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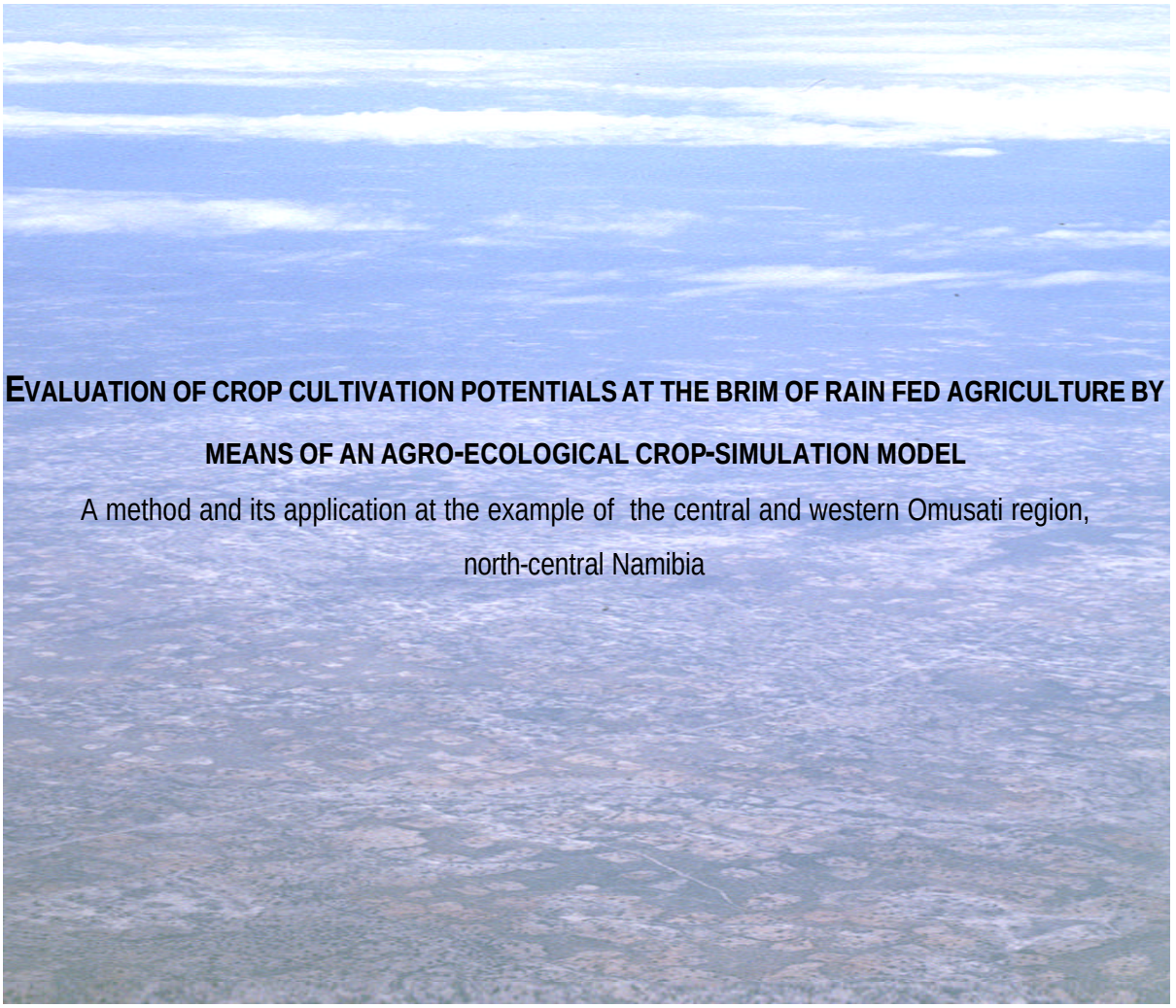

EVALUATION OF CROP CULTIVATION POTENTIALS AT THE BRIM OF RAIN FED AGRICULTURE BY MEANS OF AN AGRO-ECOLOGICAL CROP-SIMULATION MODEL

A method and its application at the example of the central and western Omusati region, north-central Namibia

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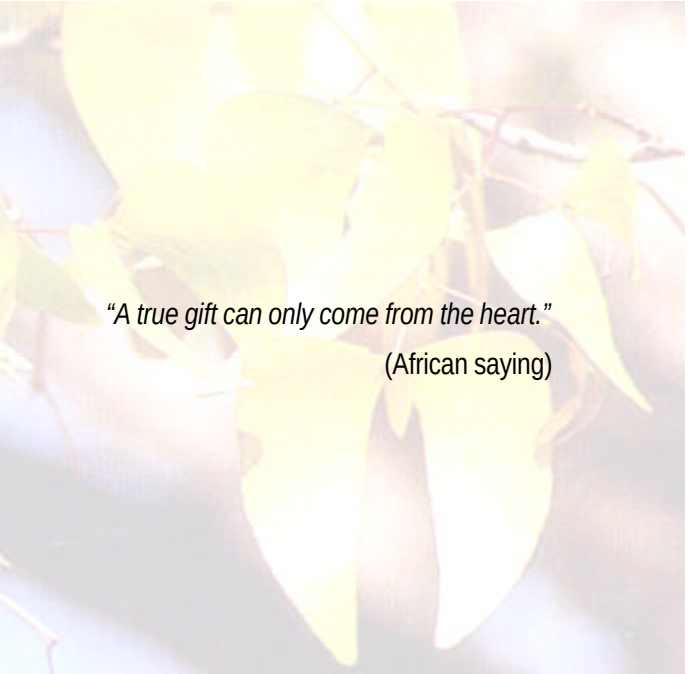
Cover: Aerial view of north-central Namibia (Photography by B. MAIBAUM, January 2002)



Dedicated to the people of Owambo and to the spirit I was allowed to experience in the course of this study - the spirit of respect, tolerance, interest, consideration, co-operation, hospitality, altruistic support and friendship.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAS: atomic-absorption-spectrometer

acc. to: according to

AET: agro-ecological type

AEZ: Agro-ecological Zoning Unit

aFc: plant available field capacity

AHP: agro humid period

AOI: area of interest

AP(s): aerial photograph(s)

app.: approximately

Bd: bulk density

bp: before present

C: Carbon

CBS: Central Bureau of Statistics

cm: centimeter(s)

C/N: Carbon/Nitrogen

CAL: Calcium-Acetate-Lactate

cal.: calorie(s)

Com.: Combretum

DAC(s): drought adapted crop(s)

DPA: discontinuous perched aquifer

DEA: Department of Environmental Affairs

DED: Deutscher Entwicklungsdienst (German Development Service)

Dipl.: holding a diploma(German academic degree similar to a masters degree)

DPA: Discontinuous Perched Aquifer

DRFN: Desert Research Foundation of Namibia

dt.: deci-ton, 100 kilograms

e.g.: for example

E: east

EC: electric conductivity

Ed(s).: Editor(s)

EEI: Etosha Ecological Institute

esp.: especially

et al.: and others

ev.: eventually

f.: following (singular)

FAO: Food and Agriculture Organisation of the United Nations

Fc: field capacity

ff.: following (plural)

four Os: see Owambo

GIS: Geographical Information System(s)

GPS: Global Positioning System

GTZ: Deutsche Gesellschaft fuer Technische Zusammenarbeit (German Agency for Technical Co-operation)

ha: hectare

HCl: hydro-chloric acid

ICRISAT: International Crops Research Institute for the Semi-Arid Tropics

IITA: International Institute for Tropical Agriculture

IRI: International Research Institute For Climate Prediction

ITC: zone of inner-tropical convergence

K: potassium

km: kilometer(s)

loa.: loamy

LSU: large stock unit

m.s.l.: mean sea level

m: meter(s)

M: molar

MAWRD: Ministry of Agriculture, Water Affairs and Rural Development

mm: millimetre(s)

Mop. : Mopane

mS: milli Siemens

MSA: main shallow (or saline) aquifer

N$: Namibian Dollars

n.a.: not available

N: north or Nitrogen (depending on the context)

NAPCOD: National Programme to Combat Desertification

NBRI: National Botanical Research Institute

NEPRU: Namibian Economic Policy Research Unit

nm: nanometer(s)

NNEP: Northern Namibian Environmental Project

North central region: see Owambo

No.: number

NWO: Namibian Weather Office

o.: on

OPO: Owamboland People's Congress

Owambo: the region that covers the four districts of Omusati, Oshana, Ohangwena and Oshikoto

Owamboland: see Owambo

p.: page

P: phosphorus

ppm: parts per million

psu: practical salinity unit

PWP: permanent wilting point

RDC: rural development centre

S: south

SAD: saline deep aquifer

sav.: savanna

SDP: Summer Desertification Project

Sec: second(s)

sesquiox.: containing sesquioxides

shr. : shrub(s)

soi.: soil(s)

SWAPO: South West Africa People's Organisation

t.: ton

TB: Tepary bean

tr.: tree(s)

UNESCO: United Nations Educational, Scientific and Cultural Organization

Vol.: Volume

W: west

WON: Weather Office of Namibia

[…]: remarks and/ or additions by the author

+ : plus/ exceeding

< : less than

> : more than

°C: degree Celsius

µS: micro Siemens

TABLE OF CONTENTS

ACKNOWLEDGEMENTS I
ABBREVIATIONS IV
INDEX VII
LIST OF TABLES XII
LIST OF FIGURES XII
CONTENTS OF ANNEX XIV
Tables and figures ..... *XIV*
Maps ..... *XV*

INDEX

1 INTRODUCTION 1-1

2 MATERIAL AND METHODS 2-1

2.1 Pre-arrangements 2-2

2.1.1 Collection of eco-physiological crop data 2-2

2.1.2 Data adaptation 2-2

2.1.3 Determination of area of interest (AOI) 2-3

2.1.3.1 Aerial photographs 2-3

2.1.4 Determination of crop species to be used for the modelling 2-4

2.1.4.1 The Tepary bean 2-5

2.1.4.1.1 Adaptation to semi-arid environments 2-6

2.1.4.1.2 Positive effects on soil conditions 2-6

2.1.4.1.3 Advantages for the farmer 2-6

2.1.4.1.4 High nutritional value 2-7

2.2 Data acquisition 2-7

2.2.1 Data enquiries 2-7

2.2.2 Interviews and Discussions 2-8

2.2.3 Adaptation of research standards 2-10

2.2.4 Collection of field data 2-10

2.2.4.1 Allocation of soil sample sites 2-10

2.2.4.2 Soil data collection 2-11

2.3 Data/ sample preparation and processing 2-12
2.3.1 Analysis of soil 2-12
2.3.1.1 Soil texture 2-12
2.3.1.2 pH-levels 2-13
2.3.1.3 Salinity 2-13
2.3.1.4 Plant available nutrients 2-14
2.3.1.4.1 P_2O_5 and K_2O 2-14
2.3.1.4.2 Nitrogen (N), N-mineralization, Carbon (C) & C/N-ratio 2-16
2.3.2 Climate data processing 2-17
2.3.2.1 Data analysis for the general description of the climatic conditions at the AOI 2-17
2.3.2.2 Assessment of evaporation at the AOI and creation of the evaporation input-data for the MARCROP application 2-18
2.3.2.3 Assessment of the spatial rainfall distribution at the AOI and creation of the rainfall input-data for the MARCROP application 2-19
2.4 Modelling 2-21
2.4.1 The use of simulation models 2-21
2.4.1.1 Different types of crop simulation models 2-22
2.4.2 The WATBAL/ MARCROP-model 2-23
2.4.2.1 Parameters required to run WATBAL and MARCROP 2-24
2.4.2.1.1 Climatic parameters 2-24
2.4.2.1.2 Plant parameters 2-24
2.4.2.1.3 Parameters related to soil moisture 2-25
2.4.2.2 MARCROP 2-25
2.4.2.2.1 Differences between MARCROP and WATBAL modules 2 and 3 2-26
2.4.2.2.2 Input-parameters required from the end-user 2-27
2.4.2.2.3 MARCROP-output 2-28
2.4.3 Evaluation of crop cultivation potentials in the AOI 2-29
2.4.3.1 Input-data and configuration of the software 2-29
2.4.3.1.1 Required ASCII-data files 2-30
2.4.3.1.2 Software configuration 2-31
2.4.3.2 Analysis of the MARCROP-output data 2-32
2.5 Administration and presentation of spatial data/ GIS 2-32
3 GENERAL PROFILE OF THE AREA OF INTEREST (AOI) 3-1
3.1 Location and general characteristics of the AOI 3-1
3.2 Physical environment 3-2

3.2.1 Geology and Geomorphology ... 3-2
3.2.2 Climate ... 3-6
3.2.2.1 Temperature ... 3-6
3.2.2.2 Evaporation, Wind and Humidity ... 3-7
3.2.2.3 Rainfall ... 3-8
3.2.2.3.1 Rainy season ... 3-8
3.2.2.3.2 Rainfall variability ... 3-10
3.2.2.3.3 Productive rainfalls ... 3-11
3.2.2.3.4 Effective rainfalls ... 3-12
3.2.2.3.5 Rainfall trend, drought and the effects of "El Nino", "La Nina" and "Benguela El Nino" ... 3-13
3.2.3 Vegetation ... 3-17
3.2.3.1 Vegetation units of the *Western Sandveld/ Western Kalahari Woodlands* ... 3-18
3.2.3.2 Vegetation units of the *Etaka-Cuvelai* ... 3-19
3.2.3.3 Vegetation units of the *Mopane shrublands* ... 3-20
3.2.3.4 Alternations of natural vegetation ... 3-20
3.2.4 Soils ... 3-21
3.2.4.1 General soil characteristics ... 3-21
3.2.5 Hydrology and water ... 3-24
3.3 Socio-cultural, demographic and socio-economic characteristics ... 3-26
3.3.1 People of the AOI – history and culture ... 3-26
3.3.2 Social structures and settlement structures ... 3-28
3.3.3 Demographic characteristics ... 3-30
3.3.4 Present settlement dynamics ... 3-31
3.3.5 Governance ... 3-31
3.3.5.1 Government authorities ... 3-31
3.3.5.2 Tribal authorities ... 3-32
3.3.6 Land and land tenure ... 3-32
3.3.6.1 Small-scale farms ... 3-33
3.3.6.2 Communal grazing areas ... 3-35
3.3.6.3 "Illegal" fencing ... 3-35
3.3.7 Socio-economy ... 3-36
3.3.7.1 The Farming system of the Owambo ... 3-36
3.3.7.1.1 Mahangu ... 3-40
3.3.7.2 Livestock keeping ... 3-41
3.3.7.3 Income structure ... 3-43

