a depth of 75 cm from the surface. Twenty-six profiles fulfilled these characteristics. The requirement “continuous hard rock” was considered to be fulfilled if it was impossible to dig any deeper, or if the material was estimated to be bedrock or saprolite. A further division into soil units Lithic Leptosols (LPq; limited in depth within 10 cm from the surface), Dystric Leptosols (LPd; having a base saturation less than 50% in at least some part of the soil), and Eutric Leptosols (Lpe; having a base saturation of 50% or more throughout) could be carried out. Apart from two exceptions, the base saturation of the Leptosols was markedly low, with values rated as low to very low.

The remaining 30 soil profiles had to be classified as Regosols (RG), the one major soil grouping left after not responding to one of the other groupings. Regosols are coarse textured soils formed from unconsolidated materials, having no diagnostic horizons other than an ochric or umbric A horizon. The Regosols were further divided into Dystric Regosols (RGd; having a base saturation of less than 50%) and Eutric Regosols (RGe; BS ≥50%). As the definition requires this low/high base saturation to be at least from 20 - 50 cm from the surface, the majority of Regosols could not be definitely classified, because many profiles did not reach 50 cm in depth. Therefore, the labels in brackets are used to indicate the tendency of the base saturation, for example RG(d).

Three different phases could be recognized in the soil profiles, namely the lithic, the skeletic and the sodic. The lithic phase requires continuous hard rock within 50 cm from the surface. It often occurred together with the skeletic phase, which refers to soil materials that consist of 40% or more of coarse fragments (> 2 mm), with a thickness of at least 25 cm, the upper part of which occurs within 50 cm from the surface. (Observe: The FAO (1990) classifies according to per cent per volume, in this study the coarse fragments were assessed in weight per cent.) The labelling of the skeletic phase in brackets (skeletic) indicates that the sample contained more than 40% coarse material, but without reaching the required thickness. All eutric and dystric Leptosols showed the lithic phase, and 70% are also skeletic. The sodic phase, finally, marks soils that have more than 6% saturation with exchangeable sodium at least in some horizons within 100 cm from the surface.

A clay enrichment of ≥ 3% downwards in the soil profile was obvious in 75% of all soil profiles consisting of more than one sample. This type of clay enrichment is diagnostic for an argic or a cambic B horizon, but as not all criteria for them can be fulfilled, a grouping in these diagnostic horizons was not possible. Therefore, clay enrichment is indicated separately combined with the soil units. In samples not showing clay enrichment, the clay content was either the same throughout the profile or decreased only slightly (1 - 2%). 15% of the Leptosols and almost 60% of the Regosols were clay enriched. (The detailed classification of all soil profiles is presented in Appendix IV.)

4.3. Surface characteristics and vegetation

The surface characteristics vary evidently within only small distances, which is why it seems meaningless to give mean values for a whole slope or even smaller parts of it. Often, coarse material dominates, mainly in the form of a pavement of weathering resistant quartz, followed by fine material and vegetation. No correlation has been found between variations of the surface characteristics and slope position, form, angle, or soil unit. On the farm Neudamm, fine material dominated the surface, but there were no differences in soil units or properties and phases; it did not seem to result in more vegetation by means of grasses either, their degree of covering was rather low with only 10 - 20%. On the other hand, shrubs were much more common on Neudamm, they covered, on average, about 30% of the slopes (between 10 and 50%; distinct variation could occur on one and the same slope). On the farms Bergvlug and Bellerode, shrub and tree cover represented around 5 - 10% on the slopes. The valley floors were often shrub-free, at the same time as the biggest and greenest trees were just found along the river beds with the most favourable ground water supply.

4.4. Slope profiles

4.4.1. Geomorphology

As presented in Figure 5, the geomorphology of the study area is divisible into three different land types or land systems within the plateau country, where the north-western part (A and B) belongs to the high mountains of the highlands and the south-eastern part (C) is classified as east-central plateau with ridges. These different land systems are made up of the same type of land facets, even if their characteristics may vary. Four land facets can be distinguished: (1) Rock outcrops, (2) Slopes, (3) Valley floors, and (4) Dongas.

(1) Rock outcrops form mainly the summits of the mountainous part of the study area (which are not included in the slope profiles as their accessibility is strongly limited), but are also found on slopes. Minor valleys without sediment filling are sometimes cut directly into the bedrock.

