

REPUBLIC OF NAMIBIA

**DIRECTORATE OF ENVIRONMENTAL AFFAIRS
MINISTRY OF ENVIRONMENT AND TOURISM**

**NATURAL RESOURCE MAPPING OF THE
KAVANGO REGION**

FINAL REPORT



CONSULTANTS IN THE EARTH SCIENCES

P. O. BOX 20690

WINDHOEK

TEL: +264 (0) 61 220 400

FAX: +264 (0) 61 230 934

e-mail: intercon@namib.com

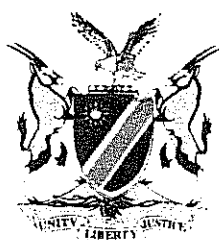
In association with:

GISL (UK) LIMITED

Dr A. Burke

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1 INTRODUCTION

1.1 PROJECT BACKGROUND

Two environmental profiles covering five of Namibia's northern administrative regions have been published by the Directorate of Environmental Affairs (MET). For each region the environmental profile is presented as a publication documenting the major environmental processes and resources and the demands placed on these resources, together with a database of current environmental information in a format suitable for further analysis and monitoring purposes. The third environmental profile in this series will be produced for Kavango Region.

1.2 MAPPING OBJECTIVES

1.2.1 Terms of Reference for the Natural Resource Mapping of Kavango Region

For the compilation of a natural resource database for Kavango Region the Directorate of Environmental Affairs engaged Interconsult Namibia (Pty) Ltd in association with GISL Ltd and EnviroScience to map the natural resource base.

More narrowly than the title suggests, The ToR limited this mapping activity to the identification, delineation and documentation of the most prominent and important **vegetation** and **soil** units of the region.

1.2.2 Mapping Specifications and Expected Outputs

Based largely on the interpretation of existing digital, geo-corrected LANDSAT TM images and orthophotos of the region, the vegetation and soils mapping was required to adopt an approach to comply with and satisfy the following end-product specifications:

- The units will be delineated and mapped in one or more layers of polygons;
- Fieldwork will be required to collect sample data for purposes of interpretation and documentation of units;
- Detailed sets of quantitative descriptive or attribute data will be compiled and linked to the polygon layers in formats which will allow for interrogation and analysis of the data, both as a separate data set and in combination with other sets of data for the region;
- The attribute data will emphasise the resource values of the units;
- All data products to be provided by this project will be compatible in ERMAPPER and ArcView data formats;
- All digital mapped data will conform to a co-ordinate system and projection to be specified by the Environmental Profiles Project;
- A detailed report on the vegetation and soils of the region will be submitted along with digital information.

1.2.3 Interpretation of ToR Requirements

The requirements of the mapping ToR outlined above were clear in that the workload could be broken down into a number of well-defined tasks to achieve the expected digital outputs. Nevertheless, a further interpretation of the ToR was necessary to clarify the scope of work required, and through this to develop an approach. The interpretation was condensed into a number of guidelines to determine data requirements and set the level of mapping intensity. These are summarised below:

- **Scale.** To map the prominent and important vegetation and soil units of a region the size of Kavango (+/- 84,000 km²) for the purpose of resource evaluation would require a reconnaissance-level investigation designed to elicit diagnostic information for both the identification of these units and the delineation of their boundaries.

➤ **Minimum Map Unit Size.** The mapping would be based largely on the interpretation of existing LANDSAT TM and orthophotos of the region. The minimum spatial extent of vegetation and soil units to be mapped (i.e. polygon size) would therefore be defined after previewing these source materials to determine the resolution and processing scale best suited to interpretation at a reconnaissance level of investigation.

➤ **Measurement of Resource Values.** The ToR offered no definition of the term "resource values". Given that the overall objective of the natural resource mapping activity would be to contribute towards an Environmental Profile of Kavango Region the emphasis on resource values was interpreted to be analogous to the data requirements of a land evaluation study¹. This would require a field programme designed to measure specific vegetation and soil attributes describing both their current environmental potential and vulnerability to external pressures, in addition to the identification of units and their boundaries.

➤ **Soil Classification:** To satisfy the data requirements of a land evaluation approach, the FAO/UNESCO/ISRIC Soil Classification Revised Legend (1991) would be the most appropriate framework to adopt for the provision of a systematic soils description of the region. Identification of soil units using the FAO Revised Legend for classification would also be required for any further analysis using the FAO procedural guidelines for land evaluation (FAO, 1993).

Opting for the FAO classification system would enable the mapping of soil resources to be based in the first instance on an unsupervised classification of remotely sensed data to provide soil polygons. A reconnaissance-level soil survey would then be carried out over the region to transect the polygon boundaries using standard FAO guidelines for description. These samples would be analysed to provide representative profiles for classification and the signatures of these profiles would be employed in a digital image processing exercise for spatial extrapolation purposes. A further short field check would be carried out to verify boundaries.

1.3 CONCEPTUAL DESIGN

To base the mapping of vegetation and soil units largely on an interpretation of remotely sensed data required a practical conceptual approach designed to:

- Identify and standardise the criteria by which to identify and highlight unit differences, and thereby provide a uniform basis for the mapping of unit boundaries;
- Provide a framework within which soil and vegetation attributes representing resource values may be measured and their possible linkages evaluated;
- Allow for a revision of unit boundaries to accommodate the findings of a field-based sampling programme, designed to validate remotely sensed data interpretation by ground-truth.

¹ A land evaluation study derives values calculated from single and combined vegetation and soil unit attributes to describe the current status of land resources in terms of the limitations and potential for selected types and intensities of land use.

1.3.1 The Land Systems Approach

The physical entity of Kavango Region appears at first glance to be one immense remarkably uniform environment dominated by vast plains of unconsolidated sands sloping gradually northwards to the perennial Okavango River channel.

This seemingly homogeneous region is in fact characterized by an intricate mosaic of distinctive landscapes and landforms differentially sculptured by aeolian processes, incised by ephemeral river valleys, and modified by human interaction. An approach based on the identification of landforms was expected to provide baseline diagnostic information essential to the identification of vegetation and soil units and for the delineation of their boundaries.

An integrated land systems approach was proposed for this investigation to disaggregate the physical environment into unique and distinct combinations of landform, surface drainage, depth of sand mantle, shallow groundwater rest water levels, growing period zones, regional climate, soils units and vegetation types. The environmental picture would then be assembled using a nested hierarchical system of re-aggregation to produce two principal levels of mapping unit - the land system and the land unit (or land facet).

The land system can be described as an area with a recurring pattern of topography, soils and vegetation within a relatively uniform climate whereas the land unit is an area within which, for most practical purposes, environmental conditions are uniform. Both definitions are rationalisations of units that arise naturally in the course of photo-interpretation; land systems are distinctive patterns extending across one or several photographs, while land units are the smallest areas that can be recognised and delineated. The units within a system are not a random collection of contiguous areas, but are often causally linked by origin, geomorphological processes or water transfer mechanisms.

1.3.2 Summary of Proposed Mapping Protocol

To establish a mapping protocol for the Kavango environment, a land system survey based principally on satellite image interpretation would be conducted in conjunction with field traverses, aerial and orthophoto interpretation to produce a tabular legend showing landforms, vegetation and soils.

The defining features of each land system would be systematically noted with a high proportion of both defining features and boundaries to be based on landform. This would not only be for practical reasons. In principal it would be desirable to identify and define land systems in terms of landforms in the interests of having a uniform basis to the mapping.

To confirm land units the following individual elements would be measured and mapped: altitude, slope angle, profile curvature, plan curvature and aspect. These would be incorporated into a preliminary polygon database to identify landform elements, and further combined into landform patterns. Land units and systems would thus be identified using an objective and uniform approach and used to derive base maps for soils and vegetation. Individual soil and vegetation parameters could then be extracted for a more detailed examination of resource values using FAO procedural guidelines for land evaluation (FAO, 1993).

2 METHODOLOGY

The previous section outlined the approach to be followed in the execution of the vegetation and soils mapping activities. This section describes the methods used to achieve the objectives of the study, and also addresses them in terms of difficulties experienced, resulting modifications to the scope of work, and the outputs achieved.

It should be noted at the outset that the manipulation of remotely sensed data formed the methodological backbone to this investigation. Furthermore, the entire proposed scope of work revolved around the high level of confidence placed in this tool as an accurate decoder of signals emitted from the Kavango Region.

The technical aspects highlighted in sections 2.1 - 2.3 of the report may therefore be viewed as a test case on the applicability of standard satellite image processing and remote sensing techniques for the mapping of the soils and vegetation resources of a semi-arid environment in Namibia.

2.1 IMAGE PROCESSING AND REMOTE SENSING PROCEDURES

Digital data for 6 geo-corrected LANDSAT TM satellite images captured on April 17th, April 24th and May 1st 1997 were made available, and manipulation of this data formed the first phase of the investigation.

The following set of procedures was devised for data treatment:

1. Check the geo-corrected satellite images for locational accuracy.
2. Finalise choice of optimal band combination (3 bands) for the production of false colour composite hardcopies (used for fieldwork and any visual interpretation of soils and vegetation). The most flexible approach would be to integrate the image processing classification and visual image interpretation procedures so that the strong points of each method can be used to classify an image.
3. Select appropriate bands for digital classification from cluster analysis.
4. Run unsupervised classification for approximately 24 classes.
5. Filter result to remove isolated pixels.
6. Ground-truth classes (using transects, random GPS spot checks, etc) to identify vegetation and soil types for each class produced by the unsupervised classification.
7. Merge and split classes where appropriate.
8. Run supervised classification using selective classes from above observations to determine if improvements can be made to the existing classification.
9. Run accuracy assessment on resulting classification (by using GPS ground observations and field survey transects).
10. Convert resulting classes into GIS polygons and attributes to allow interrogation and analysis of important vegetation and soil types.
11. Produce hardcopy maps showing soils, vegetation and land systems.

2.1.1 Expected Outputs

For the first phase of the investigation the process outlined above was expected to produce mapping polygons with a single attribute for soils and vegetation (i.e. a soil class or a vegetation type). Field exploration and the collection of secondary information would provide further data on underlying natural, physical and human factors (e.g. elevation, slope, soil erodibility, landuse, rainfall) to "fine-tune" the mapping units and to assign other attributes to the polygons.

At a later stage of the investigation the spatial analysis component of the remote sensing task would take two forms. The simplest form would aggregate multiple polygon classes into single polygon classes by reclassifying the polygon attributes (merging) to produce land systems. A second analysis would involve the

"disaggregation" of polygons into more complex polygons (splitting) by using multiple themes to generate a more composite resulting theme. This technique would be used to re-assemble soils and vegetation attributes into themes reflecting resource values such as "soil productivity" and "land management limitations".

2.1.2 Actual Outputs

2.1.2.1 Steps 1 - 5

Steps 1-5 were carried out according to standard image processing and remote sensing procedures. For the soils investigation preliminary band combination trials were made on the satellite data to cross-check compliancy with known landform and soil boundaries mapped for previous studies of the region (FAO, 1984; Schneider, 1987; Simmonds, 1997 & 1998). Band combination 3 5 4 was found to be appropriate as it appeared to highlight gross landform boundaries as well as the presence of pans.

An unsupervised classification of a composite of the 6 Landsat TM satellite images was performed on a combination of 6 bands. This was produced as a map of 36 land cover classes in digital and hardcopy formats at a scale of 1:125 000 and used as a first approximation for a land cover classification.

2.1.2.2 Reconnaissance Field Survey

A reconnaissance field survey was carried out during February 1999 to test whether correlations between boundaries of the unsupervised classification and boundaries perceived in the field could be established.

Field checks commenced in northwest Kavango where landform, soils and vegetation variability were expected to produce the clearest distinctions in land resource signatures, and continued south-eastwards to areas where landscape morphology became less distinct.

The field checking procedure revealed no relationship at all between the signatures and landforms, soils or vegetation. In some areas one land cover class could account for up to eight land resource combinations and in others up to three classes would account for no observed differences. Field checking of the 6-band false colour composite data (Landsat TM) also picked up woefully inadequate boundary definitions.

Field evidence strongly indicated that the frequency and spatial extent of fire sequences played a key role in determining the quality of land cover features. With respect to the effects of fire on soils for example, charcoal and ash cover altered surface horizon colours to the point where significantly different colours appeared to be identical. On the basis of surface colour, therefore, boundaries derived from the unsupervised classification of satellite data appeared to highlight fire boundaries rather than soil changes.

With respect to the effects of fire on vegetation, the originally proposed remote sensing approach was found to be inappropriate because it was impossible to isolate the multiple effects of many years of veld fires and subsequent regrowth induced by both anthropogenic and climatic events.

Based on similar difficulties with satellite image interpretation in the neighbouring North Central Region it became evident that even a supervised classification using the reconnaissance field data was unlikely to produce the desired result and this was therefore not attempted.

In short the methodology fell apart at Step 6 and was redesigned to accommodate the data matching difficulties outlined above.

2.2 REVISED METHODOLOGY

2.2.1 Preparatory Work

To re-establish a workable mapping framework and yet to preserve the integrity of the land systems approach a change in methodological emphasis was warranted. This involved moving away from the heavy 'top-down' dependence on satellite image interpretation and adopting a more manual 'bottom-up' approach based on field evidence. For this to be attained the land systems approach was modified to introduce the concept of land regions as a third mapping level to replace the supervised classification. Land regions, demarcated as discrete regional surface drainage areas containing clusters of land systems, were used to produce a basemap.

2.2.1.1 Land Region Mapping

The land regions map was compiled manually at a scale of 1:250 000 from a 1:50 000 topographic information database obtained from the Surveyor General. This was digitised. Land regions were then split into component land systems, the defining features of which were systematically noted. A high proportion of both defining features and boundaries were based on landform as represented by differences in surface topography.

2.2.1.2 Secondary Data Review

Secondary mapped data identifying possible underlying environmental parameters determining vegetation and soil distributions were standardised to base map scale and prepared in a GIS-compatible format to enable the production of map overlays illustrating single theme representations. The reviewed thematic information included:

- False colour LANDSAT TM images
- Geology (Geological Survey, 1980)
- Land Use Units (De Sousa Correira & Bredenkamp, 1987)
- FAO Land Types (FAO, 1984)
- Veld Types (Page, 1980)
- Agroecological Zones (De Pauw, 1996)
- Soil Associations classified by the South African Taxonomic System (Loxton *et al*, 1971; McVicar *et al*, 1977; Schneider, 1987)
- Topographic maps (Surveyor General)
- Water rest level contours (Namibia Groundwater Consultants, 1991).

2.2.2 Field Survey

A field survey route was established to traverse the boundaries of all land regions and the systems contained within. The main field survey was carried out concurrently with the soils and vegetation sampling programmes during April and May 1999, and the survey route was recorded by GPS.

The land regions/systems map was verified by field checks taken at 64 sample sites. FAO land evaluation guidelines were used in the field to confirm land units. The following individual elements were measured and described: altitude, slope angle and aspect, profile curvatures, land system and facet, micro-topography, surface condition and drainage, and erosion-deposition status.

2.2.2.1 Vegetation Survey

The two main descriptors used for vegetation were structure and composition. Vegetation structure was determined by estimating average height and canopy cover for each stratum (herb, grass, shrub and tree layer), while vegetation composition was obtained by listing all plant species per stratum with corresponding estimate of cover abundance according the Braun Blanquet method (Kent & Coker 1994). Thirty-seven sampling points with detailed information on vegetation structure and composition were established in this

manner. Voucher specimens of unknown plant species were collected for later identification and lodging at the National Botanical Research Institute in Windhoek.

In addition to the information described above, the extent of vegetation types was recorded by logging the position of each perceived vegetation boundary with a GPS en route.

2.2.2.2 Soil Survey

The soil survey was designed to acquire field data pertaining to the character and distribution of soils and land unit parameters represented in the project area. The survey was carried out at reconnaissance level in terms of observation density, and adopted a catenary transect approach to identify relationships between landform, slope position and soils.

Thirty-eight test pits and 25 auger holes were used to describe profiles and sample the major soil associations within land systems identified on the map. This was supplemented by a further 42 auger holes drilled to verify soil boundaries. Profile pits were dug at least twice in each significant land unit identified, although accessibility problems precluded the sampling of one land region.

All observations were located by GPS. Soil horizons were described in accordance with the FAO Guidelines for Soil Description (1977), and colours were determined on moist samples using the standard Munsell colour chart.

2.2.3 Data Analysis and Interpretation

2.2.3.1 Land Elements

Individual land surface measurements were incorporated into a preliminary polygon database to identify landform elements.

2.2.3.2 Vegetation Analysis and Initial Interpretation

The boundary points of main vegetation types recognised in the field (a total of 441 data points) were displayed on various false colour versions of the satellite image, on orthophotos and on the scanned and digitised background information used to prepare the main field survey.

Neither satellite image, nor any other background sources showed a satisfactory correlation with the vegetation types observed in the field. Based on the field observations it was evident that the main woodland and shrubland types recur throughout the entire region, but often localised and associated with different landforms. Since none of the prepared secondary sources of information allowed the mapping of these often localised vegetation types, the prepared land regions/systems basemap was considered to be the most important mapping source for vegetation cover.

2.2.3.3 Soil Analysis

Soil characteristics were determined on representative samples of each significant horizon in all soil pits. Soil property determinations were made by field and laboratory analysis. Physical, chemical, descriptive and analytical soil survey results were uniquely coded by sample and site identifiers and entered into Excel worksheets. Worksheet information was linked to land unit and system polygon identification codes.