3.3.7.3.1 Incomes generated by agricultural activities 3-43
3.3.7.3.2 Other sources of income 3-44
3.3.8 Infrastructure 3-45
3.3.8.1 Physical infrastructure 3-45
3.3.8.2 Institutional and touristic infrastructure 3-46

4 RESULTS 4-1

4.1 Findings of aerial photo interpretation (including observations during the field work) 4-1

4.2 Findings of soil survey 4-2
4.2.1 Soils of the Cuvelai palms and fruit trees on oshanas -vegetation unit 4-2
4.2.2 Soils of the Mopane shrubs & low trees on loamy sands -vegetation unit 4-3
4.2.3 Soils of the Mopane-Combretum savanna on sandy soils -vegetation unit 4-3
4.2.4 Soils of the Western sand plains -vegetation unit 4-4
4.2.5 Soils of the Western mopane-pan mosaic -vegetation unit 4-5
4.2.6 Soils of the Mixed savanna on loamy to sandy soils -vegetation unit 4-5
4.2.7 Mineralisation rates 4-6

4.3 Findings of the modelling procedure 4-6
4.3.1 Results of the statistical analysis 4-6
4.3.2 Agro-ecological analysis of modelling results 4-7
4.3.2.1 Relations between soil and calculated relative yields 4-8
4.3.2.2 Relations between calculated relative yields, rainfall amount and temporal rainfall distribution 4-9
4.3.2.3 Relative Yield in relation to planting date 4-12
4.3.2.4 Yield and climatic phenomena 4-13

5 DISCUSSION 5-1

6 SUMMARY 6-1

7 REFERENCES 7-1

7.1 Literature 7-1

7.2 Interviews 7-7

7.3 Maps 7-8

7.4 Aerial Photographs 7-8

7.5 Data sets 7-8

7.6 World wide web sites 7-9

LIST OF TABLES

Table 2-1: Nutritional values of Tepary beans and other common crops 2-7
Table 2-2: Calculated percentage of evaporation increase per month and kilometre from Mahanene to Okaukuejo 2-18
Table 2-3: Calculated percentage of rainfall decrease per month and kilometre from Ongandjera/ Okahao to Otjovasandu 2-20
Table 2-4: Mean number of days with rainfall during January-March (1960-1989) at Otjovasandu and Ongandjera/ Okahao 2-21
Table 2-5: Sequences of hydrature phases that are characteristic for the specific AETs of Tepary beans 2-29
Table 2-6: Characteristic values of available Field capacity (aFc) and Field capacity (Fc) of each vegetation unit of the AOI, as applied in the modelling procedure 2-32

Table 3-1: Mean daily wind speeds (km/h) at Ondangwa 3-7
Table 3-2: Mean monthly distribution of rainfall from south-west to north-east at the AOI 3-8
Table 3-3: Development of cultivated area in the Omusati region (1996-1999) 3-34
Table 3-4: Development of livestock numbers in the Omusati region (1996-1999) 3-42

Table 4-1: Occurrence (%) of reclassified calculated yield classes from 1960/61 – 1988/89 in relation to soil unit and modelling scenario 4-7
Table 4-2: Temporal distribution (%) of planting dates with best seasonal modelling results (1960/61 – 1988/89) 4-12

LIST OF FIGURES

Figure 2-1: Flow chart of an evaluation of crop cultivation potentials by means of the MARCROP-simulation model 2-1
Figure 2-2: Growth form and fruits of the Tepary bean 2-5
Figure 2-3: Location of the AOI in relation to the climate stations used for the assessment of regional evaporation and rainfall variations 2-18
Figure 2-4: Overview on the most important factors of the soil-plant-climate-system 2-22
Figure 2-5: Schematic overview on a GIS analysis procedure at the example of an assessment of soil erosion potentials 2-33

Figure 3-1: Sequence of geological deposits in north-central Namibia 3-3
Figure 3-2: View from the *Dolomite hills* into the AOI 3-4
Figure 3-3: Climate diagram of Ondangwa (north-central Namibia) 3-6
Figure 3-4: Long-term mean monthly rainfall (mm, 1960-1989) and calculated mean monthly evaporation (mm) at Ongandjera/ Okahao 3-7
Figure 3-5: Mean distribution (%) of seasonal rainfall amounts in relation to month at Ongandjera/ Okahao 3-9
Figure 3-6: Monthly distribution of rainfall amounts per rainy season at Ogandjera/ Okahao (1960/61-1988/89) 3-9
Figure 3-7: Deviation (mm) of seasonal (Nov-Apr) rainfall amount from the seasonal long-term mean at Ongandjera/ Okahao (1960/61 - 1988/89) 3-10
Figure 3-8: Innerseasonal mean long-term distribution (%) of rainfall maxima at Ongandjera/ Okahao (1960/61 - 1988/89) 3-11
Figure 3-9: Monthly long-term (1940-1999) distribution of days with productive rainfall at Tsumeb, Oshikuku and Okaukuejo 3-11
Figure 3-10: Seasonal numbers of days with rainfall and with productive rainfall (≥ 10mm) at Ongandjera/ Okahao (1960/61-1988/89) 3-12
Figure 3-11: Distribution of rainfall within the ecosystem of the Oshana region 3-12
Figure 3-12: Seasonal rainfall amounts and the rainfall trend at Ongandjera/ Okahao from (1960/61 - 1988/89) 3-13
Figure 3-13: Number of days with productive rainfall (≥ 10mm) per rainy season at Ongandjera/ Okahao (1960/61-1988/89) 3-14
Figure 3-14: Bush track in the area of the *Mopane shrubs and low trees on loamy sands* – vegetation unit 3-20
Figure 3-15: Effects of grazing on vegetation cover – the area in the back of the picture is protected from grazing by a fence, whereas the area in front is used as pasture 3-21
Figure 3-16: The *Cuvelai*, and neighbouring *Kunene* and *Cubango/ Okavango* drainage systems, and zones of annual average rainfall (mm) 3-24
Figure 3-17: Cross section, showing the main aquifers of north-central Namibia 3-25
Figure 3-18: Population distribution in Namibia 3-26
Figure 3-19: Traditional homestead (*ongandjo*) surrounded by fields 3-29
Figure 3-20: *Cuca-shop* in north-central Namibia 3-29
Figure 3-21: Cultivated area in relation to population density 3-34
Figure 3-22: Relation between cultivated area and household size 3-36
Figure 3-23: This figure gives an overview of the labour sequences in farming throughout the year. 3-38
Figure 3-24: Mahangu field in north-central Namibia 3-40

Figure 3-25: Seasonal cattle movements in north-central Namibia 3-42

Figure 4-1: Clearing in the south of the AOI 4-1
Figure 4-2: Large field close to the settlement of Amarika 4-2
Figure 4-3: Typical soil profile in the area of the *Western sand plains* – vegetation unit, exposed in the PUERCKHAUER-Bohrer 4-4

CONTENTS OF ANNEX

Tables and figures

Annex 1-1: Selected data on population growth and population engaged in agricultural activities

Annex 2-1a-b: Copy of the data collection sheet used for the soil survey
Annex 2-2: Table displaying available field capacity and field capacity in relation to soil texture and bulk density
Annex 2-3: References concerning the WATBAL and MARCROP crop simulation models
Annex 2-4: Pan coefficients (Kp) to convert Class-A-Pan evaporation values into reference crop evapotranspiration (Eto) values
Annex 2-5: Table with planting dates applied in the modelling

Annex 3-1: Seasons (1960/61- 1988/89) classified by risk of crop drought, rainfall and number of rainy days at Ongandjera/ Okahao

Annex 4-1a-b: Explanations concerning the soil profile data in annex 4-2 to 4-7
Annex 4-2: Findings of the soil survey in the area of the *Cuvelai palms and fruit-trees on loamy sands* - vegetation unit
Annex 4-3: Findings of the soil survey in the area of the *Mopane shrub and low trees on oshanas* - vegetation unit
Annex 4-4a-c: Findings of the soil survey in the area of the *Mopane-Combretum savanna on sandy soils* - vegetation unit
Annex 4-5a-d: Findings of the soil survey in the area of the *Western sand plains* - vegetation unit
Annex 4-6a-b: Findings of the soil survey in the area of the *Western mopane-pan mosaic* - vegetation unit
Annex 4-7a-b: Findings of the soil survey in the area of the *Mixed savanna on loamy to sandy soils*- vegetation unit
Annex 4-8: Explanations regarding annex 4-9 to 4-15

Annex 4-9a: Total MARCROP-calculation results (1960/61 – 1968/69)
Annex 4-9b: Total MARCROP-calculation results (1969/70 – 1978/79)
Annex 4-9c: Total MARCROP-calculation results (1979/80 – 1988/89)
Annex 4-9d: Best calculation results per season, scenario and soil unit
Annex 4-10: Correspondence of calculation results from scenario A and B by soil unit
Annex 4-11: Total number and percentage of reclassified, best seasonal calculation results by scenario, class, soil unit and decade
Annex 4-12: Total number and percentage of best seasonal calculation results by scenario, class, soil unit and decade
Annex 4-13a: Scenario A - percentage and absolute numbers of calculation results by soil unit (29 seasons, best result/ season)
Annex 4-13b: Scenario B - percentage and absolute numbers of calculation results by soil unit (29 seasons, best result/ season)
Annex 4-14a: Comparison scenario A/B - percentage of calculation results in relation to the soil units (29 seasons, best result/ season)
Annex 4-14b: Comparison scenario A/B - absolute numbers of calculation results in relation to the soil units (29 seasons, best result/ season)
Annex 4-15a: Scenario A - best seasonal calculation results (1960/61-1968/69) in relation to rainfall distribution
Annex 4-15b: Scenario B - best seasonal calculation results (1960/61-1968/69) in relation to rainfall distribution
Annex 4-15c: Scenario A - best seasonal calculation results (1970/71-1978/79) in relation to rainfall distribution
Annex 4-15d: Scenario B - best seasonal calculation results (1970/71-1978/79) in relation to rainfall distribution
Annex 4-15e: Scenario A - best seasonal calculation results (1980/81-1988/89) in relation to rainfall distribution
Annex 4-15f: Scenario B - best seasonal calculation results (1979/80-1988/89) in relation to rainfall distribution

Annex 5-1: Comparison of best seasonal calculation results (scenario B, best result per season, soil units I & IV) of Tepary beans and Bambarra groundnut

Maps

Map 1: Location of the area of interest (AOI) and the four administrative regions of north-central Namibia

Map 2: Topographical map of the central and western Omusati region
Map 3: Major landscapes of the central and western Omusati region
Map 4: Vegetation units of the central and western Omusati region and position of soil sample sites
Map 5: Major soil types of the central and western Omusati region
Map 6: Landuse in the central and western Omusati region
Map 7: Infrastructure of the central and western Omusati region

1 INTRODUCTION

At present many developing countries worldwide experience population growth rates higher than 2,5%. At this ratio we would expect the population size to double within 29 years. In many of those countries, the majority of the population is still living in rural areas and the incomes of people are mostly still based on agricultural activities (see annex 1-1). This situation is expected not to change in the near future. As a consequence, the proportion of land used for cultivation is permanently increasing in these countries.

The expansion of cultivated lands is not only observed in areas with environmental conditions that are favourable for agriculture, but also in semi-arid to arid regions, e.g. in eastern Africa (BERNARD et al., 1989; HORNETZ, 1994), the *Sahel* region (MAINGUET, 1991) or in Namibia (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995).
Given the natural environment of semi-arid and arid regions, agriculture usually has to cope with many risks. The most serious among these risks are the dangers of soil erosion, soil exhaustion and of crop failures that are caused by drought[1], as high rainfall variability[2] is a natural characteristic of most semi-arid regions[3].
Because of these risks, areas with unfavourable rainfall, were traditionally exempted from permanent human activities or used as extensive grazing and hunting grounds, especially in semi-arid to arid Africa (see MENDELSOHN et al., 2000; MAINGUET, 1999; IBRAHIM, 1992). However, population pressure and the lack of arable land elsewhere, are currently forcing people to establish farming livelihoods in such areas – despite the danger of recurrent crop failures, that often leave the affected farmers *"food insecure, and hence poor, simply because their land is unable to produce sufficient crops under existing conditions"* (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995, p.3).

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[1] In context of this study, the term *drought* is used in the sense of an *agricultural drought*. According to MAINGUET (1991, p.32 f.), an agricultural drought is characterized by a failure or a sufficient deficit of rainfall and plant available soil water that is necessary for the development of crops and natural vegetation. The occurrence of such a moisture deficit is most serious during the germination and growth phase of plants. While a *meteorological drought* (= negative deviation of mean rainfall amounts) only may create stress on plant life, an agricultural drought is causing disruptions of rural economies. *"In an extreme agricultural drought, crops fail, and animals, and perhaps people, die"* (MAINGUET, 1991, p.32). It should be noted, that the choice of crops with a comparably high water demand, e.g. maize, and the extension of grazing and cultivated areas into naturally dry areas during years with favourable rainfall, increases the risks of the occurrence of agricultural droughts.

[2] Concerning rainfall variability, deviations of 20-50% from the annual mean are quite usual in semi-arid regions. In more arid areas deviations can even exceed 50% (see MAINGUET, 1991, p.25)

[3] Regarding definitions of what constitutes a semi-arid and what is an arid climate, numerous more or less corresponding definitions can be found in the literature. Often these definitions seem to depend on the background of the author and/ or the region he/ she is looking at. Just for orientation a very common and basic definition should be cited at this point: Semi-arid *"are climates, in which total annual evaporation rates usually exceeds total annual rainfall amounts. Nevertheless, during three to five months of the year rainfall amounts are higher than the analogue evaporation rates"* (LESER et al., 1995b, p.203). [Warm] arid *"are climates with a mean annual evaporation that is exceeding mean annual rainfall. Evaporation usually is higher than the rainfall amounts throughout the year. A typical feature of* [warm] *arid regions is the lack of a* [distinctive] *drainage system. Rivers evaporate on their course or end up in lakes without drainage or in evaporation pans/ salt pans"* (LESER et al., 1995a, p.38). According to MAINGUET (1991, p.3), mean annual rainfall amounts of 150-600mm are typical for semi-arid regions, while arid regions usually receive a mean annual amount of less than 150mm.