(2) Slopes occur in different forms, angles and lengths. The slopes are predominantly convex, sometimes with straight sections across the middle slope and concave lower slope. This pattern is especially obvious in land system B. Figure 18 shows a typical slope profile from this area. However, a comparison with the other slope transects (see Appendix IV) shows that the slope form can vary markedly. Even the inclination of the slopes shows great variations, there are slope angles between 1° to 45°; at outcrops nearly vertical walls may be present. In general, the slope angle decreases from land system A to land system C. The FAO (1991) characterised the morphology of land system C as nearly level upland, but a classification as gently undulating upland, slightly dissected by streams, may be more appropriate. Figure 19 illustrates a profile of this land type, while a profile from land system A with steep slopes is found in Appendix IV.

(3) The valley floors differ markedly in their extension and characteristics. Most of the valleys, especially the bigger ones, are filled with fine grained colluvial sediment of a depth between a few decimetres up to three or four meters. Their inclination lies normally between 0.5° and 3° in both directions (from the slope to the water channel and along the channel). The border between lower slope and valley floor is morphologically distinct only in the wider valleys, but is not as expressive in the undulating upland, where slope and valley floor often form a smooth curve. The rivers in the valley floors are ephemeral, carrying water only during the rainy season in late summer. Marked river channels are not always fully developed, but sometimes gravely riverbeds are found. Smaller valleys in the mountainous area often have sediment-free valley floors or contain only little sediment.

(4) As explained in Section 2.5, dongas are erosional forms like gullies, occurring in the fine grained sediment of the valley floors. Their depth varies between a few decimeters up to three meters and more (depending on the thickness of the sediment), causing severe erosion problems. The eroding power is immense; downcutting into the weathered bedrock beneath the sediment is not unusual. Protecting features like walls or similar barriers seldom fulfil their function. On their upper end, most dongas show an undercut head, but a relatively smooth and gradual change from intact valley floor to incised donga has also been seen. The occurrence of dongas does not seem to be influenced by factors like inclination, valley size or position in the drainage system. Since 1979 (date of the aerial photographs), new dongas have developed and some of the old ones have extended.

4.2.2. Soils

Figure 20 provides an example of the typical spatial distribution of the soils and their characteristics (for the other slope profiles, see Appendix V). Absolutely valid rules for the distribution of the soil units, properties and phases cannot be laid down, but tendencies are obvious. On upper slopes mainly Leptosols occur, which even cover about two-thirds of the middle slopes. On lower slopes and valley floors, Regosols are the dominating soils. Two Leptosols are found on valley floors, but their presence is restricted to smaller valleys with no or little sediment of colluvial material. The Regosols on upper and middle slopes and about 70% of them on lower slopes show mostly a lithic and/or skeletic phase.

Figure 18

Figure 19

Figure 20

This typical distribution of Leptosols on the upper parts of a slope and Regosols on the lower parts and on the valley floors results in the fact that their physical and chemical differences are similar to the differences in relation to slope position (see Tables 6 and 8 and Figures 7 - 17). As an example, the texture class "sandy loam" is dominating markedly among Leptosols, while some finer texture classes mainly occur in combination with Regosols, and this relationship is reflected in the presence of finer texture classes on lower parts of the slopes.

The units of eutric and dystric in both Leptosols and Regosols are distributed without a pattern; both units occur on every part of the slope and do not show a correlation with certain slope transects either. Furthermore, no other marked differences in physical or chemical parameters are found between dystric and eutric soils.

The sodic properties are present mainly in the valley floors, and only once on a middle slope. The sodic phase, however, occurs in every slope position.

The clay enrichment is not restricted to certain slope classes, it can be found in soil profiles from every part of a slope, even if the valley floors intake first position with about 30% of all clay enriched profiles.

A good correlation between soil characteristics and slope form could not be found, the distribution of the different soils does not seem to depend on this factor. There is perhaps a slight tendency that the skeletic and the lithic phases are more common on convex slopes than on straight or concave ones. A somewhat surprising result of the comparison between slope form and soil characteristic is the dominating clay enrichment in convex parts.

The slope angle does not seem to have a marked influence on the soil distribution either. Certainly, the steepest slope covered by a Regosol has a slope angle of 11° (°/400°), steeper slopes are all carrying Leptosols, but on the other hand Leptosols can be found in valley floors or on slopes inclining only 1°. Therefore, the soils or their distribution on the slightly undulating uplands do not differ markedly from those of areas with more relief energy.