Although not specifically required for classification purposes, dry bulk density and total porosity measurements were made to estimate the degree of soil compaction observed in test pit profiles in order to determine effective depth for land evaluation.

Clay fraction cation exchange capacities (CEC clay) were determined in addition to total soil CEC to highlight differences in base concentrations of all soils for which a low organic matter content was indicated. Total charcoal contents were estimated independently of other forms of carbon.

Soil analytical procedures followed standard reference methodologies. Tests used for the determination of soil properties complied with the requirements of the revised FAO system of soil classification (FAO/UNESCO/ISRIC; 1988) and land evaluation (FAO; 1991). Laboratory analyses were carried out by

Analytical Laboratory Services (Windhoek) who performed method validation by direct reference and sample exchange through the Agri Laboratories Association of Southern Africa (ALASA).

2.2.4 Verification of Land System Boundaries

A two-day flight survey was undertaken during August 1999 to cross-check the boundaries and extent of identified land systems. With the help of an additional 103 geo-referenced waypoints and notes made during the flight, the draft land systems map was reviewed, corrected and finalised.

2.2.5 Soil Classification and Boundary Mapping

The soils were classified to FAO group, unit and phase levels, and their boundaries drawn on a topographic base map at 1:250 000 scale. Soil unit boundaries were drawn using the following interpretative tools:

- ☐ A soil classification legend was established to reflect the evolutionary and geographical backgrounds to soil development in the region, and a field-verified set of catenary sequences was established at the landform scale to reflect soil change and identify unit boundaries.
- ☐ The boundaries of soil catenas were traced by analysis of recent (1996) aerial photographs at 1: 80 000 scale.
- ☐ Soils maps published for areas adjoining Kavango Region were referenced together with the mapped results of previous field-based studies on landform/soil associations in the region (Simmonds; 1997, 1998) to confirm boundaries and ensure their regional continuity. These included:
 - NW Ngamiland, Botswana (Jamagne, 1990)
 - Cubango Province, Angola (Minader, 1996)
 - NE Otjozondjupa Region (DRFN, 1999)
 - Commercial farms bordering south-central Kavango Region (Wierenga, 1999).

2.2.6 Land Systems Map Production

At the lowest level of aggregation land unit boundaries were drawn around areas where physical conditions were found to be uniform ((homogeneous). The total number of land unit types differentiated reflected the complete array of environmental settings found in Kavango, while the number of single land unit areas found within any one land system expressed the variability in local landscape surface conditions.

Individual land unit areas were identified to derive a land systems map of the region. Contiguous land unit types were found over and over again to be linked by surface geology, the occurrence of shallow groundwater and active geomorphological processes, factors which added considerable weight to the distinctive characterization of land systems. Although not traced on the final land systems map, land unit boundaries were fully described by soil unit changes, soil phase and catenary position, and therefore the soils map can be used to locate the position of specific land unit areas within each land system.

Vegetation assemblages were generally found to be uniform at the land unit level of aggregation and this precluded their use in the characterisation of land units. At the land system level, however, vegetation association boundaries were significantly clearer and were therefore employed either as supporting evidence to delineate system boundaries or to clarify boundaries that were fuzzy on the basis of other physical evidence.

At the highest practical level of aggregation, land regions were demarcated as clusters of land systems contained within discrete regional surface drainage areas. Within each drainage region individual land systems were represented as areas with a recurring pattern of topography, landform, depth of sand mantle, soil and vegetation associations within relatively uniform growing period zones.

Each land system was given a unique number code (e.g. 7.2, displayed on the map) linked to a single combination of characteristics in terms of vegetation composition, soil unit array, geological context, geomorphological processes and climatic zonation. Land units are included in both the database and the

annotated legend by connotative title (e.g. 'local depressions and flat areas with thin sand mantle') to demonstrate the localised nature of linkages found between catenary position, soil units and vegetation types.

2.2.7 Final Data Analysis and Mapping of Vegetation Types

As none of the remote sensing sources (various versions of analysed satellite imagery and black/white orthophotos) provided a satisfactory basis for mapping individual vegetation types, the final land systems map was used as a base map to depict the distribution of general vegetation types in the Kavango Region.

The majority of vegetation types recognised in the field were distributed across the entire region, but not necessarily associated with the same land system in different parts of the region. Hence, in order to derive general vegetation types, the vegetation types recognised in the field were listed according to presence in a particular land system and a map unit was assigned based on the dominant one to two field vegetation types. A map unit thus presents an amalgamation of different field vegetation types and is thus referred to as "general vegetation type". The general vegetation types are accompanied by schematic diagrams depicting the distribution of individual field vegetation types contained in each map unit in relation to landform (Section 5, Figs. 1 - 6).

Due to extensive disturbances related to land use and fires throughout the region, the conventional aim of vegetation mapping to map "potential natural vegetation" (i.e. vegetation types which would have occurred today, were it not for the impact of man) could not be fulfilled. The prepared map thus presents a baseline of general vegetation types in the late 1990's which are expected to undergo further development and changes according to local and regional impacts of different land use practices.

Each map unit is associated with a set of vegetation types, which in turn are linked to appropriate data of species composition and structure in a database (Table 1).

Table 1. Linkage of map units to field and database information.

Map Unit	Schematic Diagram	Database
General Vegetation Type	Vegetation type 1 (field)	Sample data 1
	Vegetation type 2 (field)	Sample data 2
	Vegetation type 3 (field)	Sample data 3

2.2.7.1 Data Structure

The field data are contained in an Excel workbook (Kav_veg_data.xls) with five individual worksheets containing data on habitat, environmental parameters, vegetation structure and species composition. A description of individual worksheets and explanatory notes to the data structure are provided in Specialist Report 1, Appendix 1. Map units (worksheet: map_unit), environmental data (worksheet: env), site data (worksheet: site), data on species composition (worksheet: cov) and species names (worksheet: species) have been stored in individual worksheets to enable linking of appropriate tables in a relational database.

2.3 SATELLITE DATA DISCREPANCIES AND MAPPED OUTPUTS

Data discrepancies observed between field evidence and satellite image signatures of specific environmental conditions resulted in a major revision to the original methodology, although the basic land systems approach remained intact. In particular, the effects of fire and the widespread surface coverage of ash contributed largely to the earliest, and ultimately unresolved, problem of verifying the unsupervised classification by ground-truth.

With respect to the vegetation mapping the chief source of data discrepancies could be traced back to the fact that the available satellite image data was inappropriate for use. The reasons for this and the repercussions on the mapped outputs are summarised below.

2.3.1 The Vegetation Map

2.3.1.1 Lack of Useful Satellite Image Map Base

The lack of a useful map base, i.e. a satellite image depicting vegetation types in the field, seriously compromised the outcome of this project activity. This resulted in a largely interpolated and coarse map of very general vegetation types linked to land region and systems rather than to land cover patterns perceived on the image.

External factors responsible for the difficulties included:

- ✓ Lack of seasonal correspondence between the dates of satellite image capture and the ground survey periods. In fact, as two years lapsed between the image capture and ground survey, two fire seasons were not shown on the satellite image. Therefore, field notes of recent fire impacts were fairly meaningless for the interpretation of the available image. Similarly, recent clearing activities would not have been represented on the older satellite image.
- ✓ The satellite information was captured in an exceptionally good rainy season, while the field survey was carried out in a poor season (see Table 1). Hence a denser cover of vegetation may have been depicted on the satellite image than was encountered during both the reconnaissance and the main field surveys. It is also likely that responses to a good rain year differ between vegetation types. This would seriously complicate and no doubt weaken any analysis based on "poor" season field data and a "good" season set of satellite signatures.
- ✓ The strong influence of fires depicted on the image masked the natural patterns of land cover.
- ✓ Time and budget constraints of the image processing/remote sensing inputs prohibited the testing of different remote sensing approaches to vegetation mapping once it became apparent that the original procedures failed to provide an adequate first approximation of land cover.

2.3.2 The Soils Map

2.3.2.1 Manual Mapping

- ✓ The lack of a suitable satellite image map base did not seriously compromise the outputs of the soils mapping activity although it did cause a considerable time delay in the completion of the soil map.

An alternative soils base map was compiled from digital topographical data sources at 1:50,000 scale, on which individual landforms were manually drafted and digitised. These were aggregated into soil catenas and land units with the support of field evidence and aerial photographic interpretation.

2.4 VEGETATION AND SOIL UNITS DESCRIPTIONS

The previous sections described the approach and methodology together with the technical challenges encountered in the production of vegetation and soils maps of Kavango Region.

Modifications to the methodology involved the collation of much secondary information, a great deal of which was used (and a few rejected) to provide some insight into the distribution of the most prominent and important vegetation and soil units. This information has been drawn together in the following sections in an attempt to comprehensively describe the evolutionary and climatic settings as well as current environmental pressures acting on these natural resources.

At the present stage very little can be quantitatively reported on causal linkages between soil and vegetation types and their distributions. There is no doubt that linkages do exist, and where factors controlling their areal extent are strongly indicated these are discussed.

2.4.1 Specialist Reports

This report was drawn from two specialist reports compiled for the soil and vegetation study components carried out. The text from these reports has been reproduced in abridged form without specific reference, and the reader requiring more detailed information should consult them directly. The reports are entitled:

Specialist Report 1:- Antje Burke (November, 1999); *Vegetation of the Kavango*

Specialist Report 2:- E. B. Simmonds (January, 2000); *Soils of Kavango Region*

The four maps accompanying these reports have been compiled in digital and hardcopy formats. For convenience, the hardcopies are reproduced at a scale of 1:400,000.

Map 1 is derived from topographic sources and illustrates the regional terrain and surface drainage features. Colour code and contour depict elevation differences. This map doubles up as a ground survey and flight path record.

Map 2 illustrates Land Systems and additionally demarcates land regions and surface drainage areas by colour code.

Map 3 describes Soil Units classified to the FAO Revised Legend (1991). This map can also be used to locate land units.

Map 4 illustrates General Vegetation Types by association of dominant species

3 CLIMATIC AND EVOLUTIONARY SETTING

3.1 CLIMATIC ZONES

Located between 17°20' - 19°12' S and 18° - 21° E, the climate of the Kavango Region is semi-arid with an average annual rainfall of 400 – 600 mm (van der Merwe 1983). The 500 mm rainfall isohyet cuts diagonally through the middle of the region in a broad loop from south-west to north-east, with lower mean annual totals recorded for the south. The region receives summer rainfall from December to April, and decades of regional climatic data record no rainfall between May and October.

The mean annual temperature of the regional weather station at Rundu is 22.2°C. Mean summer and winter temperatures differ by more than 5°C with a mean summer temperature (December to February) of 24.8°C and a mean winter temperature (June to August) of 17.1°C (P. Hutchinson, May 1999). Diurnal temperature ranges are highest in winter when frosts can occur. The frequency of high winds increases significantly from August onwards, reaching a maximum in November just prior to the onset of the rainy season. During the same period wind speeds also increase.

With respect to data collection activities undertaken for this investigation, rainfall conditions from 1996 to 1999 were extremely variable with an exceptionally good year in 1997 (Table 2).

Table 2. Total rainfall per season (July – June, measured at Rundu Airport) and corresponding activities during this project.

Season	Rainfall (mm)	Activity
1996/97	791.5	Satellite images captured
1997/98	254.5	-
1998/99	485.6	Field surveys

3.2 AGRO-ECOLOGICAL ZONES

The Agroecological Zones Map of Namibia (De Pauw, 1996) locates Kavango across six agroecological zones containing four growing period zones (Table 3). The latter are defined as areas experiencing a continuous period [specified] when both temperature and water availability conditions are able to support crop growth.

Table 3. Growing Period Zones and areas of influence in Kavango Region

Dominant Growing Period Zone	Associated Zones	Length of Growing Period	Areas of Influence in Kavango Region
GP1	GP2	Average and dependable growing period more than 120 days	Extreme north along the terraces bordering the Okavango river
GP2	GP3/GP1	Average growing period 91-120 days; dependable growing period 80% of average	North-west, west, north-central and north-east
GP3	GP4/GP2	Average growing period 61-90 days; dependable growing period 60% of average Average growing period 61-90 days; very short dependable growing period	South-west, central, south-central, east and south-east

Explanatory notes supplied by FAO (1991a) characterise arid climatic zones by an LPG (length of growing period) of less than 75 days and seasonally dry tropical areas by a dry season lasting between 90 and 285 days. This characterisation places Kavango region in a climatic transition zone, experiencing both arid and semi-arid conditions as reflected by average and dependable lengths of growing period.

Similarly, from the information used to derive the growing periods and their spatial extent in Table 2, it is evident that a north-east/south-west climatic gradient divides Kavango into two sub-regions in terms of moisture regimes, and therefore of potential moisture availability. Much of the region can expect an average growing period of 61-90 days, although the probability of this ranges from less than 60% in the south-west to over 80% in the north-east. A thin strip of the region to the extreme north experiences an average growing period of more than 120 days in most years. The variability of climatic parameters, rainfall in particular, therefore increases along this gradient in a south-westerly direction.

3.3 GEOLOGICAL AND GEOMORPHOLOGICAL OVERVIEW

3.3.1 Topography and Regional Drainage Characteristics

The perennial Okavango River flows eastwards along the northern border of Namibia. Situated south of Angola where the river rises, and west of the Botswana where it empties into the Okavango Delta, the administrative boundary of Kavango Region lies entirely within the south-western reaches of the Okavango River basin.

Topographically, Kavango is flat to gently undulating with maximum altitude differences of approximately 200 m across this vast region. The steepest relief gradients are encountered towards the Kavango River and where dry rivers (omiramba) have incised the surface mantle of sand. Regional elevations gradually descend from 1200 m.a.s.l in the extreme south and south-west to 1150 m.a.s.l west of Rundu, and to 1000 m at Andara on the Caprivi West boundary. The south-north regional gradient is thus of the order of 0.8 m/km (0.08%).

Gentle slope factors combined with the deep, highly permeable soils of the sand plains encourage very little surface runoff, and with the exception of rare high intensity rainfall events, soil absorption capacities are rarely exceeded. However, where long slopes, unstable soils and intensive forms of land use are combined, aeolian and sheet-wash erosion surfaces are evident.

Deep horizontal drainage occurs after heavy rains in the catchment areas of well-defined omiramba, although surface flow is ephemeral and generally truncated by sand drift and alluvial deposits. Surface waters collecting at the confluences of deep omiramba with the eastward draining Okavango River are largely the result of lateral flooding by the Okavango River.

In the extreme south and south-west of the region no omiramba are developed. Drainage mainly occurs via shallow depressions into numerous pans where impeded drainage conditions are found in shallow to moderately deep soils overlying and adjacent to calcrete outcrops. Calcrete crusts and hardpans caused by alternating dry and wet cycles have encouraged seasonal ponding in many localities and appear near the surface where sand cover is thin or lacking.

3.3.2 Landforms and Geological Context

Kavango region can be described as a large aggradational land surface characterised by an increasing differentiation of aeolian sands. True Kalahari sands deposited on the margins of the Kalahari Basin during the Tertiary desert-forming era (1.8 to 66 million years BP) underlie younger red sands deposited and later redistributed from the Late Holocene period to the present. During the latter period, wetter conditions prevailed from 49,000 to 34,000 years BP. From 34,000 to 27,000 years BP a period of aridity favoured the precipitation of calcrete deposits, after which a short return to wetter conditions prevailed (27,000 to 25,000 years BP). In the most recent geological time frame, from 25,000 BP to present, a distinct return to aridity has been documented (Heine & Geyh, 1984).

The land surfaces of Kavango are characterised by extensive areas of aeolian sand-drift and dune formations deposited on calcrete erosion surfaces, the calcretes having been formed by quasi-pedogenic processes associated with receding water surfaces under increasingly arid conditions.

Sand drift plains cover extensive areas of northern, north-eastern and central Kavango. The depth of sand mantle increases generally to the north and east, as does the extent to which those sands have been worked and reworked by wind. The plains slope gradually to the north-east and east, and are incised by a

number of well-defined omiramba. Over large tracts of the northern sand plains surface drainage features are imperceptible or non-existent.

A broad, indistinct sandy plateau in central Kavango marks the water divide between eastern-draining omiramba from the largest north-draining Omatako omuramba. This area is pitted with shallow depressions and defined by average slope gradients of less than 0.07%.

Fault systems produced by tectonic activity commencing during the early Cretaceous period exert a strong influence on the directions of omiramba in Kavango. Omiramba were initially incised along fault-weakened zones during a pluvial period post-dating the formation of calcrete layers at the top of the Kalahari Sequence. During subsequent periods of aridity intense aeolian processes have deposited dune sands on the floors of the omiramba valleys. Omiramba valleys are thus a combination of recent fluvial deposits, sandy side slopes of aeolian origin, and steep calcrete faces.

The eastward draining omiramba have incised into underlying calcretes at increasing depths towards the east, with the result that their valleys tend to narrow along their length. It is apparent that recent aeolian activities in addition to fluvial processes have influenced the form of these valleys and their environs. Dunes and drifts of wind blown-sand commonly fringe the eastern omiramba, being more pronounced on southern banks.

Basement formations comprising basalt and quartzite underlie localised areas in the south-east corner of Kavango, but do not surface in the region.