In context of this study, semi-arid and arid regions that are repeatedly affected by dry spells or drought, but still permit successful rain-fed agriculture during most of the years, are referred to as *areas at the brim of rain-fed agriculture*. In doing so, it has to be mentioned, that it is more or less impossible to define a generally applicable limit for rain-fed agriculture. This is because a variety of factors, such as length of rainfall season, temporal and quantitative rainfall distribution, evaporation, water retention and drainage of soils, surface run-off, ground cover, varying specific crop-water requirements, cultivation techniques and many others, determine a successful cultivation of crops (see FRANKENBERG, 1985; JAETZOLD, 1980; JAETZOLD 1979).[1]

It has been mentioned already, that regions with unfavourable rainfall patterns usually were avoided or only used in an extensive way by traditional cultures. Not at least due to the consequences of colonialism and the continuous population growth, these traditional cultures and economies mostly do not exist any longer (see BRAUN, 1985; BROWN, 1993) and today farming activities in risky (regarding rainfall patterns) environments have become a common fact.

One of the agricultural strategies used to cope with the fact of rainfall variability and dry spells would be the application of irrigation schemes (see MAINGUET, 1999). However, irrigation schemes also have many risks, such as soil salinisation, negative influence on groundwater levels and others (see WARREN et al., 1996). In addition, the costs of implementing and maintaining irrigation schemes often conflict with local and largely no-commercial agricultural systems. Therefore MAINGUET (1991) states*: „ My own conclusion is that it is absolutely vital that irrigation, especially large projects, in mainly arid and semi-arid ecosystems, should be considered only as the last option of management and if no other solution for development exists.“*

Another, more sustainable way to limit the risks of crop failures would be the application of *drought adapted crops* (DACs), which can reduce the exposure to agricultural droughts. In contrast to *high potential crops*, like e.g. highly productive wheat or maize varieties, DACs are characterised by comparably shorter vegetation cycles, less water demand and a higher resistance towards dry spells. Some of these crops, especially legumes, also have the additional advantage to improve soil fertility, by fixing atmospheric nitrogen via symbiotic bacteria.

Worldwide, several universities and institutes, e.g. the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) or the International Institute for Tropical Agriculture (IITA), conduct research on DACs and contribute also to the creation of new breeds.

However, before any DAC can be introduced to a specific region and become cultivated by farmers, a number of aspects have to be considered. For example it is an important factor to find out if the chosen crop is able to produce a satisfactory yield under the given climatic and soil conditions in the intended area of introduction. In addition, the crop should also meet the demands of the people that are supposed to cultivate it (CHRISTIAN & WOHLLEBER, 1996, p.15).

[1] To get a rough idea under which conditions rain-fed agriculture is about to end it should be noted that, according to JAETZOLD (1980), in tropical and sub-tropical areas with an average rainfall of only 200-300mm in two consecutive humid months, successful rain-fed agriculture is extremely at risk. This is the area that JAETZOLD calls the *“Agro-Sahel“*.

To find out about a crop's applicability in a certain region, usually on-site *trial and error* experiments have to be conducted (K. FLEISSNER, interview; HORNETZ, 1991). The problem with these important experiments is that they are time-, labour- and often cost-intensive. Another difficulty is the significance of their results: Vitality and yield of crops depend a lot on the availability of water during their vegetative period. In other words, they depend heavily on climatic conditions, especially rainfall and evaporation, as well as the time they are planted in relation to the occurring rainfalls. Yet, high rainfall variability is a characteristic feature of semi-arid and arid zones. Assuming that a trial and error cultivation-experiment with a crop variety was conducted for five years, the results will only reflect the performance of the crop variety for this quite short period of time. Just in case the climatic conditions were very favourable during that five years, it still remains unsure how the plants will perform during periods with less or more erratic rainfalls.

Another disadvantage of trial and error experiments is that their results usually cannot be transferred from the experimental area to other regions, where soil or climatic conditions are different (see HORNETZ, 1991, p.70).

To address these problems, *agro-ecologic simulation models* can be a valuable addition to field experiments. Provided that

long-term climatic data, especially of rainfall and evaporation, of the area of interest

and factors like

soil-water characteristics of the area of interest

as well as important

eco-physiological crop data, e.g. water demand, length of the phenological phases and root development,

are considered by the model, the simulation results can reflect the response of plants towards climate over a far greater period of time than field experiments can do.[1]

This thesis is the attempt to describe the application process of an agro-ecological simulation model.

The model that is used, is called MARCROP[2] and was developed at the Department of Cultural and Regional Geography at the University of Trier/ Germany, with the aim of evaluating cultivation potentials of DACs in semi-arid areas (see HORNETZ, 1997, p.220).

To understand why this thesis was written in its very own style, it should be mentioned that it was composed in co-operation with the Desert Research Foundation of Namibia (DRFN). DRFN is a non-governmental organisation which is based in Windhoek/ Namibia. In addition to a variety of research activities concerning biological, ecological and development topics, DRFN is the organizer of the *Summer Desertification Project* (SDP). The SDP is an annual course for Namibian students of geographical, environmental and agricultural

[1] A precondition for the accuracy of a model is of course that the model has been validated for the concerned climatic region.

[2] The name MARCROP was derived from MARginal CROPs.

sciences, to provide additional qualifications and practical skills for applied research. It is hoped that the method described in this thesis may be useful as a guideline for some of the up-coming SDPs.
On this background, the evaluation of crop potentials was demonstrated at the example of the central and western *Omusati* region in north-central Namibia (see annex, map 1).

Central and western Omusati as the area of interest (AOI) was chosen, because the present situation there is representative for many other semi-arid and arid regions:
Omusati is the most western of four administrative regions that form north-central Namibia. The four regions, *Omusati, Ohangwena, Oshana* and *Oshikoto*, are also known as *four Os*, *Owamboland* or simply *Owambo,* because it is the traditional settlement area of the *Owambo* tribes. The Owambo culture is traditionally characterised by *agro-pastoralism*. However, by far not every household can afford to own livestock and therefore these households have to concentrate exclusively on farming.
The population census of 1991 found that Omusati had a population of almost 190.000 persons by that time. According to the CENTRAL BUREAU OF STATISTICS /NATIONAL PLANNING COMISSION (2001, p.8f.), 23.032 households in Omusati were planting crop in the season 1998/ 1999. 28% of this households reported, that they had no other source of income than agriculture.
In 1991 the population growth rate was estimated to be approximately 2,7% per year. Accompanied by this growth is the expansion of areas, which are used for settlement and cultivation - a trend that can be observed at an increasing rate in the central and western Omusati region[1]. Most of the affected areas in central and western Omusati were traditionally used as communal grazing ground. Therefore the space was previously more or less unoccupied, a fact that made and makes the establishment of new farming households easier.
On the other hand, the traditional use of the area for grazing seems perfectly reasonable, because rainfall in Owambo is decreasing from the north-east to the south-west, making central and western Omusati one of the driest areas in Owamboland and putting farming activities at high risk. While in the far north-east of the AOI mean annual rainfall is already at low 450mm, it is decreasing over ~100km to a mean annual around 300mm in the far south-west. The rainfall is confined to one rainy season that usually starts in November, reaches the peak in January to March and ends in April. The rainy season in north-central Namibia is characterised by a high variability of rainfall amounts, number of rainy days as well as temporal and spatial distribution of rainfall. The mean annual evaporation is about 3000mm.[2]
The soils of the AOI can be generally described as reddish-brown to greyish sands and loamy sands. Clay pans, hardpans, calcrete outcrops and salt accumulations are also common. The pH-levels are around neutral and the

[1] The expansion of settlements and cultivated area in Omusati becomes obvious by comparing topographical maps and series of aerial photographs that were produced since the 1960´s to the present. The expansion is also reflected in the annual agricultural statistics. The exact increase of cultivated area in Omusati and the AOI in particular, could not be quantified in context of this study. For the whole north-central Namibia, which shows a development comparable to Omusati, an annual expansion of 2,7% is mentioned in MENDELSOHN et al. (2000, p.54).

[2] The evaporation value is derived from an interpolation between climate-stations that are adjacent to the AOI (see chapter 2.3.2.1). There evaporation was determined by *Class-A-Pan* method.

contents of plant-available nitrogen, phosphorus and potassium are low. The natural vegetation is characterised by a relatively dense *Mopane-Savanna* in the northern and eastern parts of the AOI, becoming sparser towards the south and the west.

To run the MARCROP-model, the necessary data for the application were collected during a stay of five months in Namibia. The most important task during that time was to do a soil survey at the AOI and to obtain the required climate data from the Namibian Weather Office (NOW). Following research in Namibia, the collected data and soil samples were processed and analysed at the University of Trier/ Germany. Afterwards, the cultivation potential of Tepary beans (*Phaseolus acutifolis* A. Gray) was calculated exemplarily with MARCROP.

The decision to run the simulation with Tepary beans was made, because they are a good representative of highly drought tolerant crops. In addition, Tepary beans have the ability to fix atmospheric nitrogen, which is a feature that has positive effects on soil fertility.

Unfortunately the time frame of this study was quite limited, so the cultivation potential of only one crop could be calculated. However, as the necessary soil and climatic data of central and western Omusati are now available in the formats that are required for a MARCROP application, the cultivation potentials of other crops can be evaluated at any time.

2 MATERIAL AND METHODS

For working on the topic of the study at hand, a work routine of several steps was necessary. Apart from already existing data, some more had to be generated and analysed, before a simulation was possible. Some of the existing data also had to be processed before they could be used. For this purpose a number of different techniques had to be applied. Figure 2-1 gives an overview over the work routine. The subsequent chapter will describe the different topics and process in detail in accordance with this figure.

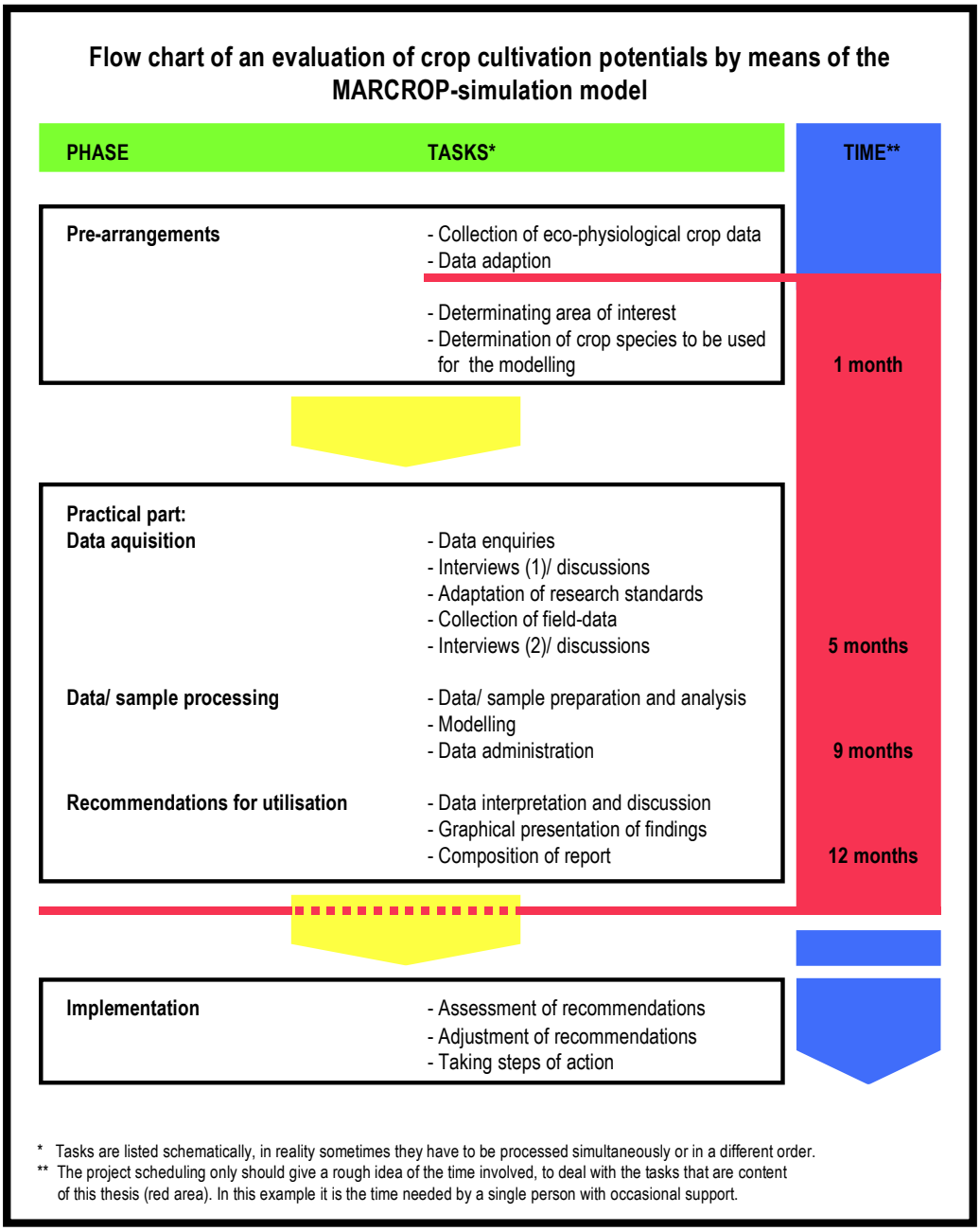


Figure 2-1: Flow chart of an evaluation of crop cultivation potentials by means of the MARCROP-simulation model (Source: own design)

2.1 PRE-ARRANGEMENTS

2.1.1 Collection of eco-physiological crop data

The process of collecting eco-physiological crop data was not part of this thesis. Nevertheless, it is the necessary precondition for the modelling with the MARCROP software: To evaluate the cultivation potentials of a crop in relation to the prevailing climatic conditions of a specific area, several eco-physiological factors (see chapter 2.4.2.1.2) have to be known about the selected crop. For the cultivation of a crop in semi-arid areas, of course the water-household of the variety and the effect of dry-spells on the development of the plants are of greatest concern. To get this particular data, different experiments under standardised conditions have been conducted for several years on a variety of crops at the Department of Cultural and Regional Geography, University of Trier/ Germany. Today these experiments are still ongoing. For this purpose the department is using a (thermo-isolated) climate chamber of ~37m³ volume. The arrangement allows the setting of a defined climate, regarding temperature, humidity, ventilation, illumination and radiation. During the crop experiments, it was tried to create a scenario that represented the typical ecological conditions of a semi-arid cropping area as far as possible. Therefore, the climatic conditions were set as they usually occur during the rainy season in the *Agro-Sahel* of Kenya and in the *Sahel* in Niger and Burkina Faso (see JAETZOLD, 1979; JAETZOLD, 1979b). The soil substrate for these experiments was composed of 80,6% fine and middle sand, 4% silt, 15% clay and 0,4% humic compost. Plant available soil moisture was 6,7mm/ 10cm soil-depth, pH-level (determined in a $CaCl_3$ -solution) was 6,93. For the full details of the experimental setting and the applied techniques, see HORNETZ (1991).