5. Discussion

5.1. Geomorphology

As already outlined in Section 2.4, the landscape evolution in central Namibia has been very complex and intricate. Today’s landscape shows a complicated pattern woven by different endo- and exogenetic processes effective at different times in the earth's history. The maybe most important exogenetic factor influencing the present geomorphology is the succession of palaeoclimates (Birot, 1968), and there is strong evidence for marked environmental changes in southern Africa during the past. Most of the literature concentrates on changes during the Quarternary, where Deacon and Lancaster (1988) give a comprehensive overview of palaeoenvironments, while articles about more specialized research topics are found in journals like Palaeoecology of Africa and the surrounding islands (Heine, editor). Tyson (1986), however, reviews climate change in southern Africa since the Precambrian. Due to the multiplicity of environmental changes, some of the present landforms and deposits may safely be assumed to be relicts, left there by different – moister or drier – conditions. Other features may reflect transitions between environments and the related disequilibrium conditions that appear to accompany (or follow) climate change (Garner, 1974). These aspects make the landscape difficult to interpret, at the same time as they may help to explain why the picture is not always as expected.

According to Büdel (1977), the study area is classified as "Warme Trockenzone der Flächenerhaltung und traditionalen Weiterbildung" ("warm arid zone of preservation of plains and continued traditional formation"), comparable to the Sahara and inner Australia. The morphology, though, does not show much of the characteristics of an arid or semi-arid landscape, like the sharpness of forms due to differential erosion or the existence of broad, perfectly plain surfaces (although Beaudet and Michel (1978) name the planation surface of Seeis (land system C) "glacis sur roches schisteuses" ("glacis on schist bedrock")). Neither are forming processes like episodic sheet flows or intensive aeolian transport fully comparable with those ongoing in arid/semi-arid areas, as there is no evidence found for, e.g., coarse material transported along slopes or aeolian depositions. Nonetheless, there might be several explanations for Büdel's and Beaudet's classifications and descriptions.

Regarding Büdel's global classification, it might just be in a scale too small for being able to reflect regional variations. Furthermore, the study area faces the problem to be borderland in two aspects: firstly, it is situated close to a semi-desert environment, the Kalahari, and secondly, it lies between the tropics and the subtropics. Therefore, the area might not show a morphology typical for the nucleus of one climatic zone, but represents a combination of two climatically controlled zones of morphodynamic processes. Another possible explanation for the complexity of the landscape is given by the great influence of tectonics. These endogenetic activities both disturbed former stages of equilibrium and induced new conditions for geomorphological processes. Even if there have not occurred any recent tectonic events, the area was markedly affected by them in the past, which might have provided conditions "unfavourable" for the development of a characteristic semi-arid morphology. This aspect is also interwoven with the time aspect, as even in optimal conditions the development of forms like pediments requires a long time of both tectonic and climatic stability. The morphodynamic processes, which according to Büdel (1977) and Beaudet and Michel (1978) should lead to a landscape typical for semi-arid environments, might not have had enough time to affect the area, and consequently older landforms are not fully reworked. Here, the idea of regular climate change turns up again. One example can be seen in the plain of Seeis - described as glacis by Beaudet and Michel (1978). This glacis is strongly dissected and shows, as the whole of the study area, a very narrow pattern of drainage, which probably is a relict from more humid periods. On the macro-scale, all denudation cycles (King, 1963, Partridge and

Maud, 1987) demand somewhat moister conditions for processes like pediplanation. Another example for a more humid palaeoclimatic phase is provided in the record left by weathering: About 50 km W of the study area, in the Khomas highlands, extremely weathered amphibolic mica schists (saprolite) is found (Kempf, 1999, in print). In the study area itself, the bedrock is strongly weathered, too, often digging is no problem. In the soil profiles on the slopes it is in most cases impossible to decide where to draw the line between regolith and bedrock. The development of these residuals of an intensive chemical weathering requires a warm and more humid climate, conditions comparable to those in the humid tropics. Also some rock summits show clear signs of chemical weathering in their rounded and stripped shape. The stripping and removing of the humid weathering profile is assumed to have taken very little time as the material has had ideal transport dimensions. Part of the eroded material from the summits and slopes builds up the present colluvium, which today is partly reworked by alluvial processes, provable by the distinct border between hillslope and sediment fill in, especially in wider valleys. It may be possible that the colluvial material on the valley floors can be derived from the climate predominant today, but the main supply has more likely taken place during environmental conditions capable of more rapid production and transportation of fine grains. Today, denudation is still ongoing, mainly on the slopes. There is no transport of coarse material from the slopes to the valley floors, which means that either intensive sheet flows are absent or the vegetation cover is sufficient, but the existence of pavements, built up by relatively weathering-resistant quartz, shows that fine material is washed or blown away. Apart from the occurrence of heavy rainfalls, when enormous amounts of sediment can be carried, the fluvially transported material mostly stays in the system, where the valley floors often serve as sediment stores.