Western Kavango is characterised by extensive systems of seif dunes, orientated in an east-west direction and deposited on calcrete surfaces during the Late Holocene. Now stabilised by vegetation, the dune systems are clearly distinguished by dune amplitude and the depth of sand mantle to underlying calcrete. The widely spaced northern dunes are associated with a deep sand mantle whereas the more narrowly spaced southern dunes are associated with a shallower sand mantle. The latter are characterised by the common occurrence of pans in dune streets, where underlying calcretes are exposed or thinly covered by recent aeolian and colluvial deposits.

The western dune system gradually loses its distinctive morphology towards the east where its fringes are characterised by feathery complexes of flattened dune outliers with in-filled dune streets, and sand-drifts characteristic of the northern sand plains.

The south-west corner of Kavango intersects the northern tip of a broad flat pediplain where calcretes are exposed or lie near the surface of shallow aeolian and predominantly red sands. The pediplain tapers out to the north and east where the calcretes gradually disappear under sand drift and seif dunes.

The perennial eastern-flowing Okavango River is characterised by point bars, meanders, ox-bow lakes and other erosional and depositional features encompassing a distinct sequence of riverine land units. The floodplain area, two to six kilometres wide, can be divided into two zones. A broad area adjacent to the present course of the river actively receives fresh sediments during regular seasonal periods of inundation. As water levels drop, ponds and lakes remain. Behind this area can be found a drier zone where the floodplain is no longer seasonally inundated. A terrace system differentially covered by alluvial and aeolian deposits is situated approximately six kilometres behind the floodplain.

4 SOILS

The soils of Kavango were classified to the FAO/UNESCO/ISRIC Revised Legend (1988) using general principles and nomenclature recommended by FAO (1990). At the first level of generalization, 6 major soil groups were identified. These were subdivided at the second level into 11 soil units, of which 3 were further subdivided into 4 additional sub-units. Through this process, one first-level and two second-level inter-grades were identified. A total, therefore, of 15 distinct soil types were identified.

4.1 SOIL PHASES

Soil phases are subdivisions of soil units based on characteristics significant to the use or management of the land, but are not diagnostic for the separation of the soil units themselves. In terms of resource value, phases add an extra dimension to the diagnostic signature of any soil unit by indicating those factors that currently constrain its potential, or may do so if managed inappropriately.

Six phases were assigned to soils in specific areas of Kavango where surface and/or subsurface features of the land (e.g. arid conditions, cementation of parent material) formed constraints to their management and use. The phases cut across boundaries of different soil units and are not illustrated on the soil map although a description is nevertheless warranted, and given below. Where evidence of such conditions was identified by field investigation, phase levels have been appended to soil units described in Specialist Report 2.

4.1.1 Phreatic Phase

The phreatic phase refers to the occurrence of a groundwater table within 5m from the surface, the presence of which is not reflected in the morphology of the soil. Therefore the phreatic phase is not shown with Fluvisols. Its presence is important for the water regime of the soil, and because of this, especially in areas under irrigation, attention should be paid to effective water use and drainage in order to avoid salinization as a result of rising groundwater.

Phreatic phase sub-units occur in the north east and east of Kavango, particularly in a wide band stretching 50km to the north and 40km to the south of Kaudam camp in the streets of the incipient dunes and floors of paleo-drainage channels.

4.1.2 Yermic Phase

The yermic phase applies to soils which have less than 0.6% organic carbon in the surface 18cm when mixed, or less than 0.2% organic carbon if the texture is coarser than sandy loam, and which show one or more of the following features connotative of arid conditions:

1. Presence in the surface horizon of gravels or stones shaped by the wind or showing desert varnish (manganese coatings at the upper surface) or both. When the soil is not ploughed these gravels or stones usually form a surface pavement; they may show calcium carbonate or gypsum accumulating immediately under the coarse material.
2. Presence in the surface horizon of pitted and rounded quartz grains showing a matte surface, which constitute 10% or more of the sand fraction having a diameter of 0.25mm or more.
3. Presence of 2% or more palygorskite in the clay fraction in at least some subhorizon within 50cm of the surface.
4. Surface cracks filled with in-blown sand or silt; when the soil is ploughed this characteristic may be obliterated, although cracks may extend below the plough layer.
5. A platy surface horizon which frequently shows vesicular pores and which may be indurated but not cemented.
6. Accumulation of blown sand on a stable surface.

Over 70% of Kavango soils meet the first-level low organic matter requirements of the Yermic phase. Forty percent (40%) of the soils also contain one or more features connotative of arid conditions although not all of these soils contain less than 0.6% organic carbon content at the required surface layer. The arid

conditions found in the soils are described almost entirely by features 4 and 6 (above) and to a lesser extent by feature 2. Features 1, 3 and 5 do not occur in the region.

4.1.3 Fragipan Phase

The fragipan phase marks soils in which the upper level of a fragipan occurs within 100cm of the surface. A fragipan is a loamy (uncommonly a sandy) subsurface horizon with a high bulk density relative to the horizons above it, is hard or very hard and seemingly cemented when dry, and is weakly to moderately brittle when moist. When pressure is applied to peds or clods they tend to rupture suddenly rather than undergo slow deformation. Dry fragments slake or fracture when placed in water.

A fragipan is low in organic matter, slowly or very slowly permeable and often shows bleached fracture planes that are faces of coarse or very coarse polyhedrons or prisms. Clayskins may occur as patches or discontinuous streaks both on the faces and interiors of the prisms. A fragipan commonly, but not necessarily, underlies a B horizon. It may be from 15-200cm thick with commonly an abrupt or clear upper boundary, while the lower boundary is mostly gradual or diffuse.

Cambic Arenosols occurring in the eastern paleo-drainage system of Kavango show the only evidence of fragipan layering, where fragipans underlie incipient argillic B (illuviated) horizons.

4.1.4 Duripan Phase

The duripan phase marks soils in which the upper level of a duripan occurs within 100cm of the surface. A duripan is a subsurface horizon cemented by silica so that dry fragments do not slake during prolonged soaking in water or in hydrochloric acid.

Duripans vary in the degree of cementation by silica and in addition they commonly contain accessory cements, mainly iron oxides and calcium carbonate. As a result, duripans vary in appearance but all of them have a very firm or extremely firm moist consistency, and they are always brittle even after prolonged wetting.

Duripan sub-units occur in Kavango in association with Calcisols and Solonetz soils and where Cambic Arenosols occur in association with Solonetz soils. The most evident duripans are located in the south-central area where they lie to the east of the Omatako omuramba on the western edge of the watershed with the eastern paleo-drainage system.

4.1.5 Rudic Phase

The rudic phase marks areas where the presence of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable. Hand tools can be used and also simple mechanical equipment if other conditions are particularly favourable. Fragments with a diameter up to 7.5cm are considered as gravel; larger fragments are called stones or boulders.

Gravel, stones and boulders are not present in Kavango, although outcrops do occur. Basement outcrops occur in the SE corner of the region near Sikeretti on level to gently undulating slope classes. Occasional calcrete outcrops occur below the crests of both east- and west-facing slopes of the main Omatako omuramba channel, and where these occur the slope angles are of the order of 5-8%. Significant areas of calcrete lie within the plough layer of soils in the longer north-flowing omiramba and in the eastern-draining Khaudom omuramba.

4.1.6 Petrocalcic Phase

The petrocalcic phase marks soils in which the upper part of a petrocalcic horizon occurs within 100cm of the surface. A petrocalcic horizon is a continuous cemented or indurated calcic horizon, cemented by calcium carbonates and in places by calcium and some magnesium carbonate. Accessory silica may be present.

The petrocalcic horizon is continuously cemented to the extent that dry fragments do not slake in water and roots cannot enter. It is massive or platy, extremely hard when dry so that it cannot be penetrated by auger

or spade, and very firm to extremely firm when moist. Non-capillary pores are filled and hydraulic conductivity is moderately slow to very slow. It is usually thicker than 10cm.

Petrocalcic phase soils are present in Kavango where a petrocalcic layer underlies a calcic B horizon (i.e. as a petrocalcic C horizon) within 100cm of the surface. Areas include the SW karst pediplain, omuramba floors and narrow dune streets, and in southern Kavango on level to gently undulating slopes forming the watershed between the paleo-drainage system to the east, and the Omatoko omuramba to the west. In the latter case, large areas of calcrete deposits were observed to underlie soil profiles at shallow depths. In these areas, where a soil unit has been classified on the basis of a petrocalcic horizon, the name assumes the phase.

4.2 SOIL CLASSIFICATION SUMMARY

The FAO/UNESCO/ISRIC Revised Legend was followed as far as possible within the limits set by the World Soil Resources Report 60 (1988). Where discrepancies existed between field evidence and guidelines for classification, efforts were made to enhance the base of the legend without diminishing the integrity of its general principles.

In particular the presence, causes and possible effects of charcoal accumulations could not be ignored and were therefore documented to qualify master horizons. In the case of soil climate where soil properties warranted a more appropriate subdivision of Arenosols, no attempt was made to invent new criteria for classification although suggestions were made for the further use of such properties to the management and future evaluation of these soils. Standard interpretation procedures using total cation exchange capacity values (total CEC) for the determination of soil fertility were also questioned, and the alternative use of CEC (clay) values was explored. These three issues are discussed briefly in the following sections 4.2.1 to 4.2.3.

4.2.1 Qualification of Soil Horizons by Charcoal Accumulation

Charcoal accumulations posed a problem with the assignment of an appropriate horizon suffix to indicate its substantial and significant presence in Kavango soils as no appropriate FAO specification could be found to document it.

On the one hand the suffix 'p' denotes disturbance by ploughing or other tillage practices, although fires are omitted. On the other hand the suffix 'h' denotes the accumulation of organic matter in mineral horizons (e.g. Ah, Bh). For the A horizon, the 'h' suffix is applied only where there has been no disturbance or mixing from ploughing, pasturing or other activities of man. The 'h' and 'p' suffixes are thus mutually exclusive and neither one specifically highlights the presence of charcoal from fire burns.

Burning is not a tillage practice *per se* in Kavango although large areas have been repeatedly burned for field preparation and to create greater landscape visibility (flushing out of game; pre-Independence military operations). Fires of various magnitudes and heat regimes have also been induced by natural events (strike lightning) and are widespread throughout the region (Trigg, 1997).

The suffix 'h' was not assigned to horizons showing accumulations of charcoal because even though its presence in different part of the profile suggests fire sequences, the disturbance caused by fires could not definitively be attributed to either natural events or the activities of man. For want of a better solution the suffix 'p' was assigned to these horizons together with specific notation in profile descriptions.

4.2.2 Arid Moisture Regime

Where factors such as local climate, parent material and catenary position combine with soil morphology to produce a "soil climate" showing a propensity for low moisture availability at critical periods of the growing season, such soils exhibit an arid moisture regime.

Under the FAO (1974) legend this property was used to characterise Yermosols and Xerosols and to separate them from soils outside arid areas which have a comparable morphology. It has now been deleted from the revised legend, along with Yermosols and Xerosols, to conform to the general principle *not* to use climatic criteria to define soil units (FAO, 1990).

This deletion had repercussions on the classification of Kavango soils where, in the absence of this diagnostic condition and with no other condition to separate them, large areas of deep, light sandy soils are classified as modal Haplic Arenosols. A useful sub-division of these soil units could nevertheless be made on the basis of differences in soil moisture availability to rank them for management purposes and environmental resource value (for supporting properties refer to the Yermic phase, section 4.1.2). The conditions defining soils with an arid moisture regime would then follow the FAO legend as it was originally presented in FAO (1974), as follows:

- In most years these soils have no available water in any part of the moisture control¹ section for more than half the time (cumulative) that the soil temperature at 50cm is above 5°C.
- There is no period as long as 90 consecutive days when there is moisture in some or all parts of the moisture control section while the soil temperature at 50cm is continuously above 8°C.
- In most years the moisture control section is never moist in all parts for as long as 60 consecutive days during the 3 months following the winter solstice, where mean summer and mean winter temperatures differ by 5°C or more and mean annual temperature is less than 22°C.

In this regard, even though Kavango is not an arid region, deep, friable and freely draining sands cover large areas. Depending on the depth of consolidated parent material and on relative slope position, some of these soils are very unlikely to have available water in the moisture control section for over 90 consecutive days while the soil temperature is above 8°C. They are equally unlikely to have available water in any part of the moisture control section for more than 50% of the time that the soil temp is over 5°C.

In terms of the climatic conditions necessary to satisfy the soil conditions described above, a cross-check of regional data revealed that the mean annual temperature of the regional weather station (Rundu) is just 0.2°C above the critical maximum of 20°C. However, the mean summer and winter temperatures differ by more than 5°C, where:

June = 16.1°C; July = 16.1°C; August = 19.0°C (mean = 17.1°C);
Dec = 25.4°C; Jan = 24.9°C; Feb = 24.2°C (mean = 24.8°C).

Several decades of rainfall data strongly indicate that no rain falls between May and October in an average year.

4.2.3 CEC Values and the Determination of Soil Fertility

With respect to soil fertility, support for the interpretation of total cation exchange capacity (CEC values) rested on evidence deduced from several other test results. The low values of total CEC determined in fact suggested a significant and almost universal state of inherent *soil infertility*.

Such indications of infertility were supported by and could be attributed to genetically low clay and silt fractions combined with extremely low percentages of organic matter measured in all horizons of test pit profiles. In other words, if the soils of Kavango were the products of reworked aeolian parent material intrinsically lacking in colloidal clay, and if CEC is a property of the colloidal fraction of a soil, then high total CEC values indicative of soil fertility could never be attained for these soils.

However, to conclude that all soils of Kavango were infertile on the basis of total CEC values completely ignored the possibility that changes in the CEC values of the finer particle fractions alone could be linked to the occurrence of particular land unit types or vegetation sequences.

Although not quantitatively expressed, it was clear that the CEC (clay) values reflected differences in *relative soil fertility status* more definitively than did the CEC (total) values. Despite the low clay and silt fractions, immature horizon development and the dearth of soil organic matter, high CEC (clay) values were

¹ The moisture control section lies approximately between 10-30cm for medium to fine textures, between 20- 60cm for medium to coarse textures, and between 30-90cm for coarse textures.

nevertheless found. This indicated that exchangeable salts were actively moving into and out of, and up and down the soil profiles.

Whether these salts arrived in solution after storm events or as upwardly mobile evaporative precipitates characteristic of secondary enrichment, differences in their levels of concentration could be highlighted by CEC (clay) values. With only 7 exceptions in a group of 75 samples, the CEC (total) values indicated low to very low fertility ratings (<5 me/100g). Among the same group of samples, significant differences in CEC (clay) values were found, with a range from 1.20 to 518.38 me/100g. These differences could largely be attributed to exogenic influences (see Section 6.1.5) and are sufficient to warrant further investigation into the use of CEC (clay) as a diagnostic property for the classification and evaluation of Kavango soils.

For the purpose of this classification both the standard FAO reference limits for CEC (total) and their recommended limits for CEC (clay) were adhered to. For the determination of soil properties requiring CEC as an integral part of their equations, both CEC (total) and CEC (clay) values were used in separate calculations. However, as no method of validation could be found for the calculations based on CEC (clay) values, no attempt was made to use them either for classification purposes or to support judgement on soil conditions except where specifically recommended.

Bearing these caveats in mind, the soils of Kavango are summarized below in the explanatory legend to the reconnaissance soil map of Kavango Region. More detailed discussions of the classification issues and interpretation of soil properties may be found in Specialist Report 2.

4.3 EXPLANATORY LEGEND TO THE RECONNAISSANCE SOIL MAP OF KAVANGO REGION

Of the eight columns offered by the Revised Legend to reflect evolutionary and geographical background, four are represented in the region. Column 1 includes soil groups not bound by specific zonal climatic conditions: the Fluvisols. Column 2 comprises groups in which soil formation is conditioned by parent material: the Arenosols. Soils of Column 4 show accumulations of salts connotative of aridic conditions or physiological drought: the Calcisols and Solonetz. Column 8 soils are distinctive in having characteristics and processes profoundly altered by human influences: the Anthrosols.

Soils conditioned by intense weathering (the Alisols described by Column 7) are marginally represented in Kavango Region both in terms of intergrade classification and modest extent of areal coverage. Description is not therefore required although the presence of these soils is indicated on the map for the sake of comprehensive notation.

4.3.1 Soils Conditioned by Parent Material

4.3.1.1 Arenosols: Soils Developed in Sands

AR	ARENOSOLS
ARh	Haplic Arenosols
ARb	Cambic Arenosols
ARo	Ferralic Arenosols
ARc	Calcaric Arenosols
Arhk	Calci-Haplic Arenosols

The most abundant parent materials of Kavango Region include the extensive wind-blown sands on which Arenosols have developed.

Arenosols are defined as soils which are coarser than sandy loam to a depth of at least 100cm of the surface, with less than 35% of rock fragments or other coarse fragments in all subhorizons within 100cm of the surface (exclusive of materials which show fluvic or andic properties). No diagnostic horizons other than an ochric A horizon or an albic E horizon are required.

Fine sands are the dominant size fraction of Arenosols in Kavango, indicating without a doubt the aeolian nature of the parent material. The total fine sand content is generally more than 50% and often greater than 70%. Clay and silt are less than 10% and often around 6%.