2.1.2 Data adaptation

For this thesis a crop variety that had been analysed under the arrangements of the climate chamber at the Department of Cultural and Regional Geography, University of Trier/ Germany, was used for the modelling with MARCROP. As MARCROP has been developed and programmed in close relation with the plant experiments in Trier, the data obtained from the experiments could easily be processed with the software, because they already had the right format that is needed to run MARCROP.

Of course there is a number of other national and international institutes, like e.g. the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) or the International Institute for Tropical Agriculture (IITA), that do similar kind of research on a variety of other drought tolerant crops. Given that other researchers or agricultural planners want to apply MARCROP with crop data obtained from other sources than the Department of Cultural and Regional Geography at the University of Trier, it has to be considered, that the data might have to be adapted to the format required by the software (see chapter 2.4.2.2.2).

Apart from that, the whole method theoretically can be applied anywhere in the warm, semi-arid to arid regions worldwide.

2.1.3 Determination of area of interest (AOI)

Several reasons why farming potentials of drought tolerant crops should be assessed in a certain area are conceivable. For example, a national or regional government, co-operative society or company wants to develop or advance agricultural activities in a region. Alternatively, a certain crop, e.g. a legume, should be introduced to upgrade soil fertility. Another reason for the application of the method can be certain demographic or socio-economic developments within a specific region.

The observation of four trends resulted in the choice of central and western *Omusati* region as the AOI for this study:[1]

Process 1: Progressing population increase (see chapter 3.3.3)

Process 2: Progressing increase of livestock numbers in north-central Namibia, especially the in the grazing areas of Omusati region, which exceed the carrying capacity of the vegetation (see chapter 3.3.7.2)

Process 3: General decrease of rainfall amounts in north-central Namibia (see chapter 3.2.2.3.5)

Process 4: Increasing establishment of farming activities in areas with rainfall conditions that put agriculture at a high risk (see chapter 3.3.2)

Process 1 and 2 could easily be proved by consulting relevant literature, such as MARTIN & LEONARD (1967) KEYLER (1996), FRIEDRICH-EBERT-STIFTUNG (1997), NGHITILA (1997), CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1994), AROWOLO (1994), MENDELSOHN et al. (2000) and CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (2001). The same is applicable for process three, with special focus on the literature of KEYLER (1996) and MENDELSOHN et al. (2000). Process 4 becomes obvious by comparing maps that depict rainfall patterns of north-central Namibia (see MENDELSOHN et al., 2000, p.9) with topographical maps (SURVEYOR GENERAL, 1975 and SURVEYOR GENERAL, 1981) and aerial photographs that cover the area of Owamboland. Especially aerial photographs were of great help to comprehend the directions of settlement dynamics.

2.1.3.1 Aerial photographs

" Aerial photographs (APs) are all those images that are orientated towards the surface of the earth and are generated by photographic means with a sensoric platform (= camera carrier) that is located above the earth's surface. Typical camera carriers are balloons and airplanes" (DIETZ, 1981, p.17).

Since the middle of the last century AP-survey flights and the production of photographs have been proven instruments of extensive and economic acquisition of spatial data. APs are not only study objects, but also a way to store information on a certain area. Being a document of landscape condition, APs have become a valuable

[1] In addition to the four trends several practical considerations led to the determination of the final borders of the AOI. These considerations were accessibility of the terrain for the field work, available time for the study and general suitability (especially regarding relief and soil salinity) of the area for agriculture.

tool for geography and geo-sciences (see SCHNEIDER, 1974, p.1). The aerial view permits the observation of spatial relations that very often can not or only very difficult be registered from an earth-bound point of view. This is why APs are a valuable tool for research e.g. on geomorphology, water catchments or vegetation. Systematically repeated survey flights over an area also permit the registration of daily, seasonal or yearly changes (see SCHNEIDER, 1974, p.2). For example *"trends of regional development can be extensively verified by evaluations at different points of time and support the arguments for decisions of development policies"* (KOMP, 1991, p.13). In practice, changes in vegetation, population dynamics or dynamics of settlement development can easily be monitored with the help of APs.

Therefore, the analysis of APs was also used to document the general settlement development in north-central Namibia.

For this study two series of APs that cover the central Oshana and the whole Omusati region were available at the General Survey of Namibia.[1] One of them was taken during flights in September 1996 at a height of 12.000 feet above ground. The pictures had a scale of 1:78500. The other one was generated during September and October 1970 at an undocumented height. The scale of these pictures is 1:50.000. The two series were compared and qualitatively analysed, primarily regarding changes in settlement structures, but alterations concerning vegetation, land use and infrastructure were considered as well.

2.1.4 Determination of crop species to be used for the modelling

The selection of crop species depends on the purpose why the crops should be introduced. In case the risks of crop failures caused by erratic rainfall should be reduced, drought tolerant, short-cyclic plants should be considered. Other specimen might be used in case a supplement fodder plant is required. Several species also can be chosen, to upgrade soil fertility by fixing atmospheric nitrogen. In case a certain crop be introduced for marketing, the choice is obvious.

A necessary precondition is of course, that specific eco-physiological data (see chapter 2.4.2.1.2) of the selected plants are available in the format, which is required for the simulation. Otherwise, these data have to be generated in accordance with the demands of the simulation-model.

In context of this study the stress was on crops with the following characteristics:

- Low water demand
- Drought tolerance/ resistance
- Ability of nitrogen fixation to uplift soil fertility
- Practical benefits for the population, respectively their livestock

[1] 1996 flight pictures: strip 3 (no. 389-402), strip 4 (no. 403-417), strip 5 (no. 499-512), strip 6 (no. 513-527), strip 7 (no. 629-641), strip 8 (no. 137-164) and strip 9 (no. 123-135); 1970 flight pictures: strip 6 (no. 5443-5465), strip 7 (no. 5440-5415), strip 8 (no. 5375-5350), strip 9 (no. 5293-5215), strip 10 (no. 5253-5230), strip 11 (no. 5173-5195), strip 12 (no. 3854-3880), strip 13 (no. 3851-3830) and strip 14 (no. 3769-3745)

As time for this study was limited, the cultivation potentials of only one crop variety could be evaluated. For several reasons the final decision was to use the Tepary bean for an exemplary simulation.

2.1.4.1 The Tepary bean (acc. to ALKAEMPER 2000 and HORNETZ 1991)

To do the simulation, a legume of the genus *Phaseolus* and family *Fabaceae* was chosen: *Phaseolus acutifolis* (A.GRAY), respectively *latifolius* (G.F. FREEMAN). The plant is widely known under the common names *Tepary bean*, *Mexican bean* and *Escomite*.

The Tepary bean (TB) descends from north-western Mexico and the south-western USA. There, non-domesticated varieties are still found in damp areas of the semi-deserts, e.g. the *Sonora*-desert. The TB is a short-cyclic, annual and self-pollinating plant, which is adapted to *"short-day"* environments. The undomesticated forms are ground-covering plants, which are able to produce shots of 3m in length. The cultivated forms are erect bushes of ~30cm in height (see figure 2-2). Tepary beans are known to be cultivated, in the area of their origin since at least 5000 years. The plants produce 1cm thick and 5-15cm long pods, those contain 3-7 beans. The roundish (~8x6 mm) beans (see figure 2-2) can be used to produce vegetable dishes and thick soups, while the surplus plant material provides a highly valuable fodder, even in dry condition.

Figure 2-2: Growth form and fruits of the Tepary bean (Source: ALKAEMPER, 2000)

According to ALKAEMPER (2000), the mean *"1000-corn-weight"* is 125-175g. The corn-yield depends a lot on cultivation method and on precipitation, respectively water supply. Yields between 8-16 dt/ ha are usual, "*in very dry areas they may be only 5 dt/ ha"* (ALKAEMPER, 2000). With little additional irrigation 20 dt/ ha can be achieved and from experiments in Algeria, yields up to 40 dt/ ha are reported (see ALKAEMPER, 2000). The yield of the surplus plant material lies between 5-10 t/ ha, depending on the water supply during the growth period. In case TBs are cultivated for bean production, it is recommended to use 20-33 kg seeds/ ha. The seeds are sown shallow, 2-3 cm deep.

Optimum conditions for cultivation are a climates with mean rainfall amounts of ~ 400-500mm during the vegetation-period and temperatures between 17-27°C, whereby temperatures must not fall below 8°C at night.

Well-drained and aerated soils, with pH-levels between 5-7,1 are best for TBs. In case of waterlogging soils, the plants should be cultivated on small dams. Regarding soil nutrients, the TB is extremely undemanding. Poor sandy soils are no problem for cultivation.

The TB has been chosen for the exemplary modelling, because of the numerous positive qualities regarding the cultivation in semi-arid areas. Those are in short: adaptation to semi-arid environments, positive effects on soil conditions, advantages for the farmer and high nutritional value.

2.1.4.1.1 Adaptation to semi-arid environments

In a semi-arid environment a plant usually has to cope with high temperatures and radiation, as well as limited, irregular water supply and very often with poor soils, too. The most remarkable strategies of TBs are *photonastic* and *parahelionastic* response: during phases of stress caused by high temperature/ radiation or drought, the plants are able to reduce transpiration loss by changing the position of their leaves in a way, that the leave blades reach a position that is parallel in relation to the arriving sunrays. To enable a fast reaction of this kind, it seems that the leaves have to be quite thin and not too much cutinised. The quite weak cutinisation of TB leaves is balanced by the plants cover of fine hairs, which also represent a successful strategy to reduce transpiration. In addition, TBs also have physiological adaptations, e.g. osmotic adjustment, to endure water stress. These adaptations enable the plant to produce at least a minimum amount of seeds for reproduction, even when the highly sensitive phases of flowering and fruit bud development were affected by temporary water stress. Experiments found that TBs even can endure periods with a temporary water supply that is equivalent to less than 20% of the prevailing evaporation (see HORNETZ, 1991).

Another strategy of TBs is avoidance of water stress: depending on the environmental and cultivating conditions, most TB varieties have completed their vegetation-cycle after 55-60 days. By having such a short cycle, the exposure to dry spells is reduced in comparison to crops with a longer cycle, such as e.g. maize or even millet.

Another exceptional reaction of TBs is the attachment of quartzite granules to the fine roots, during times of drying out soils, as it is described by SPRENT (1975) in HORNETZ (1991, p.163). It is assumed that the plants produce a root secretion called *Mucigel*, that binds the granules to the roots. These granules can act as condensation nuclei for steam that is mobile within the capillary system of the soils and can get absorbed by the roots.

2.1.4.1.2 Positive effects on soil conditions

The binding of quartzite granules does not only have positive effects on the water supply of the plants, it also promotes the stability of soil structure and helps to reduce erosion. Regarding the prevention of erosion the cultivation of TBs is generally rated positive, as the plants cover the cultivated soils very well.

Another positive effect on soils is the symbiosis that TBs maintain with *rhizobia*, mostly of the *Canavalia*- and *Limabean*-lines. These nitrogen-fixating bacteria actively promote nitrogen concentrations of soils.

2.1.4.1.3 Advantages for the farmer

Due to the described symbiosis of nitrogen-fixing rhizobia and TBs´ adaptation to nutrient poor soils small-scale farmers do not have to invest in costly mineral fertilizers. As TBs are highly resistant to parasites, fungi and crop

pests, usually no expenses have to be made for pesticides etc.. Another fact that must not be forgotten is the reduced risk of drought related total crop failures, due to TBs´ short vegetation-cycle.

2.1.4.1.4 High nutritional value

TBs are known for their high protein contents of 21-32%. Despite the lack of the amino acid *Tryptophane*, the nutritional value, concerning essential amino acids, is still very high. Carbohydrate levels range from 60-72%, fat is usually at 1,5%, minerals at 3-5% and fibre at 3,5-5%.

The calorie value of seeds is 380 cal. and compared to other tropical staple crops the TBs maintain a strong position concerning their value for human nutrition (see table 2-1).

As even the surplus plant material has protein levels of 9,9-14,45%, the shots of TBs provide a highly valuable fodder, too.

Table 2-1: Nutritional values of Tepary beans and other common crops (Source: HORNETZ 1991 & ALKAEMPER 2000)

Crop	Protein (%)	Carbohydr. (%)	Fat (%)	Calories
Tepary bean	21,0 – 32,0	60,0 – 72,0	1,5	380
Bambarra groundnut	18,8	61,3 - 72,2	6,2	367 – 412
Maize	4,4	70	3,8	347 – 358
Cassava (dry)	1,4	39	0,5	306

2.2 DATA ACQUISITION

To do an assessment of the cropping potentials of a specific area involves a broad knowledge of the concerned region. More information than just the data that are required by the simulation software is necessary. What is also required are maps for orientation and general information on the natural environment, on soil nutrient levels, the social and economic situation of the population, traditions, infrastructure etc. – in short, every available information that is useful for the understanding of the present situation and possible future developments in a specific region. Only with attention to those facts, it is possible to make recommendations that meet the real situation of an area and the demands of the local population.

2.2.1 Data enquiries

Before starting the practical field work in the AOI, four weeks were spent to gather already existing data on the AOI and on Owambo in general. Literature, maps, aerial photographs, climate data and GIS-data sets concerning natural, socio-economic and cultural aspects of north-central Namibia were reviewed.