A complex evolution, as outlined above, complicates the interpretation of a landscape. The delineation of land systems and land facets, though, helps to divide the landscape into manageable units, which can be characterized by their morphology and active processes. This approach seems to be superior to classical geomorphological mapping in several ways. Firstly, it is a much less time-consuming procedure, secondly, it gives valuable results even in situations of unfavourable mapping provisions, and thirdly, the understanding for the system "landscape" increases, as several factors constituting the physical environment have to be considered simultaneously. Furthermore, a land systems description probably provides all information - or at least the geomorphological part - necessary for soil management and land use planning. However, in this study there were some difficulties to detect "certain predictable combinations of surface forms and their associated soils and vegetation" (Cooke and Doornkamp, 1990); this is discussed more in detail in the following section about soils.

5.2. Soils

According to the catena concept, there is an assumed close correlation between slope form and soil properties, and it is usually expected that meaningful relationships between slope and soil will be the inevitable result of any properly conducted study. If this always was true, this soil investigation would have been considered as a failure, as no clear correlation between slope form or slope position and the major soil groupings or even specific soil properties could be outlined. However, the soil is greatly influenced by all processes operating in the ecosystem and by the history of the landscape. Considering the complex landscape evolution of the study area with its erosive phases and regular periods of climate change as described above, it might not be self-evident to expect any relationships, as realistic correlations only occur if the processes of soil formation are in the same sort of equilibrium with the surface and subsurface processes acting on the slope. Therefore, distinctive soil-slope relationships are found mainly in extreme situations dominated by frigid or arid conditions, by landslides, by duricrusts or by highly porous parent material. Under non-extreme conditions, as in the present environment, the processes of slope erosion, slope deposition and pedogenesis are probably almost inextricably interwoven. Conclusively, it can be considered premature to relate climate - geomorphological systems to soils (especially when the interference between climate and geomorphology is not as intricate as in central Namibia), and thus this lack of significant correlations may be just as meaningful as an indicator of landscape status as the highest statistical relationship between soil and slope (Gerrard, 1992; Ollier, 1976).

Climate change, denudation cycles and all other factors of influence during the past have not only had an impact on the morphology and soil-slope relationships, but of course also on the properties of the soils themselves. Therefore, not only the catena concept is of little applicability here, but the soils do not fit perfectly into descriptions of typical soils developed in semi-arid areas either (see for example Brady, 1990; Faniran and Areola, 1978). This lack of some of the common characteristics like upwards movements of soluble constituents or distinct alkalinity, depends probably on the long denudation history of the area. According to the weathering record and the clay accumulation, the soils have to be very old and consequently, they have had a long time to develop. Despite this fact, the soils are very shallow. The question is whether the limited depth is due to regular denudation which prohibited the proper development of the soil, or if the soils should be considered as remains from older, deeper soils. This question is difficult to answer, but there is evidence supporting the second possibility. The soils are mostly skeletic, in which the coarse material consists of remains of weathering-resistant quartz veins in the mica schist. Furthermore, the soils lack distinct A-horizons and the slopes often show an erosion pavement, which is characteristic for residual slopes. Also, the somewhat higher clay content on lower slopes and in convex parts can be explained with the hypothesis of old and denudated soils: Firstly, lower slopes can serve as a store for material transported from upslope, and secondly, convex sequences of slopes act as a barrier for overland flow, which is why the transport capacity decreases in these parts, causing deposition.

The marked influence of denudation on the soils can also explain the minor differences between the two major soil groupings, Leptosols and Regosols. As already presented earlier (in Section 4.2.), the classification of the soils according to the Revised Legend of the FAO/Unesco Soil Map of the World (1988) was involved with difficulties, as this classification system is based on the use of diagnostic horizons related to general principles of soil genesis. Here, no diagnostic horizons could be identified - but with the background of an erosional landscape this fact should not be surprising. Strictly speaking, the Leptosols and Regosols of the study area only belong to different major soil groups because of differences in depth, and the definition of the Regosols is based on the fact that no criteria of the other major soil groupings could be fulfilled. Nonetheless, both Regosols and Leptosols are described as non-bound to specific, zonal climatic conditions (FAO, 1988) and are typical for elevated, accidented terrain where soil formation is hindered by erosion (Driessen and Dudal, 1991) - characteristics being in accordance with the present conditions. Therefore, the FAO soil classification certainly is applicable in this case, but it might be questionable to what extent this system provides a useful soil description for planning purposes. The amount of information gained about soil properties should ideally be more comprehensive, but with regard to the worldwide applicability of the FAO classification this demand seems to be unattainable.