These soils are marked by the absence of any significant soil profile development and profiles are generally uniform throughout the depth. They are highly permeable and storage of available water is low within normal rooting depths. This is supported by high porosity values of about 42% with a predominance of large and free-draining pores. Consequently these soils are poor in moisture retention and experience prolonged periods of moisture stress. The low moisture availability can be attributed to their predominantly sandy textures. Surface horizons have slightly higher moisture contents of about 8% compared to that of subsurface horizons which is in the range of 3-6%.

In common with the Arenosols of neighbouring northwest Ngamiland (Botswana) and northeast Otjosondjupa Region, these sands behave remarkably like structurally stable soils under most rainfall conditions. Although not aggregated they also do not develop crusts on the loose sand surfaces. Infiltration rates are high with initial rates being much higher (DRFN, 1999), in keeping with the coarse granular textures and lack of surface crust development. Runoff therefore can be expected to be minimal even on slopes with up to 5% inclination. Thus, in terms of erodibility, they can be considered to provide a certain amount of resistance to erosion.

4.3.2 Soils Conditioned by Limited Leaching

4.3.2.1 Solonetz: Sodic Soils

SN	SOLONETZ
SNh	Haplic Solonetz
SNhx	Haplic-xanthic Solonetz
SNk	Calcic Solonetz

Solonetz soils are formed in Kavango where sodium is present in the soil matrix in excess over calcium. These soils are found in conditions of impeded drainage controlled by shallow layers of indurated or consolidated parent materials on the high plains of the ephemeral watershed. In low catenary positions they are found in association with pans and shallow underlying calcrete on the gently undulating sand plains and omiramba floors of the eastern drainage region.

All Solonetz soils in Kavango are recognised by a thin loose litter cover resting on black humified surface material about 2-3cm thick. This overlies a brown granular A horizon which abruptly changes into a natric B horizon with coarse prismatic or columnar structure elements and grading with depth into a massive subsoil.

Sodium carbonate (Na_2CO_3) may be formed in these soils by the evaporation of water containing sodium bicarbonate or by the biological reduction of sodium sulphate. Under either of these conditions clay is dispersed and worked into the subsoil, forming a dense accumulation horizon with columnar or prismatic subsoil structures. Clays held in surface horizons are decomposed in the high pH conditions resulting from the presence of Na_2CO_3 , and in conditions of periodically low salt content combined with high exchangeable sodium.

The essential characteristic of Solonetz soils is therefore a natric B horizon which has an exchangeable sodium percentage (ESP) of 15 or more. Such a high value will also affect the concentration and balance of other ions, particularly the divalent ions that are preferentially adsorbed at the exchange complex. The high ESP of Solonetz is both directly and indirectly harmful to plants whereby a high proportion of sodium ions in the soil induces toxicity directly in salt sensitive plants and obstructs the uptake of other essential plant nutrients.

In terms of textural characteristics the Solonetz soils occurring in Kavango are variable, depending on the depth and consolidation of parent material and on catenary position. Fine to very fine sands dominate the sand fraction with a content of 50-75%, although sand content as a whole varies from 21-90%. Similarly in the finer particle fraction silt contents vary from 5 to 72%, although clay content remains low at 3-9%. Soils on lower topographic sites in eastern Kavango are generally heavier textured, whereas soils in areas of

impeded drainage on local high ground (where duripans underlie soils of the ephemeral catchment divide) are light textured. Solonetz soils with local concentrations of clay are waterlogged in the wet season.

Moisture retention properties of the Solonetz soils are not dependent on pore size distribution alone as part of the soil moisture is always retained due to osmotic potential. Due to these conditions, moisture content is never constant and this property does not reflect moisture availability to plants.

4.3.2.2 *Calcisols: Soils with a Calcium Carbonate Accumulation*

CL	CALCISOLS
CLh	Haplic Calcisols
CL1	Luvic Calcisols
CL1p	Hyper-Luvic Calcisols
CLp	Petric Calcisols

Calcisols occur in Kavango in all land systems with the exception of the Okavango floodplain. These soils always occupy low catenary positions in local landscape sequences and are always found in association with shallow calcrete deposits. Whereas the pans scattered across Kavango are not always associated with calcrete, those pans which are formed on petrocalcic layers are found in association with Calcisols.

The most prominent feature of Calcisols is the translocation of calcium carbonate from the surface horizons to an accumulation layer at depth. This layer may be soft and powdery or consist of hard concretions or calcite pendants, and can eventually become indurated and cemented.

In terms of profile characteristics the Calcisols of Kavango are distinctly recognizable by a thin brown A horizon over a darker brown Bck horizon and/or a yellowish brown Cck or Cmk horizon that is speckled with white calcite mottles. The organic matter content of the surface soil is low on account of sparse vegetation and rapid decomposition of vegetal debris. The surface soil is crumb or granular, but platy structures also occur where this horizon is enhanced by a high percentage of adsorbed magnesium. Subsurface horizons are weakly platy in structure or structureless. The highest calcite concentration is found in the deeper B horizons.

The Calcisols do not appear to follow any noticeable trend in particle size distribution although medium textures prevail with fine to very fine sands dominating the sand fraction at 40-70%. Silt fractions vary between 7 and 37% and clays between 5-14%.

Total porosities are remarkably high at 41-64%, with an overall increase in pore size due to the presence of calcium carbonate in the profiles. Consequently there is an increase in the proportion of freely draining macro-pores and a decrease in the proportion of slow and non-conducting micropores which would otherwise retain adsorbed moisture. Moisture retention properties are therefore lower than the clay contents indicate, although available moisture levels are considerably higher. Infiltration rates are moderate with average values being more closely related to the higher porosities in the calcic horizon than to the proportion of micropores.

The Calcisols are therefore inherently well drained. Where the surface soils are silty in the south-east corner of Kavango, slaking and crust formation no doubt hinders infiltration, causing runoff, sheet-wash erosion, and in places the exposure of a petrocalcic horizon. Where they lie on shallow petroclastic horizons on the southwest pediplain, however, they tend to become waterlogged.

They are also potentially fertile soils as they are rich in mineral nutrients, although the high calcium may also result in iron and zinc deficiencies.

4.3.3 Soils Conditioned by Relief

4.3.3.1 Fluvisols: Soils of Alluvial Lowlands

FL	FLUVISOLS
FLd	Dystric Fluvisols

Fluvisols have developed in recent fluvial deposits on the floodplain of the Okavango River. On the banks and active floodplain of the Okavango river these soils are periodically wet in all or part of the profile due to the presence of seasonal flood water.

The floodplain area, two to six kilometres wide, can be divided into two zones in terms of soil development and modification. A broad area adjacent to the present course of the river actively receives fresh sediments during regular seasonal periods of inundation and hence the soils are regularly rejuvenated. The soils of this zone, although used for wet season cropping and dry season grazing, are not profoundly modified by agricultural activities and can therefore be classified by their fluvic properties.

Soil profiles and auger holes show stratified layers of coarse and fine materials with a predominance of fine to very fine sands and silts in shallower horizons and an increase in clay content with depth. Significantly, the deposition of clay layers is uncommon and clay contents even at depth are consequently lower than would be expected in these alluvial soils. This attribute can be linked to the scarcity of clays in the provenance areas (Minader, 1996). Surface clay contents are lower than subsurface horizons with an average of 6%, increasing irregularly to 14% in lower horizons. Low clay contents combined with low and irregular levels of organic matter are also linked to relatively low nutrient concentrations and CEC (total) levels. Whereas these soils are not infertile, they are also not highly productive.

4.3.4 Soils Conditioned by Human Influence

4.3.4.1 Anthrosols

AT	ANTHROSOLS
ATd	Dystric Anthrosols

Away from the main Okavango River channel in a broad zone of variable width, the floodplain is no longer seasonally inundated. In this area soils resembling buried Fluvisols at depth and Arenosols nearer to the surface have developed on colluvial sands lying over older dry fluvial deposits.

Intensively used for both dryland and irrigated cultivation, these soils have been significantly modified. Evidence from borehole records and sample analyses (Weirenga, 1999) indicate that the original morphology of these soils would have included buried accumulation horizons of stratified coarse and fine materials under moderately deep fine sands of colluvial and aeolian origin. Analytical and profile records from Mashere Agricultural College indicate that the surface horizons have been physically mixed by ploughing, chemically altered by the addition of organic materials, leached by irrigation water and generally deficient in potassium.

These soils therefore have been classified as Anthrosols to indicate the degree to which modification by agricultural use has altered a number of their diagnostic properties. Judging by the inherently low CEC status of the Arenosol group, by the relatively low nutrient concentrations of the underlying Fluvisols, and by the fact that organic additives are needed to increase the concentration of base cations, these soils have been categorized as Dystric Anthrosols.

4.4 SOIL UNIT SUBDIVISIONS

Soil units classified in the legend to the reconnaissance soil map of Kavango Region are given overleaf in abridged form (Table 4). For a detailed description of diagnostic horizons and properties refer to Specialist Report 2 (Sections 4.1 – 4.2), where these characteristics are presented together with a discussion of qualifying features significantly present in Kavango soils.

Table 4. Soil Unit Classification with Diagnostic Properties and Horizons (abridged)

AR ARENOSOLS	CL CALCISOLS	AT ANTHROSOLS
Soils which are coarser than sandy loam to a depth of at least 100cm of the surface, having less than 35% of rock fragments or other coarse fragments in all subhorizons within 100cm of the surface, exclusive of materials which show fluviu or andic properties; having no diagnostic horizons other than an ochric A horizon or an albic E horizon.	Soils having one or more of the following; a calcic horizon, a petrocalcic horizon or concentrations of soft powdery lime within 125cm of the surface; having no diagnostic horizons other than an ochric A horizon, a cambic B horizon or an argic B horizon which is calcareous; lacking the characteristics which are diagnostic for Vertisols or Planosols; lacking salic properties; lacking gleyic properties within 100cm of the surface.	Soils in which human activities have resulted in profound modification or burial of the original soil horizons through removal or disturbance of surface horizons, cuts and fills, secular additions of organic materials, long-continued irrigation, etc.
ARh Haplic Arenosols Arenosols having no diagnostic horizon other than an ochric A horizon; lacking ferralic properties; lacking gleyic properties within 100cm of the surface. Deep to very deep moderately well to somewhat excessively drained, dark grey to white sands to sandy loams.	CLh Haplic Calcisols Calcisols lacking an argic B horizon and a petrocalcic horizon. Moderately deep to deep, imperfect to moderately well drained, dark brown and greyish brown to yellowish brown, sands to sandy loams.	ATd Dystric Anthrosols Anthrosols which have a base saturation (by Na ₂ OAc) of less than 50% at least from 20 to 50cm from the surface. Moderately deep to deep, moderately well to well drained, dark brown fine sands to sandy loams. This unit of classification does not appear in the FAO revised legend. Based on field experience, however, it best describes the soil characteristics modified by man on the old and now drying Okavango floodplain (no longer periodically inundated). It is suggested as a refinement to the legend.
ARhk Calci-Haplic Arenosols Haplic Arenosols having calcic properties within 125cm of the surface; lacking the properties diagnostic of Calcisols and Calcaric Arenosols. Deep to very deep, well drained, dark reddish brown, loamy medium-fine sands.	CL1 Luvic Calcisols Calcisols having an argic B horizon; lacking a petrocalcic horizon. Moderately deep to deep, imperfectly to moderately well drained, brownish black, fine loamy sands.	SN SOLONETZ Soils having a natric horizon.
ARb Cambic Arenosols Arenosols showing colouring or alteration characteristic of a cambic B horizon immediately below the A horizon; lacking lamellae of clay accumulation; lacking ferralic properties; lacking an albic E horizon with a minimum thickness of 50cm; lacking gleyic properties within 100cm of the surface; non-calcaric. Deep to very deep, well to somewhat excessively, strong brown to red, loamy sands to loamy fine-medium sands.	CL1p Hyper-Luvic Calcisols Luvic Calcisols resting on very calcareous material which has more than 40% CaCO ₃ equivalent. Moderately deep, imperfect drainage, brownish black to greish yellow brown, fine sandy loams.	SNk Calcaric Solonetz Solonetz having a calcic horizon or concentrations of soft powdery lime within 125cm of the surface; lacking a gypsic horizon; lacking stagnic properties and lacking gleyic properties within 100cm of the surface. Shallow to moderately deep, poor to imperfect drainage, dull yellowish orange to dark reddish grey, fine sandy loams to silty loams.
ARc Calcaric Arenosols Arenosols which are calcaric; lacking gleyic properties within 100cm of the surface. Deep to very deep, moderately well to well drained, dark grey to pale brown fine sands to loamy sands.	CLp Petric Calcisols Calcisols having a petrocalcic horizon. Shallow to moderately deep, imperfect drainage, dark reddish grey to brownish grey, sandy loams.	SNhk Calci-haplic Solonetz Haplic Solonetz having calcic properties; lacking the properties diagnostic of Calcaric Solonetz. Shallow to moderately deep, poorly drained, dull yellowish brown sands.
ARo Ferralic Arenosols Arenosols showing ferralic properties, and colouring of the B horizon expressed by chromas of 5 or more or hues redder than 10YR; lacking a clay increase or lamellae of clay accumulation within 125cm of the surface; lacking an albic E horizon with a minimum thickness of 50cm; lacking gleyic properties within 100cm of the surface; non-calcaric. Deep to very deep, well to excessively drained, yellowish brown to dark red, coarse sands to loamy fine sands.	FL FLUVISOLS Soils showing fluviu properties and having no diagnostic horizons other than an ochric, a mollic or an umbric A horizon, or sulphidic material within 125cm of the surface.	SNh / SNhx Haplic Solonetz / Haplic-xanthic Solonetz Solonetz having an ochric A horizon; lacking stagnic properties and lacking gleyic properties within 100cm of the surface. Moderately deep to deep, poor to imperfect drainage, greyish brown to dull yellow orange/brown, silty fine sands to sandy loams.
	FLd Dystric Fluvisols Fluvisols having a base saturation (by NH ₄ Oac) of less than 50% at least between 20 and 50cm of the surface; lacking a sulphidic horizon and sulphidic material within 125cm of the surface.	

5 LAND SYSTEMS AND ASSOCIATED VEGETATION TYPES

Seven land regions, 19 land systems and 62 land units were identified and mapped for Kavango Region. The main features defining the land systems within each region are described in this section as an annotated legend to the final Reconnaissance Land Systems Map of Kavango Region (Map 2). Land Regions (LR) are included in the description and their boundaries are outlined on Map 2 by the colour coding of the systems:

LR1 Western Stabilised Dunes: Pale Yellows

LR2 Karst Pediplain: Brown

LR3 Northern Sandplain: Oranges

LR4 Omatako Drainage: Blues

LR5 Ephemeral Catchment Divide: Grey

LR6 Southern/Eastern Panveld: Mauve

LR7 Eastern Flowing Paleo-Drainage: Greens

The properties and distribution pattern of the most prominent and important soil units of the region as a whole have already been described. In this section soils are catalogued by land unit to characterize their locations in more detail and to identify their associations with individual landforms and local catenary sequences.

The characteristics of vegetation types are described where it was possible to associate their distribution patterns and boundaries with specific land systems.

5.1 LAND REGION 1 WESTERN STABILISED DUNES

Western Kavango is characterised by extensive systems of seif dunes orientated in an east-west direction and deposited on calcrete surfaces during the Late Holocene. Now stabilised by vegetation, the dune systems are clearly distinguished by dune amplitude and the depth of sand mantle to underlying calcrete. The widely spaced northern dunes are associated with a deep sand mantle whereas the more narrowly spaced southern dunes are associated with a shallower sand mantle. The latter are characterised by the common occurrence of pans in dune streets, where underlying calcretes are exposed or thinly covered by recent aeolian and colluvial deposits.

Table 5. LR1 Western Stabilised Dunes

Map Code	Land System	Land Unit	Soil Unit
1.1	Wide Dunes	Dune crests and slopes	Cambic Arenosols
		Inter-dune valleys: no pans	Haplic Arenosols
1.2	Narrow Dunes	Dune crests and slopes	Cambic Arenosols
		Inter-dune valleys: thin sand mantle, no pans	Ferralic Arenosols
		Inter-dune valleys: pan zones	Petric Calcisols
1.3	Dune Fringes	Dune crests and slopes	Cambic Arenosols
		Inter-dune valleys: thin sand mantle, no pans	Ferralic Arenosols
		Sand-drift plain	Haplic Arenosols
		Pan zones	Petric Calcisols

The western dune systems gradually lose their distinctive morphologies towards the east where the fringes are characterised by feathery complexes of flattened dune outliers with in-filled dune streets, and sand-drifts characteristic of the northern sand plains.

5.1.1 Vegetation Types Associated with Land Systems of the Western Stabilised Dunes

5.1.1.1 *Baikiaea plurijuga* – *Schinziophyton rantanenii* Woodland on Stabilised Dunes

Simplified map unit	Teak – mangetti woodland
Associated land systems	1.1 Wide dunes, 1.2 Narrow dunes
Associated vegetation types	<i>Baikiaea plurijuga</i> woodland, <i>Schinziophyton rantanenii</i> woodland, <i>Pterocarpus angolensis</i> woodland, <i>Burkea africana</i> woodland, <i>Acacia erioloba</i> shrubland – woodland, <i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Bauhinia petersiana</i> shrubland

Several woodland and shrubland types are associated with the west-east running stabilised dunes of western Kavango. The typical sequence of vegetation types is closely associated with landform and likely determined by rooting depth. Thus *Baikiaea* and *Schinziophyton* woodlands with deep-rooted trees dominate on dune crests, followed by *Pterocarpus angolensis* (Kiaat) on dune slopes and shrubland with *Acacia erioloba*, *Terminalia sericea*, *Acacia fleckii* and *Bauhinia petersiana* prevalent in dune valleys (Fig. 1).