The libraries and archives of the following institutions and organisations were frequented:

- Central Bureau of Statistics (CBS)
- Department of Environmental Affairs (DEA)
- Desert Research Foundation of Namibia (DRFN)
- Directorate of Forestry
- Friedrich Ebert Stiftung, Namibian office
- Gesellschaft fuer Technische Zusammenarbeit (GTZ), Namibian office
- Hydrological service at MAWRD
- Ministry of Agriculture, Water Affairs and Rural Development (MAWRD)
- Ministry of Mines and Energy
- Namibian Economic Policy Research Unit (NEPRU)
- National Botanical Research Institute (NBRI)
- National Library of Namibia
- Namibian Weather Office of (NWO)
- Surveyor General, Namibia

During the stay in Owamboland, the enquiry was continued at institutions that are based in northern Namibia. Those were:

- Agricultural Extension Office of MAWRD in Ongwediva
- Northern Namibian Environmental Project (NNEP) in Oshakati
- Rural Development Centre (RDC) in Ondgwediva

2.2.2 Interviews and Discussions

To complete the information and to find out about recent developments in Namibia, Owambo, and the AOI several non-quantitative and non-standardized interviews were held with experts in the fields of environmental management and planning, agriculture, economy and rural development as well as with local farmers. Some of these persons had to be interviewed a second time after the field work, because some observations had created new questions.
The following experts have been interviewed:

- Amamboo, O., local facilitator for the northern regions, DRFN
- Davies, D., geographer, NNEP
- Pisani du, L., agro-meteorologist, MAWRD
- Fitter, J., head of Namibian office, GTZ

- Fleissner, K., senior researcher, Legumes Research Programme, MAWRD
- Kalunduka, M., project manager, RDC in Ongwediva
- Kroll, T., project manager, GTZ
- Mendelsohn, J., researcher, Atlas GIS project, DEA
- Negumbo, Mr., head of Agricultural Extension Office of MAWRD in Ongwediva
- Olszewski, J., former officer at NWO, now associated with DRFN
- Rothkegel, B., director of Agricultural Planning Commission, MAWRD
- Seely, M., head of DRFN
- Strubach, B., head of NBRI

Farmers were interviewed during the field work in the AOI, whenever there was time and occasion. Unfortunately no translator was available, so only English- or English/ Afrikaans-speaking people could be interviewed.
Because all interviews were non-formalized, it is impossible to give an overview over their results. Statements or facts that were important or interesting for the study are rather quoted directly at the relevant passage within the text.

In addition to the interviews, several discussions and conversations concerning research problems held with supervisors, researchers and expert scientists. Those were:

- Beukes, H., researcher, Agro-Ecological Zoning (AEZ) at MAWRD, Namibia
- Davies, D., geographer , NNEP, Namibia
- Emmerling, C., Department of Soil Science, University of Trier, Germany
- Helbig, A., Department of Climatology, University of Trier, Germany
- Hornetz, B., Department of Cultural and Regional Geography, University of Trier, Germany
- Jaetzold, R., Department of Cultural and Regional Geography, University of Trier, Germany
- Klintenberg, P., DRFN, Namibia
- Krug, J., DED, Namibian branch
- Licht, K., Department of Climatology, University of Trier, Germany
- Mendelsohn, J., researcher DEA, Namibia
- Mouton, H. soil researcher, AEZ/ MAWRD, Namibia
- Niemeyer, J., Department of soil science, University of Trier, Germany
- Warren, G., Department of Soil Science, University of Reading, United Kingdom

2.2.3 Adaptation of research standards

A quite extensive part of this thesis comprised field work for data (predominantly on soil) collection and data processing/ presentation by means of a *Geographical Information System* (GIS, see chapter 2.5).
To make all the newly created data comparable and available for other projects in Namibia, the sampling-, analysis-, processing- and presentation methods were adapted to Namibian standards as far as possible. For example, the soil profile descriptions followed the guidelines used by the AEZ-unit at MAWRD. They are a composition of the 1990 "FAO Guidelines For Soil Profile Description" and own experiences of Namibian soil scientists. The guideline was extended by methods derived from the German 1994 "Bodenkundliche Kartieranleitung" only as far as it was necessary for the project.
For the administration, processing and display of geographical data, the AEZ-unit, the DEA and the NNEP in Namibia are using the ArcView-Gis software. Large datasets and maps concerning Namibia have already been created by these three institutions. Therefore it was decided, to use ArcView-Gis for this study as well.

2.2.4 Collection of field data

From 23rd of December 2001 to 11th of February 2002, with an interruption of one week, the necessary field work was conducted in the AOI and its adjacent regions. Due to other appointments and technical problems the field work could not start earlier. Luckily, the rains in the AOI had not begun then and also did not start during the period of the field work. This was important, because soil condition should be assessed as it is at the beginning of the cropping season. In addition heavy rains would have left many tracks in the AOI impassable for days.
Apart from general observations and interviews concerning the natural and social environment, the most important task was to collect specific soil data, such as soil depth and water retention, expressed by field capacity, respectively available field capacity, of the soils. These data are precondition to run the simulation model.
In addition, a complete profile description was carried out at seventy-one sample sites, of which fifty-nine finally were used for the study. This was necessary to find out about the soil types and their general suitability of the soils for crop cultivation.

2.2.4.1 Allocation of soil sample sites

Before the start of the field work the review of already existing soil maps (FAO & UNESCO, 1977; MENDELSOHN et al., 2000, p.19) has shown, that the general soil conditions in the AOI are quite in-homogenous.
To address this fact and to collect soil data that reflect the real situation at the AOI as close as possible, the map of vegetation types in north-central Namibia (see MENDELSOHN et al., 2000, p.22-23 and annex, map 4) was used as a guideline for the soil survey. This method was chosen, because "[vegetation]...*is not an independent factor like parent rock or climate but results from the interaction of rock, climate and soil."* (SCHROEDER, 1984, p.78). As quasi no major geological variations, no dramatic relief energy and no great variations in climatic

conditions exist in the AOI, it was assumed that the various vegetation types of the AOI are primarily related with the soil conditions. This assumption was confirmed in an interview with J. MENDELSOHN. Thus it was tried, to choose the sample sites in a way, that they were well distributed over the six occurring vegetation units (see chapter 3.2.3) Besides that, the number of sample sites in each unit should depend on the proportion of space that each particular vegetation unit is comprising of the total AOI.
In addition to this guiding principle, it was the available time and the accessibility of the area that determined the final number of sample sites and their location. At the end the sample sites that entered the study were distributed as followed:

- *Cuvelai palms & fruit-trees on loamy sands*: 5 sites
- *Mopane-Combretum savanna on sandy soils*: 16 sites
- *Mopane shrubs & low trees on loamy sands*: 6 sites
- *Western sand plains*: 18 sites
- *Western mopane-pan mosaic*: 7 sites
- *Mixed savanna on loamy to sandy soils*: 7 sites

To determine the global position of a sample site during the field work, a *global positioning system* (GPS; GPS 12 by GARMIN) was used.

2.2.4.2 Soil data collection

The soil description was accomplished in accordance with the data collection sheet used by the AEZ-unit at MAWRD and the “Guidelines For Soil Profile Description” (FAO, 1990). To describe bulk-density, soil texture and HCl-reaction the “Bodenkundliche Kartieranleitung” (AG BODEN, 1994) was used, because these methods are more detailed and more familiar to the author. Annex 2-1 shows a copy of the complete data registration sheet that was used for the survey.
To obtain an image of the structure of the soil profile at a sample site, at tool called “PUERCKHAUER-Bohrer” was used. This soil auger is a half-open steel-pipe with ~ 3,5cm diameter, 1m length and a cusp on one end. On the other end it has a massive steel head, so the auger can be driven into the soil with a sledgehammer. The head also has a hole to carry a crossbar, which allows to pull the auger out of the soil again. Given that this is done carefully, the borer contains material that represents an undisturbed profile, which is exposed, as the pipe is half open. At sites where this technique was not suitable or where the result seemed questionable, profile-pits were dug to describe the profiles.
HCl-reaction was tested on-site with 10%-HCl-acid and the soil-colour was determined according to the “Revised Standard Soil Color Charts” by OYAMA (1970).
A quite exact way to measure (available) field capacity is by means of undisturbed soil samples. These are collected with the help of metal cylinders that are stabbed into the profile. Afterwards the distribution of pore-sizes can be determined in a soil laboratory and (available) field capacity can be derived from the results. The method

is described in several publications, e.g. SCHLICHTING et al. (1995), ABTEILUNG BODENKUNDE DER UNIVERSITAET TRIER (1992). Despite that the cylinders were available for the survey, their application proved to be of no use under the given circumstances. To obtain the undisturbed samples was very time-intensive and their transport off road and cross-country in an undisturbed condition was simply impossible. As a result, (available) field capacity was derived via *bulk-density* and *soil-texture*. The method and the necessary tables are documented in AG BODEN (1994, p.125ff & p.297; also see annex 2-2). Bulk-density and soil-texture were determined on-site, with a common manual method called *finger test*, which is described e.g in AG BODEN (1994, p.137 ff.) and in FAO (1990).

During the soil-survey an amount of approximately 400g of well-mixed soil was filled into plastic bags at every profile site. These samples were used to cross-check the results of the on-site soil-texture assessment and to determine soil-salinity, pH-levels, the amount of plant available phosphorus (P_2O_5), potassium (K_2O) and mineral nitrogen (N_{min}). (see chapter 2.3.1)

2.3 DATA/ SAMPLE PREPARATION AND PROCESSING

After the stay in Namibia, the collected data and the soil samples were processed and analysed. Following this was the calculation of Tepary cultivation potentials.

2.3.1 Analysis of soil

All the soil samples were analysed at the laboratory of the Department of Applied Physical Geography and at the laboratory of the Department of Soil Science at the University of Trier/ Germany. When not explicitly mentioned, all the soil analyses were carried out with air-dried soil material, which has been sieved to grain sizes of 2mm or less. All the weighing of samples and chemicals during the process was done with fine scales by SARTORIUS.

2.3.1.1 Soil texture

To double-check the results of the onsite soil-texture evaluation, twelve soil samples, each with a control parallel, were analysed under laboratory conditions. Applied was a combined method of *wet sieving* and the *standardized sedimentation* method according to KOEHN. The methods are internationally accredited and documented, e.g. in SCHALLER (1993, p.54 ff.). The twelve samples that were selected for the cross-check with the results obtained in the field had been chosen in a way, that all the grain-compositions that were identified in the field were represented in the analysis.

The results of eight samples were identical with the onsite-assessment. The results of the remaining four samples showed a soil-texture slightly finer than the ones determined in the field. As the differences were only gradual and the soil samples had to be treated with a mortar (that might have crushed an amount of particles) before they could be analysed in the laboratory, it was decided to rely on the data as assessed in the field.

2.3.1.2 pH-levels

The pH-levels of the soils from each sample site were measured by pH-meter (pH-Meter 5512 by METROHM HERISAU). An amount of 10g of soil was suspended in 25ml of demineralised water. The suspension was allowed to rest for thirty minutes. Afterwards the pH-levels were measured for the first time. 24 hours later, the pH-levels were determined a second time and the mean average of the two rounds was calculated. The whole method is described in SCHALLER (1993, p.205ff.).

Another common way to determine pH is to use 0,1M KCl- or $CaCl_2$-solution instead of demineralised water. To transform values of pH-levels that have been determined with demineralised water, the factor 1,2 respectively 0,6 has to be subtracted to obtain the results a KCl- respectively a $CaCl_2$-solution would bring.

2.3.1.3 Salinity

Several ways are known, to evaluate the concentration of soluble salts, which are found in every soil. As salts are electrolytes, a relatively simple method to determine salinity is to measure the electric conductivity of the soil solution. The higher the content of electrolytes within a solution, the smaller is the electric resistance and the higher is the electric conductivity (SCHALLER, 1993, p.252).

The conductivity was measured with a temperature-compensated conductivity-meter (Conductivity-Meter LF95/Set by WTW) combined with a conductivity-cell (Tetralon96 by WTW). The measurement range of the system is from 0,0µS/cm² – 199,9mS/cm², at a possible temperature range of –5 - +50°C. The specific cell-constant of the conductivity-cell is 0,609/cm².

Each of the fifty-nine soil samples was tested. For the analysis, the same solution that was prepared to determine pH-levels (see chapter 2.3.1.2) was used.

To make the results internationally comparable, conductivity is usually expressed in mS/cm² *specific conductivity* of the dry soil. To obtain the specific conductivity, the results of the analysis had to be multiplied with the specific cell-constant of the conductivity-meter (SCHALLER, 1993, p.252). As all the results were derived from a 1: 2,5 soil-water suspension, they did not reflect the real conductivity at the sample site, because there the soils were dry. Therefore, the results had to be converted into the actual conductivity at the time the soil-samples were taken. As all the soils were dry at the time the samples were taken, the results of the analysis have to be converted with the following formula, which also considers the cell-constant of the conductivity-meter:

$$\boxed{EC_{ds} = \{250 \times (EC_{an} \times CC)\} / WC_{ds}}$$

EC_{ds} : electric conductivity of dry soil (mS/cm²)
EC_{an} : electric conductivity measured in analysis (mS/cm²)
CC : cell-constant
WC_{ds} : water content of dry soil

WC_{ds} was calculated with the following formula:

$$\boxed{WC_{ds} = puW + 0.1aFC}$$

puW : plant-unavailable soil-water
aFC : available field-capacity

According to AG BODEN (1994, p.297) puW was calculated with the following formula:

puW = FC – aFC FC : field-capacity

Field capacity and available field capacity were obtained during the soil survey (see chapter 2.2.4.2).
The whole method of conversion the results of the analysis into the specific conductivity of a dry soil is documented in SCHLICHTING et al. (1995, p.39 and p.47).

The nature of the salts was not analysed, because the methods are too time and labour intensive and the results would have been of minor importance in this study. However, the relatively high pH-levels and the reviewed literature let assume, that predominantly alkaline salts and sodium are contained in the soils of the AOI.

2.3.1.4 Plant available nutrients

To get an idea about the concentration of the most important plant nutrients (P_2O_5 , K_2O and mineral nitrogen), twenty-four soil-samples were analysed, each with a control-parallel. The samples were selected in a way, that they represented the different vegetation (respectively soil) units of the AOI. Of larger vegetation units more samples were analysed than of smaller units: Two samples out of the area of *Cuvelai palms & fruit-trees on loamy sands*, three each out of the areas of *Mopane shrubs & low trees on loamy sands* and the *Western mopane-pan mosaic*, six out of the area of the *Mopane-Combretum savanna on sandy soils* and seven out of the *Western sand plains* were tested.

2.3.1.4.1 P_2O_5 and K_2O

To determine P_2O_5 and K_2O 5g soil were suspended in 100ml of calcium-acetate-lactate-solution (also known as *CAL*-solution) and shaken for two hours. During this treatment, the CAL-solution was desorbing the K- and P-ions from the soil-particles the same way as plants would do it under natural conditions. The method is accredited internationally and very common. It allows comparison of soil nutrient levels worldwide. The complete procedure is documented e.g. in SCHALLER (1993, p.267ff.).
After shaking, the suspension was filtered and the cleared solution was used for the further analysis:

Phosphorous concentrations were measured by photometer (UV/ VIS spectrometer series 8700 by UNICAM) at a wavelength of 710nm. Before this could be done, the solution had to be dyed with a special solution. The mixture consisted of 4 different solutions:

- Solution 1: 500ml aqua dest. + 138ml concentrated sulphuric acid
- Solution 2: 1000ml aqua dest. + 40g ammoniummolybdate(4%)
- Solution 3: 100ml aqua dest. + 0,2734g potassiumantimontartrate
- Solution 4: 1,76g ascorbic acid, filled up wit aqua dest. to 100ml

They dying-mixture contained ten parts of solution 1, three parts of solution 2, one part of solution 3 and six parts of solution 4.