The presentation of the soil classes and properties in profiles and not in a map has two reasons. For the first, the slope profiles correlate well with the idea of land systems, and for the second, the distribution of the soils does not clearly vary between, for example, different land systems, and even if the occurrence of Leptosols higher upslope than Regosols would represent a statistically provable correlation and not only a slight tendency, it would be impossible to map these changes on a basis of air photographs in a scale of 1 : 50 000.

Finally, some general remarks about the problem of donga development. A certain amount of this kind of gully erosion is natural, but to which extent is difficult to say. The factors affecting gully erosion can be divided into intrinsic variables that exist within the geomorphological system, for example soils, vegetation, morphology and climate, and extrinsic variables (e.g., overgrazing and farming practices) that are foreign to the system and cause the system variables to change (Stocking, 1981, in Nordström, 1988). These different variables influence and interact with each other according to an intricate pattern. Probably, it is the sum of several stress factors coinciding in their different amplitudes that the area affected suddenly cannot cope with, not one factor alone causing the crossing of the threshold of a new erosion cycle (Nordström, 1988). As the present study has not focused especially on triggers for gully erosion, no definite statements about the dongas present can be made, and especially statements about anthropogenic environmental impact have to be based on a thorough understanding of the natural characteristics and processes of an area (Eriksson, 1998). According to Schultz (1988), the required grazing area per 500 kg live weight (approximately equivalent to one cow or ten sheep) in a tropical or subtropical arid region is 10 - 15 ha, and regarding these values the stock number on the farms Bergvlug and Neudamm lies within these limits. Overgrazing might therefore not necessarily been the major cause of the development of dongas on these farms, but one has to keep in mind that this statement is based on only one reference. Furthermore, it is important not only to look at the general stock number correlated to the whole farm area, but to consider the probably relatively higher grazing pressure on the valley floors. To reduce the spreading of dongas, it might be meaningful to try to limit grazing and trampling on the most affected colluvial soils in order to establish a healthy and dense grass cover, which probably is the most effective protection measurement, as it increases infiltration, decreases run-off, and reduces desiccation cracking (Nordström, 1988).

6. Conclusions and recommendations

From a geomorphological and soil-scientific point of view, the character of the study area is strongly influenced by its denudation history and complex landscape evolution. This fact results in three major concluding remarks according to the aim of the study, providing a basis for environmental management projects founded on investigations of soils and geomorphology.

1. The land system approach was helpful to record the nature of the large and initially unknown study area over a short period of time, both regarding morphology and processes. Furthermore, the understanding for the entire ecosystem increased as all influencing factors were studied simultaneously.

2. The catena concept proved not to be applicable in an environment affected by long-term denudation. However, the form in which a catena often is studied and presented, namely with the help of slope profiles, seemed to be valuable even in this special conditions, especially because slope profiles are closely linked to land systems.

3. The FAO soil classification system was not of especially good advantage in the present study, as it could not provide sufficient information about the soils.

On the basis of these conclusions, the following recommendations should be considered for studies with aims similar to the present one:

Each landscape is highly individual, and it is important not to uncritically use "commonly accepted" models and guidelines, but to try to find out the parameters considered being decisive. This case study can, therefore, be seen as an example of how different techniques, methodologies and ways of thinking and acting can be combined in a systematic process to gather information. In this process it is of immense importance to look at the landscape development, to have an integrated view and to avoid studying only single factors or parameters. Every soil surveyor and land use planner has to be aware of the fact that his/her object of interest is part of the landscape and strongly influenced by its history, both regarding landscape evolution and former land use. Knowledge from geographers and land users, especially from indigenous people if present, should therefore always be taken into consideration.