Within the woodlands trees are widely spaced, averaging about 20 % crown cover. *Croton gratissimus*, *Terminalia sericea*, *Combretum collinum* and *Baphia massaiensis* form often dense stands of shrub undergrowth, while *Digitaria seriata* is the most important grass component.

The dune valleys are covered by a mosaic of grassland and shrubland with occasional *Acacia erioloba*, *Lonchocarpus nelsii* and *Combretum collinum* trees. The shrubs *Combretum hereroense*, *Acacia fleckii* and *Bauhinia petersiana* often form single species thickets. Occasional depressions support grassland with species such as *Anthephora pubescens*. Shallower rooting depth possibly caused by impeding layers of cemented fine material (hard pan) may explain the prevalence of shrubs and grasses in these habitats.

Today the majority of dune valleys have been cleared for agriculture and multiple sequences of re-growth of shrubs and trees mask the natural distribution of vegetation types.

LAND REGION	WESTERN STABILISED DUNES				
MAP UNIT	Teak – Mangetti woodland (<i>Baikiaea plurijuga</i> – <i>Schinziophyton rautanenii</i> woodland)				
Vegetation Type	<i>Acacia erioloba</i> – <i>Combretum hereroense</i> shrubland	<i>Pterocarpus angolensis</i> woodland	<i>Baikiaea plurijuga</i> – <i>Schinziophyton rautanenii</i> woodland	<i>Pterocarpus angolensis</i> woodland	<i>Bauhinia petersiana</i> shrubland
DOMINANT SPECIES & STRUCTURE	<i>Acacia erioloba</i> <i>Bauhinia petersiana</i> <i>Acacia fleckii</i>	<i>Pterocarpus angolensis</i>	<i>Baikiaea plurijuga</i> <i>Schinziophyton rautanenii</i>	<i>Pterocarpus angolensis</i>	<i>Combretum hereroense</i>
SOIL FAMILY	CALCISOLS	ARENOSOLS			
LAND SYSTEM	WIDE DUNES		NARROW DUNES		
Land Unit	Interdune valley	Dune slope	Dune crest	Interdune valley	

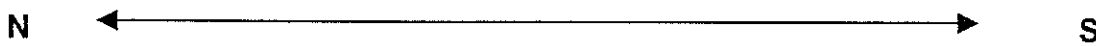


Fig 1. Schematic diagram (not to scale) of *Baikiaea plurijuga* – *Schinziophyton rautanenii* woodland with associated soil families on western stabilised dunes.

5.1.1.2 *Burkea africana* – *Bauhinia petersiana* Woodland and Shrubland on Dune Fringes

Simplified map unit	<i>Burkea</i> – <i>Bauhinia</i> woodland and shrubland
Associated land system	1.3 Dune fringes
Associated vegetation types	<i>Burkea africana</i> woodland, <i>Bauhinia petersiana</i> shrubland, <i>Baikiaea plurijuga</i> woodland, <i>Burkea africana</i> – <i>Terminalia sericea</i> shrubland, <i>Dichrostachys cinerea</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Catophractes alexandri</i> shrubland

The dune fringes present a transitional zone between dunes and sandplain, still showing the west-east alignment of dunes where dunes are present, but the dunes are lower, widely spaced and often not continuous. The vegetation of sandplains and dune valleys is thus more prominent.

Burkea africana woodlands are prevalent on dune crests and areas with reasonable sand cover, while *Baikiaea plurijuga* woodlands form occasional outliers on higher dunes.

The dunes valleys support mainly *Bauhinia petersiana* shrubland, with patches of *Terminalia sericea* shrubland and *Catophractes alexandri* and *Dichrostachys cinerea* indicating possible hardpan formation and calcrete crusts in the subsoil. *Schmidtia pappophoroides* is one of the dominant grasses in these shrublands.

5.2 LAND REGION 2 KARST PEDIPLAIN

The southwest corner of Kavango intersects the northern tip of a broad flat pediplain where calcretes are exposed or lie near the surface of shallow aeolian and predominantly red sands. The pediplain peters out to the north and east where the calcretes gradually disappear under sand drift and seif dunes. Thought to be the fringe of a calcrete apron skirting the Karst Otavi mountain complex, the pediplain is characterised by numerous pans and dune remnants.

Table 6. LR2 Karst Pediplain

Map Code	Land System	Land Unit	Soil Unit
2	Karst pediplain	Gentle rises and flat areas: thin sand mantle	Calcaric Arenosols
		Depressions on hard plain	Petric Calcisols

5.2.1 Vegetation Types Associated with Land Systems of the Karst Pediplain

5.2.1.1 *Acacia erioloba* – *Terminalia sericea* Shrubland on Pediplain

Simplified map unit	Camelthorn – Silver <i>Terminalia</i> shrubland
Associated land region	2. Pediplain
Associated vegetation types	<i>Baikiaea plurijuga</i> woodland, <i>Burkea africana</i> woodland <i>Acacia erioloba</i> shrubland, <i>Combretum collinum</i> shrubland, <i>Bauhinia petersiana</i> – <i>Terminalia sericea</i> shrubland, <i>Catophractes alexandri</i> shrubland

Only the remnants of dunes and the fringes of pans support larger trees, e.g. *Baikiaea* and *Burkea* woodland patches on dunes and *Acacia erioloba* trees near pans (Fig. 2). Occasional *Ziziphus mucronata* and *Peltophorum africanum* trees also occur although shrubs such as *Terminalia sericea*, *Bauhinia petersiana*, *Combretum hereroense*, *Acacia fleckii*, *Baphia massaiensis* and *Combretum collinum* dominate the vegetation cover. Dense patches of *Catophractes alexandri* indicate calcrete crusts near the surface.

Grasses can form locally dense patches in depressions with *Hyparrhenia hirta* and *Antheophora pubescens* being the most prominent.

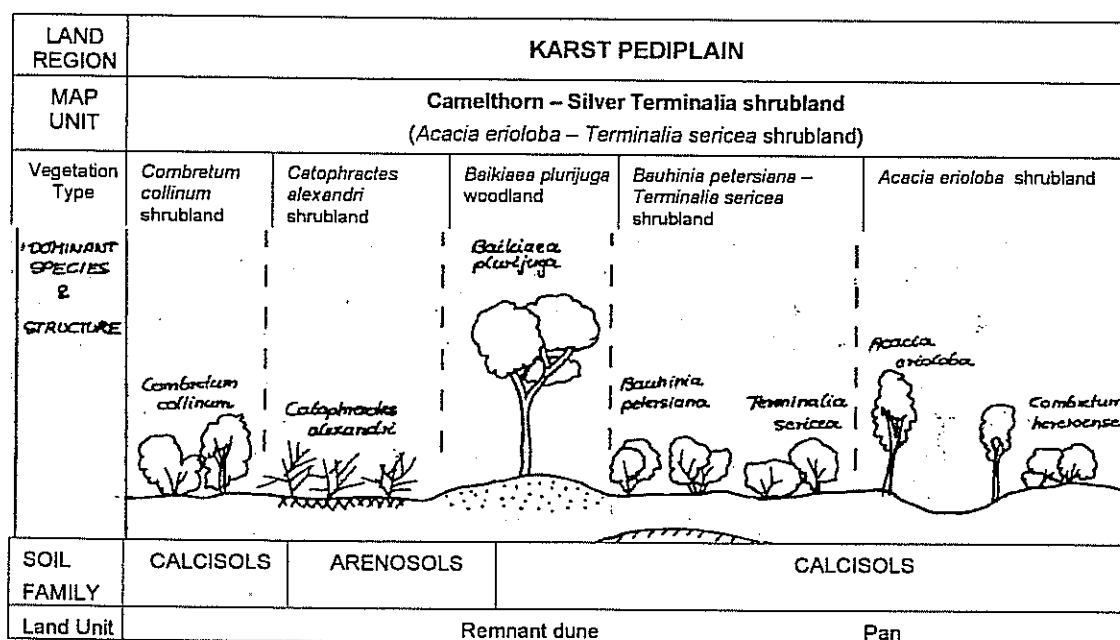


Fig. 2. Schematic diagram (not to scale) of *Acacia erioloba* – *Terminalia sericea* shrubland and associated soil families on karst pediplain.

5.3 LAND REGION 3 NORTHERN SANDPLAIN

Sand drift plains cover extensive areas of northern, north-eastern and central Kavango. The depth of sand mantle increases generally to the north and east, as does the extent to which those sands have been worked and reworked by wind. The plains slope down gradually to the north-east and east, are incised by a number of well-defined north and east draining omiramba, and are bordered by the perennial Kavango River system in the north. Over large tracts of the northern sand plains surface drainage features are imperceptible or non-existent.

Fault systems produced by tectonic activity commencing during the early Cretaceous period exert a strong influence on the directions of omiramba. Omiramba were initially incised along fault-weakened zones during a pluvial period post-dating the formation of calcrete layers at the top of the Kalahari Sequence. During subsequent periods of aridity intense aeolian processes have deposited dune sands on the floors of the omiramba valleys. Omiramba valleys are thus a combination of recent fluvial deposits, sandy side slopes of aeolian origin, and steep calcrete faces.

The perennial eastern-flowing Okavango River is characterised by point bars, meanders, ox-bow lakes and other erosional and depositional features encompassing a distinct sequence of riverine land units. The floodplain area, two to six kilometres wide, can be divided into two zones. A broad area adjacent to the present course of the river actively receives fresh sediments during regular seasonal periods of inundation. As water levels drop, ponds and lakes remain. Behind this active floodplain area can be found a drier zone where the floodplain is no longer seasonally inundated. A terrace system, differentially covered by alluvial and aeolian deposits, is situated to the hinterland of the floodplain.

Table 7. LR3 Northern Sandplain

Map Code	Land System	Land Unit	Soil Unit
3.1	Okavango river and terraces	Floodplain: seasonally inundated	Dystric Fluvisols
		Floodplain: dry back floor & base of terraces	Dystric Anthrosols
		Terraces: mid slopes	Haplic Arenosols
		Terraces: crests	Ferralic Arenosols
3.2	Sand plain incised by short omiramba	High sites & flat areas: central & northern sand plain	Haplic Arenosols
		Flat areas with shallow water table: NE Kavango	Ferralic Arenosols
		Local depressions with shallow water table	Haplic Calcisols
		Flat areas: NW Kavango	Haplic Arenosols
3.3	Northern omiramba	Omiramba crests and slopes	Cambic Arenosols
		Omiramba floors: thin sand mantle	Ferralic Arenosols
		Omiramba floors: deep sand mantle and/or colluvial deposits	Cambic Arenosols
		Omiramba floors: pan zones	Haplic Calcisols
3.4	Dune Outliers - wide dunes, NE Kavango	Crests and mid-slopes	Cambic Arenosols
		Interdune valleys	Haplic Arenosols

5.3.1 Vegetation Types Associated with Land Systems of the Northern Sandplain

The northern Kalahari sandplain is dissected by various north and east-flowing omiramba and is bordered by the perennial Kavango River in the north. Although the permanently flowing Kavango River is associated with wetland and riverine vegetation distinctly different from the hinterland, their localised distribution limits mapping of these vegetation types at a regional scale. They are thus included and discussed in broad terms within this section. The northern sandplains present three general vegetation mapping units:

- Okavango valley fields and shrubland
- Kiaat – Mangetti woodland and
- Camelthorn shrubland.

5.3.1.1 Okavango Valley Fields and Shrublands

Simplified map unit	Okavango valley fields and shrublands
Associated land systems	3.1 Okavango River and terraces
Associated vegetation types	<i>Acacia nigrescens</i> – <i>Peltophorum africanum</i> riverine forest, <i>Combretum imberbe</i> – <i>Acacia erioloba</i> shrubland, <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland, <i>Catophractes alexandri</i> shrubland, floodplain grasslands

Floodplain, river bank, old flood plain (terrace) and terrace slope comprise the main sequences of landforms bordering the Kavango River (Fig. 3). Grasslands with species such as *Vossia cuspidata*, *Cynodon dactylon* and *Setaria sphacelata* dominate the floodplain, while riverbanks originally supported riverine forests with *Acacia nigrescens*, *Peltophorum africanum* and *Diospyros mespiliformis* as dominant trees and a dense shrub undergrowth of various species. However, due to intense clearing and cultivation along the river, riverine forest has disappeared almost entirely and only few, localised patches remain. Today's river banks and terrace present an open parkland with few trees, cultivated land and many villages in between. Remnants of shrubland with *Combretum imberbe*, *Acacia erioloba*, *Terminalia sericea* and *Bauhinia petersiana* indicate the potential vegetation types of former terraces. However, human impact has also resulted in an increase in shrubs, often on old farmland and may thus give a false indication of what may have occurred naturally on these old floodplain terraces.

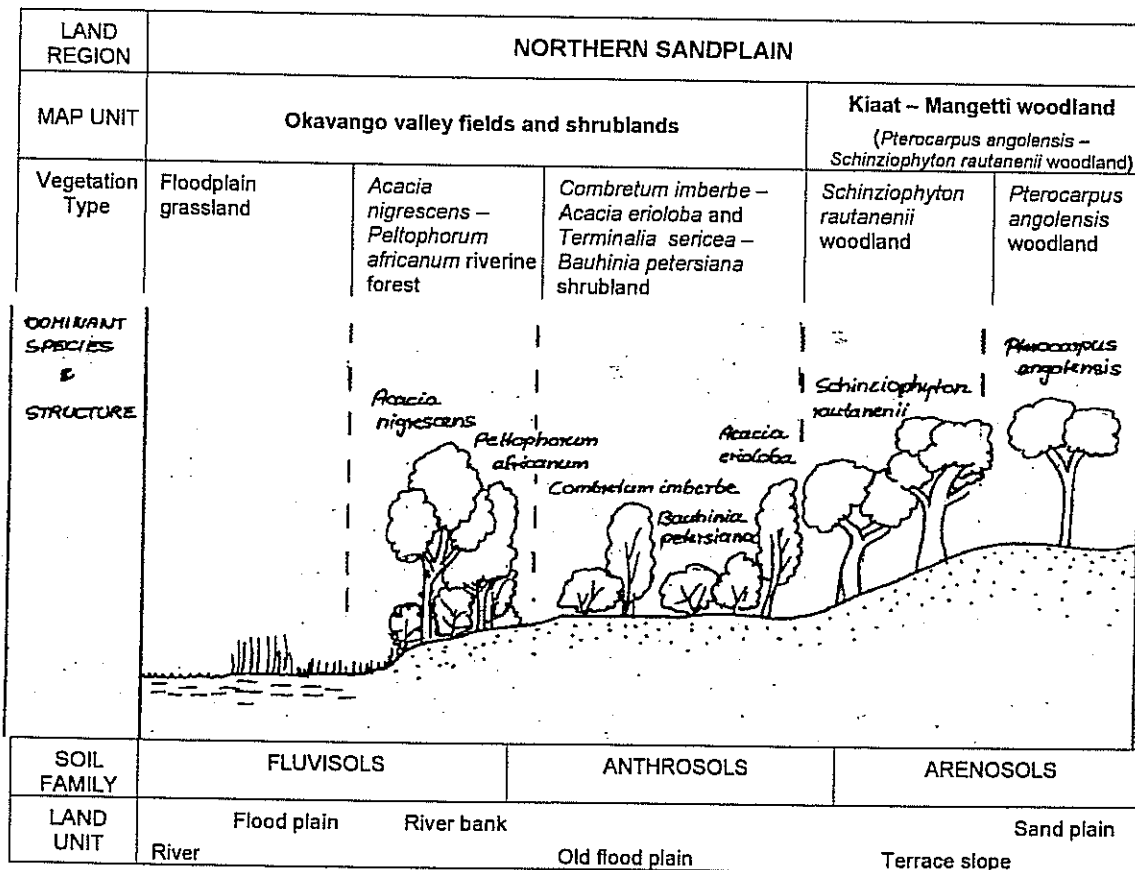


Fig. 3. Schematic diagram (not to scale) of *Pterocarpus angolensis* – *Schinziophyton rautanenii* woodland and associated soil families on northern sandplain.

5.3.1.2 *Pterocarpus angolensis* – *Schinziophyton rautanenii* Woodland on Northern Sandplain

Simplified map unit	Kiaat – Mangetti woodland
Associated land systems	3.2 sandplain incised by short omiramba, 3.4 eastern outliers of wide dunes
Associated vegetation types	<i>Pterocarpus angolensis</i> woodland, <i>Schinziophyton rautanenii</i> woodland, <i>Baikiaea plurijuga</i> woodland, <i>Burkea africana</i> woodlands

The terrace slopes support open stands of *Schinziophyton rautanenii*, possibly still prevalent despite human impact because of their value as fruit trees.

The northern sandplain forms a sheet of several meters of sand cover with very few pans. Although *Pterocarpus angolensis* and *Schinziophyton rautanenii* woodlands are prominent, localised patches of *Baikiaea plurijuga* and *Burkea africana* woodlands occur throughout this map unit. *Combretum collinum* forms another important tree component, while *Combretum zeyheri*, *Combretum psidioides*, *Bauhinia petersiana* and *Baphia massaiensis* are prominent in the shrub layer. Common grasses associated with these woodlands comprise *Digitaria seriata*, *Schmidtia pappophoroides* and *Urochloa brachyura*.