2ml of this mixture was diluted with 7ml aqua dest. and 1ml of the sample solution. After shaking, the whole suspension had to rest for 30min before it could be measured by photometer.

As the whole method determined PO_4 and not the required P_2O_5, the results had to be converted into mg P_2O_5/ 100g soil, with consideration of the dilution during the process, the system inaccuracy and the amount of used soil-sample. The following formula was applied:

[{(ppm x 1000) / 5} x 0,7473] / 10 - BS

ppm	: parts per million = output value of the photometer
1000	: dilution factor
5	: g of soil sample used for analysis
0,7473	: conversion factor PO4 into P_2O_5
10	: conversion factor g/ kg into mg/100g
BS	: result of the blind sample (a sample without soil was analysed, too, so the inaccuracy of the analytical system could be determined)

The method is documented in ABTEILUNG BODENKUNDE DER UNIVERSITAET TRIER (1998).

To measure potassium no colouring was necessary. The solution of the CAL-breaking down could be determined directly with an atomic-absorption-spectrometer (AAS). For this study the Spectra AA 300 Atomic Absorption Spectrometer by VARIAN was used, burning a flame fed by an air-acetylene gas mixture. As the ASS measures elementary potassium, the results had to be converted into mg K_2O/ 100g soil, with consideration of the dilution during the process, the system inaccuracy and the amount of soil used. The following formula was applied:

[{(ppm x 1000) / 5} x 1,2064] / 10 – BS

ppm	: parts per million = output value of the AAS
1000	: dilution factor
5	: g of soil sample used for analysis
1,2064	: conversion factor K into K_2O
10	: conversion factor g/ kg into mg/100g
BS	: result of the blind sample (a sample without soil was analysed, too, so the inaccuracy of the analytical system could be determined)

The method is also documented in ABTEILUNG BODENKUNDE DER UNIVERSITAET TRIER (1998).

2.3.1.4.2 Nitrogen (N), N-mineralization, Carbon (C) & C/N-ratio

Nitrogen

Regarding crop yields, nitrogen is the most determining amongst all plant nutrients. Nitrogen is found in variety of different chemical combinations in soils. They can have the form of organic compounds such as proteins, amino acids, nucleic acids, the form of minerals like ammonium and nitrate or the form of gases, such as ammoniac, elementary nitrogen, nitrite and laughing gas. Depending on different circumstances like pH-level, temperature, solar-radiation, soil moisture, micro-organism activity as well as aerobic or anaerobic soil conditions, these chemical combinations are transformed permanently by mineralisation, nitrification, de-nitrification, biological fixation, nitrate-ammonification, ammoniac release, just to name the most common processes. These activities do not only happen within the soil exclusively, there is a lot of interaction between pedosphere and atmosphere.The only way plants can absorb nitrogen is in the two mineral forms, say ammonium and nitrogen.

Several methods, e.g. the *$CaCl_2$/ DTPA*-method and the *N_{min}*-method (see SCHALLER, 1993, p.279ff. and 287ff.) are known to analyse the concentrations of the two minerals within soils. However, precondition to apply these methods is, that the soil sample is transported immediately and well cooled from the sample site to the laboratory, where it has to be analysed at once. Otherwise, the minerals will undergo different forms of transformations, usually caused by micro-organisms, and the analysis will not reflect the real situation anymore.

Conditions during the field work did not allow a rapid transport of cooled samples to laboratory. Therefore, just N_{total} (= N fixed in organic compounds) concentrations of the soil samples could be determined.

The analysis was done by the laboratory staff of the Department of Soil Science at the University of Trier/ Germany. N_{total} was determined by gas-chromatograph (CHNS-O Element Analysator by EUROVECTOR), by means of pyrolytic oxidation of the soil inherent organic substance. The output-values represented the percentage of N_{total} within the soil body.

N-mineralisation, Carbon (C) & C/N-ratio

Having N_{total} contents and the mineralisation rates, the concentrations of plant available N can be estimated. Mineralisation of organic N (N_{total}) is almost exclusively driven by bacteria and fungi. Therefore, the rate of mineralisation depends on the environmental conditions that regulate the activity of such micro-organisms. Mineralisation is most rapid at intermediate humidity with good soil aeration, optimal temperature and neutral to slightly alkaline reaction (see SCHROEDER, 1984, p.39). Especially at temperatures between 30-40°C, the mineralisation rate is increasing rapidly, with an optimum at 50°C. A dry phase following a phase with moist soil conditions will increase mineralisation additionally (SCHEFFER & SCHACHTSCHABEL, 1992, p.263). During periods when soil falls dry (a common feature in semi-arid and arid regions), the mineralisation is reduced dramatically or even ceases temporarily.

Another factor that is influential on the mineralisation rate is the C/N-ratio. According to SCHROEDER (1984), the C/N-ratio is a relative index for *"ease of decay and biological activity"* (SCHROEDER, 1984, p.39). Microbiological activity, that is responsible for decay and mineralisation, is limited by shortage of protein N, which is needed for

metabolism. Therefore, a C/N-ratio above 25:1 indicates a low rate of mineralisation, while at ratios below 20:1 much N is mineralised (see SCHROEDER, 1984, p.39).
To determine the C/N-ratio, the C content of soil has to known. The C analysis was done in the same way as N_{total}-levels were measured (see above).

2.3.2 Climate data processing

The description of the general climatic conditions at the AOI and the need of daily rainfall and monthly evaporation data for the modelling required the analysis and processing of climate data. Those were obtained from the Namibian Weather Office and the Hydrological Division at the Ministry of Agriculture, Water Affairs and Rural Development. The data that were be used are daily rainfall from 1st of January 1960 – 31st of December 1989 of the stations in *Ongandjera/ Okahao*, *Otjovasandu* and *Ermo*, as well as mean monthly *Class-A-Pan* – evaporation data from 1951 – 1985 of the stations in *Mahenene* and *Okaukuejo*.
Before the actual data analysis was done, all data sets were visually tested for data gaps and for data plausibility. The plausibility check was done visually and by comparing the monthly and yearly maximum, minimum and mean values of each year with those of the other years and with data of other stations in north-central Namibia.
All the data were handled and analysed with the Microsoft Excel software.
Please note that the results of the climate data analysis are not mentioned in chapter 4 *"Results"*, because the climate data analysis was just a precondition for the description of the climate at the AOI and for the application of MARCROP. Therefore, the findings of the analysis are documented in chapter 3 *"General profile of the area of interest"* and in chapter 2.3.2.2 ff., where the MARCROP application is described.

2.3.2.1 Data analysis for the general description of the climatic conditions at the AOI

In chapter 3.2.2 of this study the general climatic conditions regarding temperature, wind, humidity, evaporation, mean annual rainfall, rainfall variability, productive rainfall, effective rainfall, rainfall trend, drought and the effects of *El Niño*, *La Niña* and *Benguela El Niño* are described. Concerning temperature, wind, humidity and effective rainfall already existing literature information was used for the description. Literature information concerning mean average rainfall amounts, rainfall trend, productive rainfall and rainfall variability was completed by the analysis of rainfall data from the Ongandjera/ Okahao station. Applied were basic statistical methods, such as calculation of mean average values, calculation of deviation from the mean average and an automated trend analysis provided by the Microsoft Excel software.
The ways in which evaporation, spatial variation of evaporation and rainfall at the AOI were determined is documented in the sections 2.3.2.2 and 2.3.2.3.
Almost no information was available on drought risks at the AOI and on the effects of *El Niño*, *La Niña* and *Benguela El Niño* on the rainfall pattern at the AOI. To make basic statements on these topics, the seasonal rainfall data of the *Ongandjera/ Okahao* climate station were classified on the background of a definition of *meteorological drought* by the SOUTHERN AFRICA REGION CLIMATE OUTLOOK FORUM (1997) and on a

definition of *crop drought* in SEELY, 1999. For the exact definitions, the analysis and the results see chapter 3.2.2.3.5.

2.3.2.2 *Assessment of evaporation at the AOI and creation of the evaporation input-data for the MARCROP application*

To describe evaporation rates, the monthly evaporation data (obtained by *Class-A-Pan* -method) of Mahenene station (about 85km north of the centre of the AOI) and of Okaukuejo station (about 163km south-east of the centre of the AOI) had to be used, because no other suitable data were available. The distance between these two climate stations is ~227km (see figure 2-3).

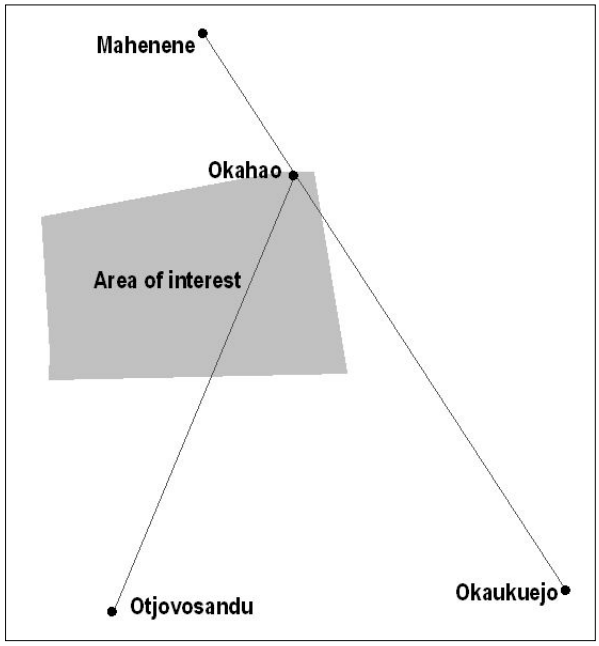


Figure 2-3:

Location of the AOI in relation to the climate stations used for the assessment of regional evaporation and rainfall variations (Source: own design, based on GIS data provided by Atlas GIS Project, DEA, Namibia, 2002)

The long-term (1951-1985) mean monthly evaporation data of the two stations were compared and the monthly *Okaukuejo/ Mahenene* -ratio of evaporation was determined. By doing this, a monthly coefficient of evaporation increase from north (Mahenene) to south (Okaukuejo) was obtained.[1] The coefficients of increase of evaporation/ km with values of Mahenene as benchmarks are shown in table 2-2.

Table 2-2: Calculated percentage of evaporation increase per month and kilometre from Mahanene to Okaukuejo

Month	November	December	January	February	March	April	Total year
Percentage of evaporation increase/ km	0,018%	0,017%	0,015%	0,008%	0,01%	0,014%	0,015%

Having these coefficients, the evaporation of any point lying on the line between Mahenene and Okaukuejo can be assessed to some degree with the following formula:

[1] According to a statement of A. HELBIG, Department of Climatology at the University of Trier/ Germany, this approach appears justifiable in regard of the homogenous, flat topography and the almost complete lack of surface water throughout the whole region (conversation 8th of July 2002).

$$V_{enew} = V_{seMah} \times C_s \times D / 100 + V_{se\ Mah}$$

V_{enew} : calculated evaporation value for a specific point on the line between Mahenene and Okaukuejo

$V_{se\ Mah}$: specific mean monthly or annual evaporation value at Mahenene

C_s : specific monthly coefficient of evaporation increase (%)/ km

D : distance (km) between Mahenene and point for which V_{enew} is calculated

The virtual line between Mahenene and Okaukuejo is crossing the north-eastern parts of the AOI. The line (coming from Mahenene) enters the AOI just north of Okahao after a distance of ~54km. From there it runs through the north-eastern part of the AOI, leaving it in the east after ~17km (see figure 2-3).

For the modelling it was necessary to have evaporation data that describe the spatial evaporation variation within the AOI as exact as possible. Yet, the described formula can only describe evaporation values for points lying on the virtual line between Mahenene-Okaukuejo. This line is crossing through the north-eastern part of the AOI only.

In addition, the calculation is only an approximation to the real situation. However, the formula was applied to describe the evaporation values throughout the whole AOI, as no alternative ways were at hand.

2.3.2.3 *Assessment of the spatial rainfall distribution at the AOI and creation of the rainfall input-data for the MARCROP application*

To get a general idea of rainfall conditions at the AOI, the rainfall data of Ongandjera/ Okahao could easily be used, as the station is located in the north/ north-east of the AOI.[1] Yet, the determination of variations in rainfall amounts throughout the AOI was a problem, similar to evaporation variation. Apart from Ongandjera/ Okahao, there is no other station situated within, or close to the AOI. However, a precise modelling procedure requires rainfall data that reflect the situation throughout the AOI as detailed as possible. To meet this requirement, a second interpolation, similar to the one with evaporation data, was done:

According to MENDELSOHN et al. (2000, p.9ff) and MARSH & SEELY (1992, p.6ff) the amount of rainfall in northern Namibia is declining from the north-east to the south-west. About 166km south-west of Ongandjera/ Okahao station and about 85km south of the southern/ south-western border of the AOI, Otjovasandu station is located (see figure 2-3). The long-term (1961-1989)[2] monthly rainfall means of each month of the rainy season (November-April) of this station were used, to do an interpolation with the analogue data of Ongandjera/ Okahao station.[3]

[1] Unfortunately data are only available until 1989, because the station was closed in 1990.

[2] The rainfall data of Otjovasandu were partly incomplete. The gaps were filled with data from Ermo station, which is located ~13km southeast of Otjovasandu. This approach seems justifiable, because analogue rainfall data of 14 years were tested for their correlation. Regarding the mean monthly rainfall the correlation factor was 0,98 and regarding the monthly numbers of days with rainfall the correlation factor was 0,97.

[3] J. MENDELSOHN of the DEA rated this method as *"perfectly reasonable"* (e-mail correspondence 10th of September 2002).

According to the calculations, there is, as it was expected, a decrease of rainfall from Ongandjera/ Okahao to Otjovasandu during November-March and a slight increase in April. The calculated percentages of decrease/km, with Ongandjera/ Okahao data as benchmark are shown in table 2-3.