With regard to the evaluated approaches, the land system approach proved to be useful for studies where it is important to gain quick but still thorough information about past and present processes of geomorphology and, to a certain extent, soils. The surveyor does not necessarily have to be a trained geomorphologist, and therefore this method can be highly recommended. Although the rapid appraisal of the soil resources gets more difficult without the "working hypothesis" of a catena concept, a soil survey can instead be based on the land systems and land facets defined and thus will automatically be linked to the entire landscape. According to the FAO classification system, it would be desirable to develop further, regionally applicable subgroups on the basis of this system, as it is already implemented in Namibia. For large-scale studies with strongly regional character, it might be of advantage to test the applicability of soil classification systems developed for similar environments as the Soil Classification of South Africa (MacVicar, 1991), and to take local knowledge into account.

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Personal communication

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9. Appendices

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Appendix I

Climate Station Windhoek/Namibia

Latitude 22°34' S   Longitude 17°06' E
Altitude 1728 m over sea level

	JAN	FEB	MAR	APR	MAY	JUN
Precipitation (mm)	73	78	81	39	8	1
Temp average (°C)	23.3	22.5	21.0	19.0	15.6	13.1
Temp mean max (°C)	29.6	28.5	26.8	25.2	22.1	19.8
Temp mean min (°C)	17.0	16.3	15.2	12.8	9.0	6.5
Vapour pressure (mb)	12	13.7	11.7	9.6	6.6	5.5
Sunshine (% of poss. sunshine)	70	70	75	78	90	95
Total radiation (cal/cm^2/day)	641	575	527	492	447	409
Evapotranspiration (mm)	152	126	116	86	64	53

	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Precipitation (mm)	0	0	2	11	29	39	361
Temp average (°C)	12.8	15.7	18.5	21.7	22.1	23.0	19.0
Temp mean max (°C)	19.8	23.0	25.2	28.8	29.0	30.1	25.7
Temp mean min (°C)	6.0	8.5	11.3	14.6	15.2	16.6	12.4
Vapour pressure (mb)	4.3	4.5	4.7	5.8	8	10.1	8
Sunshine (% of poss. sunshine)	96	97	90	82	76	70	82
Total radiation (cal/cm^2/day)	441	506	585	624	669	647	546
Evapotranspiration (mm)	55	86	110	149	154	160	1311

(Source: FAO, 1984)

Appendix II

Vegetation list

Names according to Coates Palgrave (1983, trees) and Müller (1984, grasses).

Trees:

Acacia spp.	
Acacia erioloba	Camelthorn
Acacia erubescens	Blue thorn
Acacia hereroensis	Mountain thorn
Acacia mellifera ssp. *detinens*	Blackthorn
Acacia reficiens ssp. *reficiens*	False umbrella thorn
Boscia albitrunca	Shepherd's tree
Combretum apiculatum	Red bushwillow

Grasses:

Aristida spp.	
Aristida meridionalis	Giant stick grass
Aristida stipitata	Sandveld long-awned stick grass
Anthephora pubescens	Wool grass
Brachiaria nigropedata	Blackfooted Brachiaria
Cenchrus ciliaris	Buffalo grass
Digitaria eriantha	Finger grass
Eragrostis spp.	
Eragrostis pallens	Broom grass
Fingerhuthia africana	Thimble grass
Schmidtia kalahariensis	Bushman grass
Schmidtia pappophoroides	Kalahari sand quick
Stipagrostis spp.	
Stipagrostis namquensis	River Bushman grass
Stipagrostis uniplumis	Silky Bushman grass
Themeda triandra	Red grass

Appendix IIIa

Appendix IIIb

Appendix IV

Appendix Va

Legend for the slope profiles

LP		Leptosols
	LPq	Lithic Leptosols (limited in depth within 10 cm from the surface)
	LPd	Dystric Leptosols (BS < 50%)
	Lpe	Other Leptosols
RG		Regosols
	RGd	Dystric Regosols (BS < 50%)
	Rge	Eutric Regosols (BS > 50%)

Lithic phase	Hard rock < 50 cm
Skeletic phase	≥ 40% material > 2mm in ≥ 25 cm
(Skeletic) phase	≥ 40% material > 2mm in < 25 cm
Sodic phase	Na+ content ≥ 6% of TEB
Sodic properties	Na^+ content ≥ 15% of TEB, or $Na^+ + Mg^{2+}$ ≥ 50% of TEB
Clay enrichment	≥ 3% downwards

I:1	Slope profile I, soil sample point 1
7,5°	Slope angle

Appendix Vb

Appendix Vc

Appendix Vd

Appendix Ve

Appendix Vf

Appendix Vg

Appendix Vh

Appendix Vj

Appendix Vk

Appendix Vl

Appendix Vm

Appendix Vn