5.3.1.3 *Acacia erioloba* Shrubland in Northern Omiramba

Simplified map unit	Camelthorn shrubland
Associated land system	3.3 northern omiramba
Associated vegetation types	<i>Acacia erioloba</i> shrubland, <i>Terminalia sericea</i> shrubland <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland

Also heavily transformed by human activities, the shallow, dry rivers (omiramaba) of northern Kavango support a mosaic of cultivated fields, old fields with largely shrubby re-growth and occasional patches of *Acacia erioloba* trees and shrubland. In addition to *Acacia erioloba*, common shrubs are *Terminalia sericea* and *Bauhinia petersiana*.

5.4 LAND REGION 4 OMATAKO DRAINAGE

Because of its extent and influence far beyond the Kavango Region, the Omatako Omuramba has been assigned an individual land region map unit. The systems within this region, comprising the broad main channel floor, the tributary areas and the upper slopes, may be viewed as areas with recurring patterns of genetically linked land units.

In terms of catenary sequencing the region is divided into systems individually displaying distinctly different erosion-deposition relationships between their component land units. Within the region as a whole the land systems also link up to form a cascading 'meta-system' functioning as a series of simple erosion catenas. This is compounded in places (particularly between the main Omatako channel and steep valley side slopes) by more complex local erosion-deposition sequences. At these locations surface wash is greatest on the lower, but steeper, parts of slopes. This has favoured the preferential removal of fine soil particles from these areas and their subsequent deposition onto valley floors, leaving residual coarse-grained soils at the base of slopes.

Table 8. LR4 Omatako Drainage

Map Code	Land System	Land Unit	Soil Unit
4.1	Main channel floor	Channel floor: pan zones	Haplic Calcisols
		Channel floor & confluences: thin sand mantle	Ferralic Arenosols
4.2	Main channel side slopes; tributary floors and lower side slopes	Mid slopes: shallow calcrete	Calcaric Arenosols
		Mid slopes: deep sand mantle	Cambic Arenosols
		Crests	Ferralic Arenosols
		Tributary floors: pan zones	Haplic Calcisols
		Tributary floors and side slopes: shallow calcrete	Calcaric Arenosols
		Tributary floors & side slopes: deep sand mantle and/or colluvial deposits	Cambic Arenosols
4.3	Tributary upper slopes	Western tributaries top slope transition to dunes: thin sand mantle	Ferralic Arenosols
		Western tributaries top slope transition to dunes: shallow calcrete, pan zones	Petric Calcisols
		Eastern tributaries: upper slopes, thin sand mantle	Ferralic Arenosols
		Eastern tributaries: upper slopes, shallow calcrete, south-west of watershed	Petric Calcisols
		Eastern tributaries: upper slopes, shallow calcrete, north-west of watershed	Haplic Calcisols

5.4.1 Vegetation Types Associated with Land Systems of the Omatako Drainage

Because of its extent and influence far beyond the Kavango Region, the Omatako Omuramba has been assigned an individual map unit. The Omatako drainage area includes three general vegetation map units:

- Omatako grassland
- Mixed shrubland and
- *Burkea* woodland and shrubland.

5.4.1.1 Omatako Grassland

Simplified map unit	Omatako grassland
Associated land system	4.1 Main channel floor
Associated vegetation types	<i>Cynodon dactylon</i> – <i>Enneapogon desvauxii</i> grassland, <i>Cynodon dactylon</i> grassland

The Omatako valley is covered by a mosaic of recent and old fields, grassland and localised patches of shrubland (Fig. 4). Occasional *Acacia erioloba* trees, and shrubby forms of *Acacia erioloba* and *Acacia fleckii* are the most prominent woody components of the vegetation, often forming dense stands at the margin of the channel floor. *Cynodon dactylon*, *Enneapogon desvauxii*, *Aristida stipitata* and *Stipagrostis hirtigluma* are some of the important grasses. The majority of the Omatako main channel and associated slopes has been greatly altered by agricultural activities.

5.4.1.2 Mixed Shrubland

Simplified map unit	Mixed shrubland
Associated land system	4.2 Tributaries and main slopes
Associated vegetation types	<i>Acacia erioloba</i> shrubland, <i>Terminalia sericea</i> shrubland <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland, <i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland, <i>Dichrostachys cinerea</i> shrubland

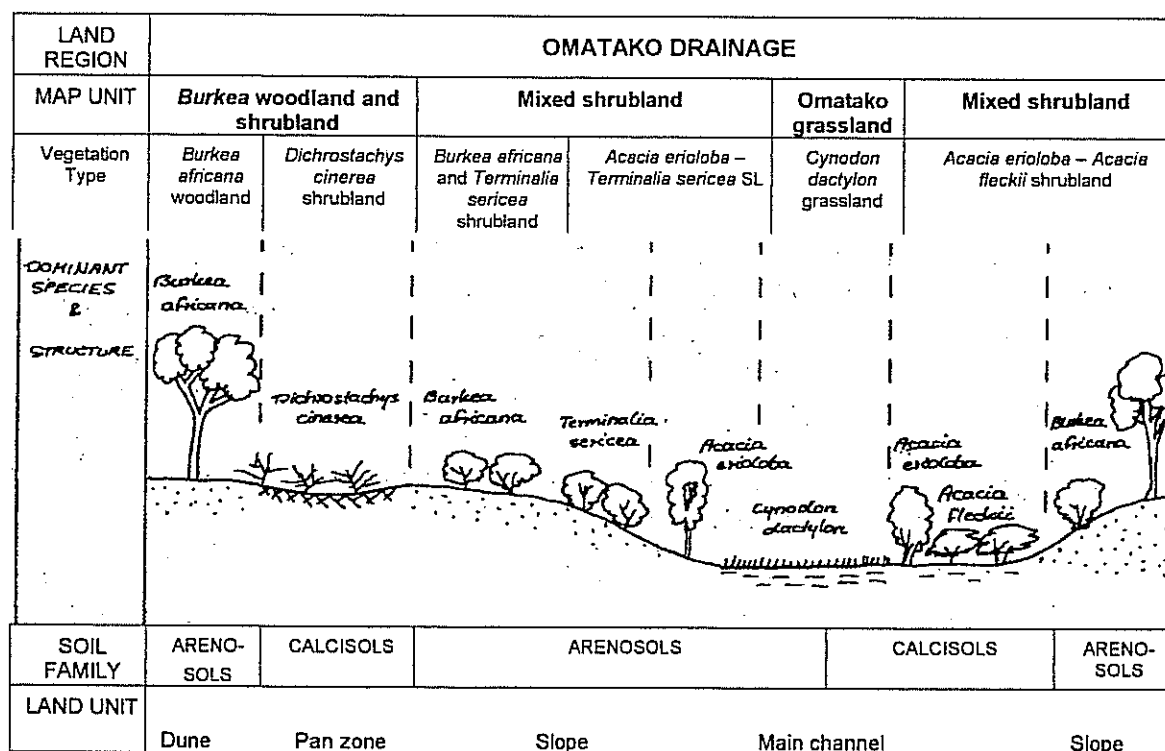
The tributaries to the Omatako and lower slopes from a transition from the main channel floor to the stabilised dunes to the west and sandplain to the east. Largely altered by agricultural activities and fires

shrubland is most prominent on these slopes, with *Acacia erioloba*, *Acacia fleckii*, *Terminalia sericea* and *Bauhinia petersiana* most prominent.

5.4.1.3 *Burkea africana* Woodland and Shrubland on Omatako Slopes

Simplified map unit	<i>Burkea</i> woodland and shrubland
Associated land system	4.3 Upper slopes and tributaries
Associated vegetation types	<i>Burkea africana</i> woodland, <i>Burkea africana</i> shrubland, <i>Dichrostachys cinerea</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Catophractes alexandri</i> shrubland

The Omatako slopes show a sequence of shrubland and woodland similar to the dune and dune valley arrangement. The shrubland of lower slopes are followed by *Burkea africana* woodlands towards the top of the slopes (Fig. 4). As agricultural activities are still evident in the tributaries to the Omatako and upper slopes, *Burkea* shrubland could also indicate the impact of disturbance by clearing and thus present re-growth of former *Burkea* woodlands. Where calcrete appears at the surface and possible other impeding layers limit root penetration, *Catophractes alexandri* and *Dichrostachys cinerea* shrubland prevail.



W ← → E

Fig. 4. Schematic diagram (not to scale) of vegetation types and soil families of the Omatako Omuramba and Omatako slopes (SL = shrubland).

5.5 LAND REGION 5 EPHEMERAL CATCHMENT DIVIDE

A broad, indistinct sandy plateau in central Kavango marks the water divide between eastern-draining omiramba from the largest north-draining Omatako omuramba. This area is pitted with shallow depressions and defined by average slope gradients of less than 0.07%. Extensive areas of indurated and consolidated parent material lie in shallow subsurface layers impeding drainage throughout the region.

Table 9. LR5 Ephemeral Catchment Divide

Map Code	Land System	Land Unit	Soil Unit
5	High Plain	Local depressions and flat areas with thin sand mantle	Cambic Arenosols
		Local crests: shallow calcrete, pan zone	Calci-Haplic Solonetz

5.5.1 Vegetation Types Associated with Land Systems of the Ephemeral Catchment Divide

One of the most complex map units, the ephemeral catchment divide provides a mosaic of localised differential substrate conditions ranging from deep sand to calcrete outcropping and possible calcrete and silcrete based impeding layers in the subsoil. As such the vegetation is dominated by open *Burkea africana* woodlands, intercepted by many localised vegetation types associated with pans and other hard substrates not visible at the surface (Fig. 5).

5.5.1.1 *Burkea africana* Woodland on Ephemeral Catchment Divide

Simplified map unit	Catchment divide
Associated land region	5. Ephemeral catchment divide
Associated vegetation types	<i>Burkea africana</i> woodland, <i>Baphia massaiensis</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Acacia erioloba</i> – <i>Peltophorum africanum</i> shrubland, <i>Acacia erioloba</i> – <i>Hyphaene petersiana</i> shrubland, <i>Bauhinia petersiana</i> – <i>Terminalia sericea</i> shrubland, <i>Eragrostis lehmanniana</i> grassland, <i>Combretum hereroense</i> – <i>Acacia fleckii</i> shrubland, <i>Dichrostachys cinerea</i> shrubland

Except for *Burkea africana*, other prominent trees are occasional stands of *Pterocarpus angolensis* and *Combretum collinum*. The tall palm *Hyphaene petersiana* is usually associated with pan margins (Fig. 5). Shrublands are diverse and include almost all shrub vegetation types encountered in previous map units. *Acacia erioloba*, *Peltophorum africanum*, *Acacia fleckii*, *Combretum hereroense*, *Baphia massaiensis*, *Terminalia sericea*, *Dichrostachys cinerea* and *Bauhinia petersiana* occur in different combinations throughout this map unit.

Accordingly the same grasses associated with these woodland and shrubland vegetation types are prevalent and include *Digitaria seriata* and *Schmidtia pappophoroides*. The centre of pans support grassland, often formed by a single species, such as *Eragrostis lehmanniana*.

LAND REGION	EPHEMERAL CATCHMENT DIVIDE						
MAP UNIT	Catchment divide vegetation (<i>Burkea africana</i> woodland)						
Vegetation Type	<i>Combretum hereroense</i> shrubland	<i>Burkea africana</i> woodland	<i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland	<i>Eragrostis lehmanniana</i> grassland	<i>Acacia erioloba</i> – <i>Peltophorum africanum</i> shrubland	<i>Burkea africana</i> woodland	<i>Bauhinia petersiana</i> shrubland
DOMINANT SPECIES & STRUCTURE							
SOIL FAMILY	ARENOSOLS			SOLONETZ	ARENOSOLS		
LAND UNIT	Plain and local depressions			Perched pan zone	Plain		

Fig. 5. Schematic diagram (not to scale) of *Burkea africana* woodland and associated soil families on ephemeral catchment divide.

5.6 LAND REGION 6 SOUTHERN PANVELD

The northern tip of the Tsumke Panveld intersects the southern Kavango boundary to the west of the transitional hardpan system of Land Region 7. The boundaries of this region were mapped from aerial photographs and confirmed by aerial reconnaissance. From this bird's eye viewpoint the high plain of the southern panveld does not appear to form part of the eastern catchment of the Omatako omuramba. By the direction of its slope gradient it should form a link to the hardpan areas of the eastern drainage system, although it stands isolated in the landscape of southern Kavango, resembling most closely the ephemeral catchment divide located further north. It may in fact be a relic ephemeral watershed now physically separated from the main catchment divide by sand drift. From secondary information sources (DRFN, 1999; De Pauw, 1996; FAO, 1984) the soils of this area are inferred to be Arenosols formed in simple catenary sequence with Calcisols overlying shallow calcrete deposits.

Table 10. LR6 Southern Panveld

Map Code	Land System	Land Unit	Soil Unit
6	High calcrete plain	Flat areas: thick sand mantle	Haplic Arenosols
		Depressions: shallow calcrete	Petric Calcisols

5.6.1 Vegetation Types Associated with Land Systems of the Southern Panfeld

5.6.1.1 Silver Terminalia – Blade Thorn Shrubland

Simplified map unit	Silver <i>Terminalia</i> – blade thorn shrubland
Associated land regions and systems	6. calcrete plain
Associated vegetation types	<i>Terminalia sericea</i> shrubland, <i>Acacia fleckii</i> shrubland <i>Catophractes alexandri</i> shrubland, <i>Burkea africana</i> – <i>Terminalia sericea</i> shrubland, <i>Burkea africana</i> shrubland

Essentially presenting the northern fringe of the Tsumkwe panveld this map unit consists largely of shrubland, with larger trees only framing the margin of pans.

5.7 LAND REGION 7 EASTERN FLOWING PALEO-DRAINAGE

Calcrete deposits underlie the extensive sand plains of this region, and where they surface or lie at shallow depths in depressions, they are associated with numerous small and large pans. Depth of calcrete, relief gradients and local water transfer mechanisms play important roles in the formation of Calcisols and Solonetz soils in this region. Where gradients are lowest Calcisols tend to form in large faintly bowl-shaped areas underlain by shallow calcrete, in association with large pans. Where relief is controlled by incipient dune formations and minor omiramba incisions through calcrete deposits, Solonetz soils tend to form in the more defined longitudinal depressions containing numerous small pans.

In the case of the omiramba draining eastwards towards Botswana, incision depths into underlying calcretes increase towards the east, with the result that their valleys tend to narrow along their length. It is apparent that recent aeolian activity in addition to fluvial processes have influenced the form of these valleys and their environs. Dunes and drifts of wind blown-sand commonly fringe the eastern omiramba, being more pronounced on southern banks.

Basement formations comprising basalt and quartzite underlie areas in the south-east of this region but do not surface. The formations are capped by surface deposits of calcrete and consolidated aeolian sands forming a complex 'hardpan' surface.

From a geomorphological point of view the hardpan land system represents a deflation zone in which the entire surface has been differentially denuded and eroded by aeolian processes. It is a residual landscape of inverted features where former dunes have been eroded down to lower positions, and now act as wind corridors between higher areas more resistant to denudation. On top of the higher areas lie the remains of former pans and their associated, now dessicating, soils. These soils are now perched on gently convex crests with ample opportunity for surface runoff as opposed to their original locations on flat, interdune floors with conditions more conducive to the collection of surface water.

The hardpan system loses its morphology towards the west in a broad transitional zone, merging with extensive sand plains and large pans east of the ephemeral catchment divide.

Table 11. LR7 Eastern Flowing Paleo-Drainage

Map Code	Land System	Land Unit	Soil Unit
7.1	Sand plain with common small pans	Low dune crests, mid slopes & flat areas: thick sand mantle	Haplic Arenosols
		Low dune crests, mid slopes & flat areas: shallow calcrete	Calci-Haplic Arenosols
		Slope bases & depressions: shallow calcrete	Calcic Solonetz
7.2	Sand plain with large pans	Low dune crests, mid slopes & flat areas: shallow calcrete	Haplic Calcisols
		Higher sites & crests of long gentle slopes: thin sand mantle	Ferralic Arenosols
		Pan zones	Haplic-xanthic Solonetz
7.3	Hard pan	Sand-drift plain: shallow calcrete	Calcic Arenosols
		Convex crests: shallow calcrete	Hyper-Luvic Calcisols
		Pan zones	Petric Calcisols
7.4	Eastern omiramba	Omiramba crests	Haplic Arenosols
		Omiramba: mid & base slopes	Cambic Arenosols
		Omiramba floors: shallow calcrete	Petric Calcisols
		Omiramba floors: pan zones	Calcic Solonetz
		Omiramba floors: thin sand mantle	Ferralic Arenosols
		Omiramba tributary floors: thick sand mantle	Cambic Arenosols
7.5	Dune Outliers - narrow dunes, SE Kavango	Crests and mid-slopes	Cambic Arenosols
		Interdune valleys: thin sand mantle	Ferralic Arenosols
		Interdune valleys: pan zones	Petric Calcisols
7.6	Transitional system between hard pan & sand plain with large pans	Crests of long rises & eastern draining tributary base slopes	Luvic Calcisols / Haplic Alisols
		Pan zones	Petric Calcisols

5.7.1 Vegetation Types Associated with Land Systems of the Eastern Flowing Paleo-Drainage Systems

Draining towards the Okavango Delta to the east this land region is characterised by remnants of shallow dunes, wide omiramba and many evident as well as subsurface pans. Five general vegetation map units are contained in this land system:

- Burkea – Baphia woodland and shrubland
- Burkea – False mopane woodland
- Silver Terminalia shrubland
- Eastern omiramba grassland and
- Silver Terminalia – blade thorn shrubland.