Table 2-3: Calculated percentage of rainfall decrease per month and kilometre from Ongandjera/ Okahao to Otjovasandu

Month	November	December	January	February	March	April (!)
Percentage of rainfall decrease/ km	0,239%	0,134%	0,206%	0,086%	0,026%	0,1%

(!): The factor for April is a factor of increase instead of decrease

By using the coefficients that are shown in table 2-3, the rainfall data pool of Ongandjera/ Okahao can be adjusted to any point lying on a virtual line with south-western direction, the line between Ongandjera/ Okahao and Otjovasandu. Rainfall amounts can be calculated with the following formula:

$$V_{r\,new} = V_{sr\,Ong} - V_{sr\,Ong} \times C_s \times D / 100 \quad (!)$$

$V_{r\,new}$: calculated rainfall amount for a specific point on the virtual line between Ongandjera/ Okahao and Otjovasandu

$V_{sr\,Ong}$: specific mean monthly or absolute daily rainfall amount at Ongandjera/ Okahao

C_s : specific monthly coefficient of rainfall decrease (%)/ km

D : distance (km) between Ongandjera/ Okahao and point for which V_{enew} is calculated

(!) : for calculations concerning April, the subtraction in the formula has to be substituted by an addition

Again the calculation is only an approximation and only applies for points lying on the virtual Ongandjera/ Okahao – Otjovasandu line. However the formula had to be applied to the whole AOI, as no other alternatives were at hand.

Another problem to describe rainfall throughout the AOI were the days on which rainfall de facto occurs. Though, a comparison has shown that mean long-term (1960 -1989) numbers of days with rainfall during January-April at Ongandjera/ Okahao (24,9 days) and Okaukuejo (21,6 days) do not vary much. The specific mean numbers of the core months (January, February and March) of the rainy season also do not differ a much between the two stations (see table 2-4).

Table 2-4: Mean number of days with rainfall during January-March (1960-1989) at Otjovasandu and Ongandjera/ Okahao

	Otjovasandu	Ongandjera/ Okahao
January	6,13	7,87
February	6,50	7,00
March	6,67	7,57

Yet, a direct comparison of each day from November - April during the period from 1960-1989 only showed a correlation of factor 0,29, regarding the absolute date of days with rainfall.
Considering all these facts and due to the lack of alternatives, it was decided to apply the same number and distribution of rainy days that were reported at Ongandjera/ Okahao for the modelling throughout the AOI.

2.4 MODELLING

Beginning in the second half of the past century, engineers had a great focus on the study of complex and dynamic systems. Inspired by the success and methods of the engineers, especially biologists started to apply similar techniques in their disciplines (see De WIT & GOUDRIAAN, 1978). Within this research approach, three terms are of significant relevance: *system*, *model* and *simulation*.
According to PENNING de VRIES & VAN LAAR (1982, p.3) a system is *"a limited part of reality that contains inter-related elements"*, while a model *"is a simplified representation of a system"*. Simulation is defined as *"the art of building mathematical models and the study of their properties in reference to those of the systems"*.

2.4.1 The use of simulation models

In the field of agro- and plant-ecology it is the goal of models, to simulate specific parts of the *soil-plant-climate-system* by means of physical and physiological processes, which have been transformed into mathematical terms (see FRENKEN, 1991, p.49). Yet, a precondition to define a system for modelling is the assumption that there exist no interactions of elements included in the system with other elements that are located outside the system. Because of this assumption no simulation ever reflects the total reality. However, the assumption is precondition for every simulation model, because otherwise the model *"would have to simulate all relations and processes down to the level of atoms"* (LITSCHKO, 1990, p.18).
Despite that limitation, crop simulation models have proved to be a tool of high value for several objectives. For example the crop modelling approach has been successfully applied in the evaluation of soil and water measures for improved crop production or the biophysical limitations to maize production under rain-fed conditions in semi-humid areas (see SHISANYA, 1996, p.110). Crop modelling can also *"support farming indirectly by being a source from which guidelines, diagrams, and extension service advice can be derived, and by enabling explict*

alternatives for agricultural development to be drawn up" (PENNING de VRIES, cited in SHISANYA, 1996, p.109).

In context of this study, the application of a crop simulation model should be introduced as a tool to evaluate the potentials and limitations of drought tolerant crops towards their cultivation in areas at the brim of rain-fed agriculture[1].

2.4.1.1 Different types of crop simulation models

In plant production systems of semi-arid zones water is the most determining factor for plant growth (see PENNING de VRIES & VAN LAAR, 1982, p.9f.) The water supply of crops is depending on *"rain* [and/ or] *irrigation, the crop rooting and growth characteristics and the capacity of the soil to store available water within the crop root zone"* (HAREGREAVES et al., 1989, p.240). Figure 2-4 (PENNING de VRIES & VAN LAAR, 1982, p. 175) gives a simplified overview of all elements that contribute to the water balance in a *soil-plant-climate-system*.

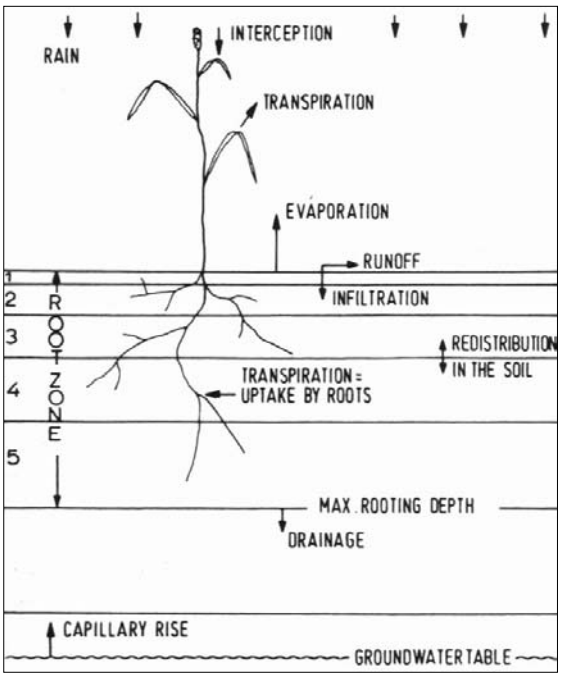


Figure 2-4:
Overview on the most important factors of the soil-plant-climate-system (Source: PENNING de VRIES & VAN LAAR, 1982)

There are various approaches to combine and express the water supply of crops with their yield expectations. *"At one end of the spectrum there are simple statistical models* […] *at the other end are complex physiological models"* (PLACE & BROWN, 1987, p.32). The first mentioned are based on the assessment of linear or non-linear correlations between climatic parameters and yield. They are purely empirical, descriptive and non-explanatory. Usually they just comprise a set of empirical data, collected at a specific site, in combination with a mathematical formula that describes the data relations. Because of the close relationship between the mathematical term and the site where the observations were made, it is almost impossible to transfer these models towards other areas (see FRENKEN, 1991, p.52).

On the other hand, there are the complex physiological models. They try to delineate the physiological processes within plants in relation to the external physical parameters that affect the plants. With increasing knowledge of the relationships within a system, these simulation models become more and more complex and precise. The advantage of this kind of models is their higher flexibility and their better suitability for transfer, concerning time

[1] It is not easy to determine an exact limit to which rain-fed agriculture is possible because the success of a crop is determined by a variety of factors, such as length of the rainfall season, temporal, spatial and quantitative rainfall distribution, evaporation, water retention and drainage of soils, surface run-off, ground cover, specific crop-water requirements and cultivation techniques (see FRANKENBERG, 1985; JAETZOLD, 1980 and JAETZOLD, 1979). However, for orientation it should be mentioned that in tropical and sub-tropical areas with an average rainfall of only 200-300mm in two consecutive humid months successful rain-fed agriculture is extremely at risk. This is the area that JAETZOLD calls the *"Agro-Sahel"* (see JAETZOLD, 1980).

and space (see BRADEN, 1982, p.7; RASMUSSON & HANKS, 1978, p.940). Despite their advantages, there is a trend since the last twenty years, away from those complicated, mechanistic models. This trend has purely pragmatic reasons: In many developing countries of the world the data sets that are required to run complex simulations are just not available. Therefore, a number of users and authors have been calling for simplified models, that could be easily applied for practical planning tasks in developing countries (see SLABBERS et al., 1979; VERSTEEG & VAN KEULEN, 1986; WIGHT & HANKS, 1981).

A type of model that meets these demands for planning and prognosis are the so called *parameterisation models* (see PENNING de VRIES & VAN LAAR, 1982, p.24; VERSTEEG & VAN KEULEN, 1986, p.250). Their position is somewhere amid simple statistical, descriptive models and the highly complex physiological models. Parameterisation models still consider some important physical factors, but retain *"a simple approach in terms of input requirements"* (PLACE & BROWN, 1987, p.32). The physical factors that finally are considered by those models are usually determined by means of sensitivity analyses (see PENNING de VRIES & VAN LAAR, 1982, p.159ff.; DIEPEN et al., 1988). In the field of crop simulation, parameterisation models are mostly pure water-balance models. By measuring water input and output components (see figure 2-4) in accordance to the condition of the plant, the water demand of the plant can be estimated and conclusions, e.g. on the relative yield-potential, can be made.

The MARCROP simulation model and software that was applied in this study is a representative of such a parameterisation model (see FRENKEN 1991, p.52).

2.4.2 The WATBAL/ MARCROP-model[1]

The MARCROP[2]-simulation model and software represents an agro-ecological simulation model, that was designed for the prediction of **relative** yields of mesophytic-xerophytic crops in semi-arid areas (see FRENKEN, 1991, p.90). It is based on an earlier simulation model called WATBAL[3], that was introduced by KUTSCH and SCHUH (see KUTSCH & SCHUH, 1983, p.239ff.) and is a typical water-balance model, consisting of three modules:

- Module 1: Determines the beginning, theoretical length and end of *agro-humid periods* (AHPs)[4] for annual crops in decades (= period of ten days), in dependence on the type of crop, the climate and the soil conditions.

[1] This thesis is focussed on the presentation of the typical, practical procedures that are necessary to do an evaluation of crop cultivation potentials by means of a simulation model. Therefore, the present chapter concentrates on a basic introduction of the MARCROP model and on the input data that are required from any potential user. The chapter renounces to describe all sub-models and mathematical algorithms on which WATBAL and MARCROP are based. All this information is documented in detail in the literature on WATBAL and MARCROP (see annex 2-3). It is highly recommended to any potential user to consult these references for a better understanding of the way in which the simulation results of MARCROP are calculated.

[2] The name is derived from MARginal CROPs.

[3] The name is derived from WATer BALance.

[4] JAETZOLD defines the AHP as those periods within a year, in which rainfall conditions in addition to the stored soil water are sufficient for the growth of most crops (see JAETZOLD, 1979b, p.87). Thereby it is commonly considered that for the initial plant growth of mesophytic and hygrophytic plants, rainfall

- Module 2: Calculates the mean decadic crop water requirements, expressed as physiological water-requirement coefficient (kc) (see DOORENBOS & PRUITT, 1977) as well as the mean optimum growth of the main root complex in dependence of the actual water supply.
- Module 3: Creates a soil-water balance of the rooting zone by using a multi-layer soil moisture model (see KOITZSCH, 1977) and calculates the resulting degree of water supply as one fraction of the actual water that is required by the crop.

The different modules within WATBAL are interlinked and from the calculations the water-balance, e.g. of a crop stand under varying soil and/ or climatic conditions, can be derived. Compared with other agro-ecological simulation models, e.g. WOFOST, the advantage of WATBAL is, that the simulation considers root growth in relation to different layers of soil moisture (see KUTSCH & SCHUH, 1983; B. HORNETZ, conversation 5th of September 2002). During several applications in Kenya the WATBAL model was successfully calibrated and validated (see SHISANYA, 1996, p.110; FRENKEN, 1991, p. 54).

2.4.2.1 Parameters required to run WATBAL and MARCROP (according to HORNETZ et al., 2001; SHISANYA, 1996; HORNETZ, 1991 and FRENKEN, 1991)

2.4.2.1.1 Climatic parameters

- Rainfall in mm at least in a decadic dimension to run WATBAL, daily rainfall in mm to run MARCROP
- Effective rainfall[1] in mm
- Initial/ productive rainfall amount in mm (see chapter 3.2.2.3.3)
- Reference crop evapotranspiration[2] (ET_0) in mm

2.4.2.1.2 *Plant parameters*

- Minimum length of vegetation period in days
- Length of the phenological crop phases in days:
  - *initial phase* = from germination of seeds or rooting of plantlets up to a plant surface cover of about 10%
  - *main vegetative (growth) phase* = from the end of the initial phase to the beginning of the peak water requirement
  - *generative phase* = phase with maximum leaf area index (= *phase of peak water* requirement)

that equals at least 40% of the evaporation of an open water-surface (= E_0 acc. to PENMAN) is necessary (see HORNETZ, 1991, p.72). According to HORNETZ (1991) several crops (e.g. Tepary beans and Babmbarra groundnuts) have adaptations to dry conditions that even permit short-term water supplies equivalent to 20% of the E_0 or even less.

[1] Effective rainfall is *"the fraction of rainfall (X/100) that actually infiltrates directly into the soil "* (SHISANYA, 1996, p.114).

[2] ET_0 can be obtained indirectly, by multiplying evaporation-rates determined according to PENMAN with the factor 0,8 (see DOORENBOS & PRUITT, 1977, p.15ff.) or by multiplying Class-A-Pan evaporation data with the so called *kp-coefficient* (see DOORENBOS & PRUITT, 1977, p.30 ff. and annex 2-4).

  - *ripening phase* = period from the end of the peak water requirement to the beginning of physical maturity (phases according to DOORENBOS & PRUITT, 1977)
- Crop water demands expressed by kc (crop coefficient)-value according to DOORENBOS & PRUITT (1977, p.35ff.) and DOORENBOS & KASSAM (1979, p.19):
  - water demand during each of the phenological phases
  - short-term minimum water requirement within the growing period
  - crop-physiologically yet endurable minimum water requirement
  - maximum (= optimum) crop water requirement
  - kc*-factor (= transforms kc values into eco-physiologically adapted kc values, in accordance with the *adapted PWP* and the *hydrature phases* → see chapter 2.4.2.2.1)
- Allometric root development during vegetation period (= percentage of root growht in relation to the development of the shoots above ground)
- Plant specific permanent wilting point (PWP) expressed in % below pF[1]-value 4,2

2.4.2.1.3 Parameters related to soil moisture

- Precipitation-reduction coefficient "R" (= X/100 in relation to actual precipitation), depending on:
  - Intensity and distribution of rainfall within the AHP (is the distribution relatively equal throughout the AHP or does rainfall occur in singular heavy rainfall events?)
  - Interception (= X/100 in relation to actual precipitation)
  - Relief, respectively run-off (= X/100 in relation to actual precipitation)
  - Infiltration rates and soil permeability (= X/100 in relation to actual precipitation)
- Soil-water-surplus parameter "S*", representing the already available soil water at the moment of planting, expressed in mm
- "K"-parameter, concerning capillary rise of soil water in mm
- Number of soil-layers (one layer is comprising 10cm)
- Maximum possible soil moisture (represented by field capacity) in mm at pF ≥ 1,8
- Plant-available soil moisture (represented by plant available field-capacity) in mm between pF 4,2 and pF 1,8

2.4.2.2 MARCROP

The MARCROP model developed out of the WATBAL modules 2 and 3. The development of MARCROP was supported by experiments in the climate-chamber at the Department of Cultural and Regional Geography at the University of Trier/ Germany and by field experiments in *Kiboko* and *Ngurunit*, located in the semi-arid south, respectively north of Kenya. There, the model was also calibrated and validated (B. HORNETZ, conversation 5th of September 2002; HORNETZ et al., 1992). During several studies in other semi-arid areas of Kenya and

[1] The pF-value represents the water potential of a soil, respectively the suction pressure of a plant, expressed as the logarithm of the height (cm) of a water column of specific diameter, which water tension would hold against gravity.

eastern Africa MARCROP was successfully applied (see HORNETZ, 1991, SHISANYA, 1996 and FRENKEN, 1991).