5.7.1.1 *Burkea africana* - *Baphia massaiensis* Woodland and Shrubland on Eastern Sandplain

Simplified map unit	<i>Burkea</i> – <i>Baphia</i> woodland and shrubland
Associated land system	7.1 Sandplain with small pans
Associated vegetation types	<i>Burkea africana</i> woodland, <i>Burkea africana</i> – <i>Guibourtia coleosperma</i> woodland, <i>Baphia massaiensis</i> shrubland, <i>Combretum imberbe</i> – <i>Acacia erioloba</i> shrubland, <i>Burkea africana</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland

Moderate sand cover and numerous small pans characterise the landforms contained in this map unit. *Burkea africana* woodlands are associated with deeper sand, while shrubland prevails on shallower soils near pans (Fig. 6). *Baphia massaiensis* forms one of the most prevalent shrub vegetation types, followed by *Combretum imberbe* – *Acacia erioloba*, *Acacia erioloba* – *Acacia fleckii* and *Terminalia sericea* shrubland.

5.7.1.2 *Burkea africana* – *Guibourtia coleosperma* Woodland on Eastern Sandplain

Simplified map unit	<i>Burkea</i> – False mopane woodland
Associated land system	7.2 sandplain with large pans
Associated vegetation types	<i>Burkea africana</i> – <i>Guibourtia coleosperma</i> woodland, <i>Burkea africana</i> woodland, <i>Acacia erioloba</i> shrubland, <i>Combretum imberbe</i> – <i>Acacia erioloba</i> shrubland, <i>Burkea africana</i> shrubland

Although similar to the previous map unit, larger and more widely spaced pans characterise this general vegetation type. The most conspicuous feature is the presence of *Guibourtia coleosperma* trees, thus resulting in *Burkea africana* – *Guibourtia coleosperma* woodland as the dominant vegetation type (Fig. 6). Shrubland is less prominent than in the previous unit and includes *Acacia erioloba*, *Combretum imberbe* and *Burkea africana* shrubland.

5.7.1.3 *Terminalia sericea* Shrubland on Hardpan

Simplified map unit	Silver <i>Terminalia</i> shrubland
Associated land system	7.3 hardpan
Associated vegetation types	<i>Terminalia sericea</i> shrubland, <i>Baikiaea plurijuga</i> woodland, <i>Terminalia prunioides</i> woodland, <i>Acacia fleckii</i> shrubland, <i>Catophractes alexandri</i> shrubland, <i>Acacia mellifera</i> shrubland

Underlying quartzite, although not surfacing, is probably responsible for the formation of a hardpan in the subsoil. This map unit shows a curious pattern of a matrix of *Terminalia sericea* shrubland on shallow soils with numerous, interspersed patches of *Baikiaea plurijuga* and *Terminalia prunioides* woodlands. Although almost no relief is evident, the *Baikiaea* woodlands are thought to be growing on remnants of dunes, while a hardpan near the surface supports the growth of *Terminalia prunioides* woodland.

Terminalia prunioides woodland shows shrub undergrowth of largely *Dichrostachys cinerea*, *Mundulea sericea* and *Croton gratissimus*, while prevalent grasses are *Aristida stipitata* and *Enneapogon cenchroides*.



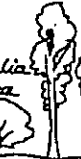






LAND REGION	EASTERN PALAEO DRAINAGE					
MAP UNIT	<i>Burkea</i> – <i>Baphia</i> woodland and shrubland (<i>Burkea africana</i> – <i>Baphia massaiensis</i>)		Eastern omiramba grassland (<i>Cynodon dactylon</i> grassland in eastern Omiramba)			<i>Burkea</i> – False mopane woodland
Vegetation Type	<i>Burkea africana</i> woodland	<i>Baphia massaiensis</i> shrubland	<i>Combretum imberbe</i> <i>Acacia erioloba</i> – shrubland	<i>Cynodon dactylon</i> grassland	<i>Acacia mellifera</i> shrubland	<i>Burkea africana</i> – <i>Guibourtia coleosperma</i> woodland
DOMINANT SPECIES & STRUCTURE	<i>Burkea africana</i> 	<i>Baphia massaiensis</i> 	<i>Acacia erioloba</i>  <i>Combretum imberbe</i> 	<i>Cynodon dactylon</i> 	<i>Acacia mellifera</i>  <i>Terminalia sericea</i> 	<i>Burkea africana</i>  <i>Guibourtia coleosperma</i> 
SOIL FAMILY	ARENOSOLS		SOLONETZ	CALCISOLS	ARENOSOLS	
LAND UNIT	Sandplain		Omuramba floor with pan		Sand plain	

Fig. 6. Vegetation types and associated soil families of the eastern-flowing palaeo drainage.

5.7.1.4 *Cynodon dactylon* Grassland in Eastern Omiramba

Simplified map unit	Eastern omiramba grassland
Associated land system	7.4 eastern omiramba
Associated vegetation types	<i>Cynodon dactylon</i> grassland, <i>Acacia mellifera</i> shrubland, <i>Terminalia sericea</i> shrubland, <i>Combretum imberbe</i> – <i>Acacia erioloba</i> shrubland

The eastern omiramba (with the Khaudom River and Nhoma River as the two main channels) are part of an ancient drainage system and, thus been exposed to erosion processes for long periods, present today wide open valleys, mainly supporting grassland in the centre and shrubland along their fringes (Fig. 6). Although *Cynodon dactylon* is the dominant grass in most parts, other grasses such as *Setaria sphacelata* and *Eragrostis echinochloidea* are locally common. In the vicinity of surface water *Phragmites australis* forms dense conspicuous stands. Dense stands of *Acacia mellifera* shrubs likely indicate the presence of subsurface calcrete.

5.7.1.5 *Terminalia sericea* – *Acacia fleckii* Shrubland on Dune Fringes

Simplified map unit	Silver <i>Terminalia</i> – blade thorn shrubland
Associated land regions and systems	7.5 eastern remnants of narrow dunes, 7.6. transitional zone
Associated vegetation types	<i>Terminalia sericea</i> shrubland, <i>Acacia fleckii</i> shrubland <i>Catophractes alexandri</i> shrubland, <i>Burkea africana</i> – <i>Terminalia sericea</i> shrubland, <i>Burkea africana</i> shrubland

Remnants of west-east aligned dunes and wide open valleys characterise this map unit. *Terminalia sericea* and *Acacia fleckii* shrubland are the most prominent vegetation types in this unit. Calcrete crusting occurs locally supporting *Catophractes alexandri* shrubland. *Burkea africana* shrubland may present re-growth in fire impacted areas or indicate subsurface hardpans preventing the growth of taller trees.

5.8 SYNOPSIS

Table 12 overleaf illustrates the array of prominent soil units and vegetation types represented in Kavango Region as a series of associations aggregated by land system.

It is worth pointing out that this large region covering 84,000 km² inherently contains an extremely limited genetic stock of distinguishable soil units and recognisable vegetation types. Nevertheless, environmental factors controlling the distribution and development of the soils have combined with those controlling the distribution and modification of vegetation types to produce 19 distinct land systems containing 62 unique land units.

These factors are explored in the final section to this report to in an attempt to provide some understanding of the current status of the soil and vegetation resources and their vulnerability to external pressures.

Table 12. Vegetation Types and Soil Associations Aggregated by Land System

LAND REGION	LAND SYSTEM	VEGETATION MAPPING UNIT	VEGETATION TYPES	SOIL ASSOCIATIONS
1 Western Stabilised Dunes	1.1 Wide dunes	Teak – Mangetti woodland	<ul style="list-style-type: none"> ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Schinziophyton rautanenii</i> woodland 	Cambic Arenosols Haplic Arenosols
	1.2 Narrow dunes	Teak – Mangetti woodland	<ul style="list-style-type: none"> ▪ <i>Pterocarpus angolensis</i> woodland ▪ <i>Burkea africana</i> woodland ▪ <i>Acacia erioloba</i> shrubland ▪ <i>Acacia erioloba</i> woodland ▪ <i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Bauhinia petersiana</i> shrubland 	Cambic Arenosols Ferralic Arenosols Petric Calcisols
2 Karst Pediplain	1.3 Dune fringes	Burkea – Bauhinia woodland and shrubland	<ul style="list-style-type: none"> ▪ <i>Burkea africana</i> woodland ▪ <i>Bauhinia petersiana</i> shrubland ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Burkea africana</i> – <i>Terminalia sericea</i> shrubland ▪ <i>Dichrostachys cinerea</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Catophractes alexandri</i> shrubland 	Cambic Arenosols Ferralic Arenosols Haplic Arenosols Petric Calcisols
			Camelhorn – Silver Terminalia shrubland	<ul style="list-style-type: none"> ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Burkea africana</i> woodland ▪ <i>Acacia erioloba</i> shrubland ▪ <i>Combretum collinum</i> shrubland ▪ <i>Bauhinia petersiana</i> – <i>Terminalia sericea</i> shrubland ▪ <i>Catophractes alexandri</i> shrubland
3 Northern Sandplain	3.1 Okavango river and terraces	Okavango valley fields and shrublands	<ul style="list-style-type: none"> ▪ <i>Acacia nigrescens</i> – <i>Peltophorum africanum</i> riverine forest ▪ <i>Combretum imberbe</i> – <i>Acacia erioloba</i> shrubland ▪ <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland ▪ <i>Catophractes alexandri</i> shrubland ▪ floodplain grassland 	Dystric Fluvisols Dystric Anthrosols Haplic Arenosols Ferralic Arenosols
			<ul style="list-style-type: none"> ▪ <i>Pterocarpus angolensis</i> woodland ▪ <i>Schinziophyton rautanenii</i> woodland ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Burkea africana</i> woodland 	Haplic Arenosols Ferralic Arenosols Haplic Calcisols
	3.2 Sandplain incised by short Omiramba	Kiaat – Mangetti woodland	<ul style="list-style-type: none"> ▪ <i>Acacia erioloba</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland 	Cambic Arenosols Ferralic Arenosols Haplic Calcisols
			Camelhorn shrubland	<ul style="list-style-type: none"> ▪ <i>Pterocarpus angolensis</i> woodland ▪ <i>Schinziophyton rautanenii</i> woodland ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Burkea africana</i> woodland
3.4 Eastern remnants of wide dunes	Kiaat – Mangetti woodland	Kiaat – Mangetti woodland	<ul style="list-style-type: none"> ▪ <i>Pterocarpus angolensis</i> woodland ▪ <i>Schinziophyton rautanenii</i> woodland ▪ <i>Baikiaea plurijuga</i> woodland ▪ <i>Burkea africana</i> woodland 	Cambic Arenosols Haplic Arenosols
			<ul style="list-style-type: none"> ▪ <i>Burkea africana</i> woodland 	Haplic Arenosols

Table 12. Vegetation Types and Soil Associations Aggregated by Land System

LAND REGION	LAND SYSTEM	VEGETATION MAPPING UNIT	VEGETATION TYPES	SOIL ASSOCIATIONS
4 Omatako Drainage	4.1 Main channel floor	Omatako Grassland	<ul style="list-style-type: none"> ▪ <i>Cynodon dactylon</i> – <i>Enneapogon desvauxii</i> grassland ▪ <i>Cynodon dactylon</i> grassland 	Haplic Calcisols Ferralic Arenosols
	4.2 Tributaries and main channel slopes	Mixed shrubland	<ul style="list-style-type: none"> ▪ <i>Acacia erioloba</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Terminalia sericea</i> – <i>Bauhinia petersiana</i> shrubland ▪ <i>Acacia erioloba</i> – <i>Acacia fleckii</i> shrubland ▪ <i>Dichrostachys cinerea</i> shrubland 	Calcic Arenosols Cambic Arenosols Ferralic Arenosols Haplic Calcisols
	4.3 Upper tributary slopes	Burkea woodland and shrubland	<ul style="list-style-type: none"> ▪ <i>Burkea africana</i> woodland ▪ <i>Burkea africana</i> shrubland ▪ <i>Dichrostachys cinerea</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Catophractes alexandri</i> shrubland 	Ferralic Arenosols Petric Calcisols Haplic Calcisols
5 Ephemeral Catchment Divide	5. High plain	Catchment divide vegetation	<ul style="list-style-type: none"> ▪ <i>Burkea africana</i> woodland ▪ <i>Baphia massaiensis</i> shrubland ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Acacia erioloba</i> – <i>Peltophorum africanum</i> shrubland ▪ <i>Acacia erioloba</i> – <i>Hyphaene petersiana</i> shrubland ▪ <i>Bauhinia petersiana</i> – <i>Terminalia sericea</i> shrubland ▪ <i>Eragrostis lehmanniana</i> grassland ▪ <i>Combretum hereroense</i> – <i>Acacia fleckii</i> shrubland ▪ <i>Dichrostachys cinerea</i> shrubland 	Cambic Arenosols
6 Southern / Eastern Panveld	6. Calcrete plain	Silver Terminalia – Blade thorn shrubland	<ul style="list-style-type: none"> ▪ <i>Terminalia sericea</i> shrubland ▪ <i>Acacia fleckii</i> shrubland ▪ <i>Catophractes alexandri</i> shrubland ▪ <i>Burkea africana</i> – <i>Terminalia sericea</i> shrubland ▪ <i>Burkea africana</i> shrubland 	Calcic-Haplic Solonetz Haplic Arenosols Petric Calcisols

Table 12. Vegetation Types and Soil Associations Aggregated by Land System

LAND REGION	LAND SYSTEM	VEGETATION MAPPING UNIT	VEGETATION TYPES	SOIL ASSOCIATIONS
7 Eastern Flowing Palaeo- Drainage	7.1 Sandplain with small pans	Burkea – Baphia woodland and shrubland	Burkea africana woodland	Haplic Arenosols
			Burkea africana – Guibourtia coleosperma woodland	Calcic-Haplic Arenosols
			Baphia massaiensis shrubland	Calcic Solonetz
			Terminalia sericea shrubland	
			Combretum imberbe – Acacia erioloba shrubland	
			Burkea africana shrubland	
	7.2 Sandplain with large pans	Burkea – False mopane woodland	Acacia erioloba – Acacia fleckii shrubland	Haplic Calcisols
			Burkea africana – Guibourtia coleosperma woodland	Ferralic Arenosols
	7.3 Hard pan	Silver Terminalia shrubland	Burkea africana woodland	Haplic-xanthic Solonetz
			Acacia erioloba shrubland	
			Combretum imberbe – Acacia erioloba shrubland	
			Burkea africana shrubland	
Terminalia sericea shrubland			Calcaric Arenosols	
Baikiaea plurijuga woodland			Hyper-Luvic Calcisols	
7.4 Eastern Omiramba	Eastern Omiramba grassland	Terminalia prunioides woodland	Petric Calcisols	
		Acacia fleckii shrubland		
		Catophractes alexandri shrubland		
		Acacia mellifera shrubland		
		Cynodon dactylon grassland	Petric Calcisols	
		Acacia mellifera shrubland	Calcic Solonetz	
7.5 Eastern remnants of narrow dunes	Silver Terminalia – Blade thorn shrubland	Terminalia sericea shrubland	Ferralic Arenosols	
		Acacia fleckii shrubland	Cambic Arenosols	
		Catophractes alexandri shrubland	Haplic Arenosols	
		Burkea africana – Terminalia sericea shrubland	Cambic Arenosols	
		Burkea africana shrubland	Ferralic Arenosols	
		Terminalia sericea shrubland	Petric Calcisols	
7.6 Transitional zone	Silver Terminalia – Blade thorn shrubland	Terminalia sericea shrubland	Luvic Calcisols / Haplic	
		Acacia fleckii shrubland	Allisols	
		Catophractes alexandri shrubland	Petric Calcisols	
		Burkea africana – Terminalia sericea shrubland		
		Burkea africana shrubland		
		Burkea africana shrubland		

6 DISCUSSION AND CONCLUSIONS

6.1 FACTORS CONTROLLING SOIL DEVELOPMENT AND DISTRIBUTION

6.1.1 Climate, Parent Material and Paleo-Geomorphological Processes

True desert soils (arid) are not found in Kavango, nor are the true semi-arid soils representative of dry woodlands, grasslands and savannas. On the one hand, the soils of the region indicate a greater aridity than would be expected from the present-day semi-arid climatic record. On the other hand, no other evidence could be found to support the existence of truly arid environmental conditions. Rocky outcrops occur although weathering has not produced coarse regolith. The sorting action of moving water and wind has not differentiated the parent material into rocky, gravelly, and sandy areas that are consistent with present-day aridity, although the genetic history of the parent material includes hyper-arid paleo-climatic conditions.

The parent material is simply an almost complete surface coverage (a virtual blanket) of pre-weathered, non-cohesive sand, whether deposited by alluvial or aeolian processes. Such parent material would certainly arrest soil formation and favour aridic soil moisture regimes, conditions that are repeatedly documented in the great majority of the soils by the immaturity of profile development and lack of horizon differentiation.

The single area of exception is located at the south-eastern corner of Kavango where shallow bedrock formations comprising basalt and quartzite underlie surface deposits of calcrete and consolidated aeolian sands, forming a complex and capped 'hardpan' landscape.

From a geomorphological point of view this hardpan land system represents a deflation zone in which the entire surface has been differentially denuded and eroded by aeolian processes. It appears to be a residual landscape of inverted features where former dunes have been eroded down to lower positions, and now act as wind corridors between higher areas more resistant to denudation. On top of the higher areas lie the remains of former pans and their associated, now desiccating, soils. These soils perch on gently convex crests with ample opportunity for surface runoff as opposed to their original locations on flat, interdune floors with conditions more conducive to the collection of surface water.

6.1.2 Indications of Genetic Inheritance by Soil Colour

The majority of soils in Kavango, in common with the neighbouring soils of northwest Botswana and south-central Angola, have formed on either sandy or loamy substrates. The older Tertiary parent materials are completely recycled, having been thoroughly weathered and eroded before their present deposition. As a result the soils developed on these substrates have not inherited the end-products of *in situ* weathering and individual soil particles of the present soils are therefore not commonly coated by oxidized iron.

The only soils in which oxidized iron coatings would give the soils a red colour are the younger red aeolian sands blown in and deposited on top of the older Tertiary aeolian deposits, and the soils developed on top of the alluvial deposits of the Okavango river terraces.

Between these two soil settings the genetic chemical conditions favouring iron coatings were probably very different. In the case of the younger red aeolian sands, it is possible that previous weathering conditions did not completely remove iron pigments, which consequently remain coated on quartz grains giving a pale pink to red colouration. In the case of soils on alluvial terraces, the immature sediments forming the parent material would have originated in humid paleo-environmental conditions of central Angola providing the source of iron.

The upward vertical movement of oxides in solution and subsequent precipitation as fine grained pigment throughout soil profiles are characteristic processes operating in the current climatic conditions of Kavango. These processes do give a distinct red colouration to soils,

with the hues, values and chromas of soil colour indicating the concentration of the source material and the intensity of its redistribution processes. The iron oxides precipitated as pigment are, however, never quantitatively abundant enough to affect the total iron content of the soils.

6.1.3 Sub-Surface Drainage Dynamics and Associated Chemical Conditions

Genetic inheritance together with the mobility of oxides in solution have produced a series of changes in soil properties from the upper to the lower members of catenas in all land systems of Kavango. The variation in soil colour is one of the more obvious sequences, and this can be related to the subsurface drainage dynamics of the predominantly sandy upper slopes.

Upland, well-drained soils are usually reddish-brown, the colour showing the presence of non-hydrated iron oxides in the soil. The iron is well dispersed and usually partly attached to the clay fraction.

With very few exceptions (ref. section 5.4), drainage on the middle and lower parts of slopes is slower. These soils remain moist longer and dry out less frequently and less completely leading to an increasing degree of iron hydration. The red colour then changes to a brown or yellow depending on the character of the hydrated iron oxides (limonite and goethite?). The colour changes are not sudden but rather gradual changes from the original reddish-brown of the upper soils to orange-browns and finally to yellow-browns on the lower slopes.

On the lowest slopes, where drainage can be very poor and where part or all of the soil profile may be waterlogged for part of the year, reduction of iron and other soil compounds takes place. Under these conditions, bacteria obtain their oxygen from the oxygen-containing compounds and these are then reduced to other compounds. These soils are usually neutral grey in colour. In parts of the soil profile where the water-table fluctuates mottling is likely to be produced.

6.1.3.1 Arenosols as Catalysts of Soil Development

Genetic inheritance, differences in drainage potential and differential mobility of oxides in solution are responsible for the gradual colour changes that are frequently seen in the catenas of Kavango. The drainage differences can be due to a variety of factors including textural change and the presence of compacted or indurated sub soils, but in each case the gradation within catenas can be related to oxidation-reduction balances.

Over 70% of the region is covered by sandy Arenosol soils with properties conducive to high internal water transfer potentials. Combining this with the relatively high topographic locations of these soils it is evident that they act as an important agent in the rapid sub-surface transfer of water between top slopes and channels (catenary influence), and between local rises and depressions.

The Arenosols of the eastern drainage region in particular appear to be taking the role of main distributary from local rises to depressions where solonetz and calcisols develop, acting as the supplier of salts. As the medium through which leakage occurs, these soils are therefore able to act as catalysts of soil development in both Solonetz soils and Calcisols by altering the *in situ* balance of sodium and calcium cations.

6.1.4 The Vertical Movements of Salts

Unlike the case of humid regions where precipitation is greater than evapotranspiration the movement of soluble constituents in the soils of Kavango is either negligible or predominantly upwards. This is due partly to the low intensity of weathering generally and to the movement of soil solution towards the soil surface during evaporation and evapotranspiration.

Many single processes such as salinization, solonization and solodization operate with generally low degrees of intensity in the region but they may all be combined and described

under the process of calcification. This term is used to describe the process that forms calcic horizons (usually within the B horizon).

Soils undergoing transformation by calcification are also described as soils dominated by accumulation of silicate clays and/or bases. Whereas accumulations of silicate clays are not common in Kavango due to the predominance of pre-weathered aeolian parent material, the accumulation of bases is a common soil characteristic in both the Calcisols and Solonetz soils of the region.

The term 'base' is used for both the cations of the alkali metals (e.g. sodium and potassium) and alkaline earth (e.g. calcium and magnesium). The basic cations are very mobile and so tend to form soluble compounds (e.g. sodium chloride) more readily in the soil. The common denominator of Calcisols and Solonetz soils in Kavango is the accumulation of bases somewhere within the profile. The accumulation may occur in all horizons or in particular horizons, depending on the controlling processes.

The accumulation of bases in the soil profile takes two main forms. They may be found as free salts (sodium chloride, calcium carbonate) in combination with soil anions, or as cations adsorbed onto the soil colloids, e.g. silicate clays.

Bases in the form of adsorbed cations are only present in soils formed on alluvial deposits where clay particles are present in sufficient quantities to warrant a loamy texture. These soils are found on the Okavango river terraces and on interdune and omiramba floors. In the remaining areas of Kavango bases as adsorbed cations are not common due to the low proportion of colloidal particles in re-worked aeolian deposits. In these areas bases are found as free salts.

The formation of free salts presupposes that the soil colloids, where present, are base-dominated. That is, the presence of free salts of a certain base element indicates a concentration in the soil of that element in excess of what is required to exchange cations on the soil colloids.

6.1.4.1 The Origin of Bases in the Soils

The bases that accumulate in the soils of arid and semi-arid areas generally originate from parent material, invasion by saline water, and rainwater. In Kavango, the bases are primarily derived from the following sources:

Parent Material

- a) The mixture of materials comprising the alluvial deposits of the Okavango River terraces derive their bases from weathered origins in humid paleo-environmental conditions of central Angola.
- b) A greater part of the regional land surface is covered by deposits of pre-weathered and unconsolidated aeolian sand - a porous, non-equilibrium assemblage of detrital materials, defined as loose, non-cohesive and granular, with grain sizes ranging from 0.0625 to 2.00mm diameter. In numerous localities these sands are cemented by calcium carbonate to produce a nodular to highly indurated near-surface layer of calcrete.
- c) Less commonly calcium carbonate cementation is replaced by silica cement giving rise to silcrete at shallow depths.
- d) Consolidated sands.
- e) Shallow buried sandstone. Possibly diagenetic with low porosity through compaction and cementation, loss of many unstable detritals, and gains of stable authigenic precipitates.

Fire Effects

- a) Burnt organic mottles and fragments. The greater part of Kavango has been subjected to repeated, and over the last 15 years or so, increasingly frequent burning of

vegetation. These are started naturally by lightning strikes on dry, easily combustible organic material, or artificially by man. Collections of burnt organic fragments on the soil surface, and burnt organic mottles dispersed down root channels are common.

- b) Ash. Thin surface deposits of nutrient-rich light coloured ash cover large areas of Kavango as a consequence of vegetation burning. Carbon detritus in the form of charcoal fragments, together with water-soluble bases released from volatilised organic compounds, are differentially deposited onto soil surfaces and subsequently incorporated into the solum.
- c) Both the rate and exact location of incorporation of these bases will depend on the timing and intensity of the first rainfall event subsequent to a burn. Prior to this event, wind may play an important role in their removal and re-deposition. Climatic records for Kavango region indicate that the frequency of high winds increases significantly from August onwards, reaching a maximum in November just prior to the onset of the rainy season. During the same period wind speeds also increase.

Water

- a) Saline groundwater.
- b) Base-rich irrigation water. Base influx through application of fertilizer salts in solution.
- c) Okavango river. Over-bank flow and seasonal inundation of nutrient-rich river water onto floodplain. Intrusion of salts in solution from river to shallow aquifers.
- d) Rainwater. Intrinsic salts.

6.1.4.2 The End-Products of Calcification

The most extreme form of the calcification process - salinization - is not evident in the soils of Kavango and therefore saline soils are not found. In terms of climatic zonation, increasing humidity encourages leaching to 'set in' and the amount of available vegetation increases. Before the effect of vegetation becomes apparent however, a series of 'desert soils' occur in the following sequence of increasing wetness: solonetz - solodized-solonetz - solodic. Solonetz soils do occur in the eastern part of the region although neither solodized-solonetz nor solodic soils, more characteristic of humid conditions, have developed.

Climatic conditions experienced in Kavango rarely encourage the formation of humus, thus limiting the type of soils formed, whether sodic, calcic or neither. Whereas the climatic conditions do encourage the rapid growth of grasses and herbs, summer temperatures are hot rather than warm and only moderately humid. From early in the dry season onwards wind also encourages the rapid desiccation of dead organic matter, providing a ready supply of combustible material rather than an accumulation of nutritive organic matter for humus formation. Therefore, although the late summer droughts and winter frost conditions would normally arrest the decomposition of organic matter and keep it available for humus formation, most potential sources of organic matter are lost through desiccation and fire well before the next rainy season, when humification processes would become effective.

6.1.5 Local Exogenic Influences on Soil Productivity

The discussions above have covered the combined and intermingled roles played by climatic regime, genetic inheritance, and the relative positioning of soil types in the formation and development of any one soil.

It is also evident that local exogenic factors exert a substantial influence on the soils of Kavango, producing conditions favouring the transport and re-deposition of wind-borne and alluvial clays and silts, the accumulation of exchangeable salts, and the transformation of genetically infertile soil bodies into pockets of high potential productivity.

Differences in relative soil fertility as indicated by CEC (clay) values (ref. section 4.2.3) can largely be attributed to the following exogenic factors:

- ⤵ Slope position in catenary sequences;
- ⤵ Local depressions on otherwise flat plains
- ⤵ Deposits of alluvial clay and silts along ephemeral river floors;
- ⤵ Depth of underlying calcrete, silcrete and sandstone deposits;
- ⤵ Presence of shallow groundwater levels
- ⤵ Effects of fire
- ⤵ Dry season wind speeds
- ⤵ Rainfall intensity of storm events and rainfall distribution pattern

Similarly, the conditions limiting micronutrient availability cannot be fully explored without considering the influence of local exogenic factors. Although many factors affect the concentrations of single micronutrients, not the least being the levels of other soil elements, the conditions summarised in Table 13 consistently appeared to control and limit their overall availability as a nutrient resource. Factors interacting with copper, iron, manganese and zinc have been included to indicate the areas of co-dependency with other soil elements and conditions, although the nature and direction of these interactions have not been investigated further.

Table 13. Environmental and Genetic Conditions Limiting Micronutrient Availability

Available Micronutrient	Interacting Factors	Kavango Soils: Conditions Limiting Micronutrient Availability
Cu	N, Fe, Mg, Mo, P, Zn	<ul style="list-style-type: none"> • Sandy texture of aeolian origin
Fe	pH, K, Mn, Ca, Mg, P, Cu, Mo, Zn	<ul style="list-style-type: none"> • Free CaCO₃ • Extreme soil moisture conditions • Soil temperature extremes • Low organic matter • Parent material deficiency (genetic)
Mn	pH, OM, K, Mo, P, Fe, Cu, Zn	<ul style="list-style-type: none"> • Soil alkalinity • Dry climate conditions
Zn	pH, Cu, N, P, Ca	<ul style="list-style-type: none"> • Calcareous soils • Low organic matter • Restricted root zones (compaction)

6.2 FACTORS CONTROLLING THE DISTRIBUTION OF VEGETATION TYPES

In broad terms classified as forest savanna and woodland (Giess 1971), the Kavango Region is largely wooded with broad-leafed, deciduous trees dominating the largest part, while frost tolerant savanna species (e.g. *Acacia* trees) protrude from the south (De Sousa Correira & Bredenkamp 1987).

6.2.1 Climate, Landform and Disturbance Regimes

Overall climate (a gradient of decreasing rains from north-east to south-west) was proposed to play a significant role in defining the distribution of vegetation, and resulted in the division of the Kavango Region into two distinct agroecological zones with different growing periods (De Pauw 1996).

Local topographic conditions reflecting different microclimatic influences and underlying substrates were also expected to play a significant role although landform, together with land disturbance regimes (fire and clearing), emerged as the two most significant environmental factors controlling the distribution of vegetation types in the Kavango Region.

6.2.1.1 Land Use and Fire Frequency

Slash-and-burn agriculture is practised throughout the region, although activities are concentrated along the perennial Kavango River and other areas where water is available. All major dry rivers (omiramba) serve as access routes and water points for settlements from where agricultural activities have extended far into the woodlands.

In addition to clearing for agriculture, fires appear to be raging through the Kavango woodlands more frequently than in the past (Trigg 1997). This can largely be attributed to burning for traditional hunting and resource management (Powell 1998), burning of fields and possibly war-time activities in the past. As a result the vegetation in the Kavango Region has been extensively altered by clearing and burning and presents an intricate mosaic of different phases of recovery from disturbance.

One of the most problematic aspects which could not be addressed adequately in this study was in fact the separation of human-induced factors (e.g. clearing and fire) from natural causes (e.g. substrate and landform) controlling the distribution of vegetation types. This was perceived particularly difficult as fire is part of the natural system, although the fire regimes themselves have been altered due to human activities.

Because of the severe impacts of clearing and fire, natural sequences of vegetation types in the field often had to be inferred and extrapolated. The interpretation of the vegetation types should thus be seen in the light of these difficulties.

6.2.2 Influence of Fire and Clearing

The contemporary vegetation in the Kavango presents a mosaic of climax vegetation and multiple successional stages caused by disturbance (fire and clearing). The climax and successional vegetation could not be separated effectively during this survey as the dynamics of Kavango vegetation is not yet understood in sufficient detail.

The predominance of shrubland, for example, has been suggested to often be attributed to impeding layers limiting root penetration (De Sousa Correia & Bredenkamp 1987), but the successive impact of fires could have a similar effect.

This pattern is further complicated by the fact that fires are not only changing vegetation composition, but also soil structure and soil development, possibly resulting in additional water deflecting or impermeable layers.

6.2.3 Conclusions on Vegetation Distribution Patterns

It is concluded that:

- Landform and disturbance regime (fire and clearing) appear to be the two most significant environmental factors controlling the distribution of vegetation types in the Region
- It is virtually impossible to distinguish between the distribution of vegetation types influenced by either anthropogenic or climatic events
- Local topography (landform), reflecting different microclimatic influences and variations in substrate, plays a more significant role in the distribution of vegetation types than differences in growing periods suggested by agro-ecological zone boundaries.

To be able to develop a more detailed map depicting individual vegetation types and thus provide a useful base for land use planning, two fundamental problems have to be resolved:

- Development of an appropriate methodology for satellite image interpretation on Kalahari sands;
- Understanding natural and human-induced environmental factors and their role in determining vegetation distribution in the Kavango.

6.2.3.1 Developing an Appropriate Methodology for Satellite Interpretation on Kalahari Sands

Two main factors potentially mask the land cover shown on satellite images of the Kavango Region: the impact of fire and the variation in thickness of sand cover. The following suggestions are based what a vegetation scientist would ideally like to use as map base for mapping vegetation cover:

- Process image to eliminate the effects of fires (e.g. by eliminating certain band widths?);
- Prepare supervised image classifications for each land region separately (e.g. one image for stabilised dunes in western Kavango, one for eastern palaeo drainage).

In addition, factors contributing to the difficulties of interpreting the recent Kavango images could be avoided by:

- Selecting images captured during the growing season in which the ground survey is carried out.

Taking practical considerations into account this could be achieved by:

- Conducting a reconnaissance ground survey during or shortly after images are taken;
- Producing a supervised classification with these field data once the satellite information becomes available;
- Carrying out the main ground truthing and field survey during the following season.

6.2.3.2 Understanding Natural and Human-induced Environmental Factors and Their Role in Determining Vegetation Distribution in the Kavango

Separating the effects of natural and human impacts on vegetation are fundamental to an understanding of vegetation dynamics in the Kavango Region and to the submission of appropriate suggestions for sustainable land use planning.

Important natural environment parameters appear to be:

- Landform and associated microclimate;
- Substrate conditions, particularly the presence of subsurface impeding layers.

The two main significant impacts correlated with human activities are:

- Fire;
- Land clearance

Only more detailed studies, possibly with monitoring over several seasons, will enable us to address these questions.

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