2.4.2.2.1 Differences between MARCROP and WATBAL modules 2 and 3

During crop experiments in the climate chamber at the University of Trier the concept of *minimal water demand* was developed and added to the original WATBAL model. This concept comprises *"adaptations of transpiration activity* [of certain plant varieties] *to deteriorated soil moisture conditions"* (HORNETZ, 1991, p.80). These adaptations comprehend strategies like e.g. osmotic adjustment, stomatal closure and parahelionastic response.

In context with the concept of *minimal water demand* two more concepts, respectively models had to be introduced to the original WATBAL: the concept of *hydrature phases* and the concept of a so called *adapted* or *eco-physiological permanent wilting point.*

<u>Hydrature-phases according to KREEB (1958; cited in HORNETZ, 1991)</u>

Hydrature can be defined in a thermo-dynamic way as the percentage of relative water activity in any water containing system. Hydrature values characterise the water condition, respectively the steam-pressure saturation-relations of a water containing system. A direct relation exists between hydrature values and potential osmotic pressure of a solution [e.g. in a plant cell]. The hydrature value of protoplasm is analogue to potential osmotic pressure and therefore is an important physiological indicator. Hydrature values at the cell surfaces of a plant are analogue to the water-potential of cells, respectively their pressure potential (= suction pressure) (see KREEB, 1974, p.99f.). Both, hydrature of protoplasm and of cell surface can be determined experimentally as described in KREEB (1977, p.92ff.).

Five *hydrature phases* are distinguished by KREEB (1958; cited in HORNETZ, 1991):

- *Phase 1*: optimum phase (H1) = hydrature that is associated with optimum water supply
- *Phase 2*: post-optimum phase (H2) = hydrature that is associated with sub-optimal water supply
- *Phase 3*: phase of increase (H3) = hydrature that is characteristic for the increase of the water potential
- *Phase 4*: end-phase (H4) = hydrature that is associated with the phase close to the highest verifiable water potential
- *Phase 5*: maximum phase (H5) = hydrature that is associated with the phase of highest verifiable water potential

The sequence of hydrature conditions/ phases of a plant during the vegetation cycle is closely related to the relative yield expectations. HORNETZ (1988) found that the decrease from phase 1 to phase 2 results in the highest yield reduction of Tepary beans. The occurrence of phase 4, where transpiration and photosynthesis are delayed by adapted plants, also results in a relatively high yield reduction.

Adapted permanent wilting point

The permanent wilting point (PWP) of most plants is usually reached at a pF-value of 4,2 (see SCHEFFER & SCHACHTSCHABEL, 1992, p.179ff.; SCHROEDER, 1984, p.46ff.). However, experiments have shown, that this value has to be questioned in the case of drought-adapted crops (HORNETZ, 1991, p.80). The PWPs of these crops (called *adapted PWP*s) are reached at pF-values that are higher than the commonly known value of 4,2 and have to be determined experimentally for each variety. The difference of plant available soil-water, which lies between the "traditional" PWP and the adapted PWP is used by MARCROP as an additional parameter to calculate the water-balance.

With the introduction of the hydrature concept and the adapted PWPs, MARCROP (based on the WATBAL model, but with modified modules 2 and 3) is now enabled to describe the water-balance of a crop stand very detailed, because plant adaptations towards water stress are now considered as well. The effect is, that the calculated results of MARCROP are more precise than those of the original WATBAL model. To reach this level of accuracy, some more modifications of the WATBAL calculation parameters were necessary (see HORNETZ, 1991, p.80 ff.):

To enable MARCROP to calculate the prevailing hydrature phases of a crop within a simulated vegetation period exactly, the software requires rainfall data on a daily scale and not on a decadic scale like WATBAL. Another factor of modification was the adjustment of the water demand values (= kc-values, see chapter 2.4.2.1.2) by a factor called kc*-factor. This factor transforms the kc-values into "eco-physiologically adapted" kc values in accordance to the adapted PWP of a specific crop and the prevailing hydrature phases.

The kc* -factor, the typical sequence of hydrature phases and the adapted PWP of a specific crop have to be determined experimentally for every crop species before MARCROP can be applied. The methods to obtain these data are described in HORNETZ, 1991.

2.4.2.2.2 Input-parameters required from the end-user

The previous sections gave a general overview of the parameters that are required to run WATBAL, respectively MARCROP. Some of these parameters are already available and held within the software. For example all required plant parameters exist for the following crops:

- Tepary bean (*Phaseolus acutifolius*)
- Bambarra groundnut (*Vigna subterranea*)
- Mwezi Moja bean (*Phaseolus vulgaris*, variety GLP 1127/ 1004)
- Rose Coco bean (*Phaseolus vulgaris*, variety GLP R)
- Morama bean (*Tylosema esculentum*)
- Siratro (*Macroptilium atropurpureum*)
- Green Gram (*Vigna radiata*)

In case it is intended to do a MARCROP-simulation with any crop that is not listed above, all the necessary plant parameters have to be provided by the user. How these data can be obtained and have to be formatted is documented in the literature that is listed in annex 2-3.

The following data has to be provided by the user in any case, because they reflect the environmental situation of the region for which crop cultivation potential should be assessed:

- Rainfall in mm on a daily basis
- Effective rainfall in mm
- Evaporation rates at least on a monthly scale, determined according to PENMAN or by Class-A-Pan method
- Number of soil-layers (one layer is comprising 10cm of the soil profile)
- Maximum possible soil moisture expressed by field capacity (Fc) in mm at pF-levels ≥ 1,8
- Plant-available soil moisture expressed by plant available field capacity (aFc) in mm at pF-levels between 4,2 and 1,8
- Information regarding the setting of the precipitation-reduction coefficient "R" (see 2.4.2.1.3)
- Information regarding the virtual day of planting

2.4.2.2.3 MARCROP-output

Due to the relationship between crop yield and hydrature conditions (determined by water supply) of the crop during the vegetation cycle, MARCROP is able to evaluate the relative yield expectations by calculating the prevailing hydrature phases of a plant within a specific cropping season.

In the output-file MARCROP distinguishes between six yield classes of relative yield, the so called *agro-ecological types* (AET)[1]:

- *Type 1*: optimum (80-100% of potential yield)
- *Type 2*: sub-optimum (60-80% of potential yield)
- *Type 3*: average (40-60% of potential yield)
- *Type 4*: marginal (20-40% of potential yield)
- *Type 5*: marginal (20-40% of potential yield)
- *Type 6a*: minimum (10-20% of potential yield)
- *Type 6b-d*: total crop failure (<10% of potential yield)

[1] AET 4 and 5 represent the same yield expectations. Nevertheless does MARCROP make a difference between these two agro-ecological types, because they reflect a different sequences of hydrature-phases.

Table 2-5 (SHISANYA, 1996, p.128) gives an exemplary overview on sequences of hydrature phases throughout the vegetation cycle of Tepary beans that are characteristic for the each AET.

Table 2-5: Sequences of hydrature phases that are characteristic for the specific AETs of Tepary beans (Source: modified after SHISANYA, 1996 & Hornetz, 1991)

AETs, representing relative yield expectations (%)	Initial phase (~to day7)	Vegetative phase (~ from day 8-19)	Early flowering & fruit building phase (~ from day 20-39)	Late flowering & fruit building phase (~from day 40-54)	Ripening phase (~ from day 55)
1 (optimum), 80 – 100%	H3 - H2	H2, usually H1	H3, usually H1	H3, usually H2	H3
2 (sub-optimum), 60 - <80%	H3	H2	H2	H3	H4
3 (average), 40 - <60%	H4	H3	H3 - H2	H4 - H3	H4
4 (marginal), 20 - <40%	H4	H4	H4 - H3	H4	H4
5 (marginal), 20 - <40%	H3, usually H2	H2, usually H1	H4	H4	H4
6a (minimal), 10 - <20%	H4	H4	H4	H4	H4
6b-d (total crop failure), <10%	H4	H4	H4	H4	H4

2.4.3 Evaluation of crop cultivation potentials in the AOI

From the north-east to the south-west has the AOI a diameter of ~110km. In the same direction the climatic conditions become more arid. With respect to this fact two modelling scenarios, called scenario A and B, were created to assess crop cultivation potentials of Tepary beans at the AOI.

Scenario A represents the more humid conditions in the north-eastern part of the AOI, while scenario B represents the less humid conditions in the central and south-western parts of the AOI.

Regarding the modelling scenarios, a virtual line that runs from Okahao in the far north-east of the AOI to the south-western corner of the AOI has to be imagined. Scenario A describes the climatic situation (regarding rainfall amount and evaporation) at a virtual point on this line, 28km south-west of Okahao. Scenario B describes the situation at a virtual point 68km north-west of Okahao.

In addition both scenarios were calculated with the characteristic soil-water parameters of each of the six vegetation units that exist in the AOI (see chapters 2.2.4.1 and 3.2.3 as well as annex, map 4).

2.4.3.1 Input-data and configuration of the software

In order to carry out a simulation for the AOI, several input data were necessary to allow the calculations of crop cultivation potentials under to the local water supply conditions. Some of the data, daily rainfall, mean daily evaporation/ month[1] and virtual day of planting, have to be available as computer-formatted ASCII-files, which are automatically identified and read by the MARCROP software. All other data and settings (see 2.4.3.1.2) can be entered directly into the interface of the programmes.

[1] Evaporation data are necessary to calculate the reference crop evapotranspiration (ET_0) (see chapter 2.4.2.1.1).

2.4.3.1.1 Required ASCII-data files

Rainfall data

The rainfall data that were used for the two scenarios are based on the daily rainfall reports (1960-1989) of *Ongandjera/ Okahao* station. By applying the regional coefficients of spatial rainfall variation (see chapter 2.3.2.3) the rainfall records were transformed into data, which reflect the rainfall amounts at the virtual simulation points of scenario A and B. The MARCROP software does not recognise the 29th of February during leap years. Therefore this day had to be deleted from the rainfall data sets. Any rainfall that had occurred on a 29th of February was added to the 1st of March reports.

Evaporation data

The evaporation data that were applied in the simulation are based on the mean monthly records at *Mahenene* station, divided by the number of days of the specific month. The data have been obtained by Class-A-Pan method and were available for the period from 1951-1985. In relation to the distance to Mahenene the mean monthly evaporation values were altered to reflected the evaporation conditions at the virtual simulation points of scenario A and B. The conversion of data was achieved by application of the coefficients of regional evaporation variation (see chapter 2.3.2.2). Finally, the Class-A-Pan data had to be transformed in to reference crop evapotranspiration values. This was done by means of the kp-coefficients according to DOORENBOS &PRUITT (1977; also see annex 2-4).

The determination of the relevant kp-coefficients was based on the following data for Mahenene station:

- Windward side distance of dry fallow: 100m
- Windspeed: light in every month
- Relative humidity during rainy season: moderate (Jan - Apr) to low (Nov - Dec)
- Reduction factor: 5%

Virtual day of planting

This data file defines those days of the year, at which the programme should start the simulation. Each day of the year has a specific number, starting with 1 for the 1st of January and ending with 365 for the 31st of December.

The programme does not recognise the 29th of February during leap years. Therefore it must not be counted.

The specific number of a day on which MARCROP should start a simulation, must be entered into the relevant ASCII-file. It is possible to define and enter several planting days for each planting season.

What can also be entered in the file is the previously available soil moisture (in mm) from rainfall events prior to the day of planting.

The days on which MARCROP should start the modelling were selected visually from the rainfall data sets. The selection was based on the following assumptions:

- Planting in Omusati usually is happens during January, February and sometimes also in March. Out of interest additional planting days were selected in the November for several seasons with promising rainfall data.
- Planting should occur on a day with productive rainfall (≥ 10mm; occasionally days with little less rainfall were also selected)
- From the day of planting the rainfall should possibly be not very erratic for the 54 subsequent days, when the ripening phase of Tepary beans begins. Especially days 1-7 and 40-54 of the vegetation cycle are yield sensitive phases.

Annex 2-5 shows the list of selected planting dates which were used for the modelling.

2.4.3.1.2 Software configuration

Climatic parameters

Erosive Rain <ER> in m: identifies the amount of rainfall that induces significant surface run-off. Due to the extremely flat and extremely weak inclined landscape, as well as the well draining soils at the AOI, this value was set at improbable 99mm

Reduction factors <r1> and <r2>: These factors concern precipitation loss by run-off, interception and direct vaporization when cooling rain falls on heated soils. With regard to the flat landscape at the AOI and empirical values on interception and vaporization from comparable African regions (according to B. HORNETZ, conversation 19th of November 2002), <r1> and <r2> were set at 0,95.

ET_0 reduction factor < ET_0>: This parameter concerns the reduction of reference crop evapotranspiration during rainfall events, when humidity in increased and solar radiation is reduced. In accordance with B. HORNETZ (conversation 19th of November 2002), this coefficient was set at 0,6, which represents an empirical value, found in regions of eastern Africa that are comparable to the AOI.

Soil parameters

Capillary water <K> mm: Concerns the plant available soil water provided by capillary rise. In the present simulation <K> was set at 0 because the typical soils of the AOI are deep and well drained, making water provided by capillary rise during the growing season neglectable (according B.HORNETZ, conversation 19th of November 2002).

During days from <TK>: Represents the number of days since the last rainfall event when the capillary rise of water starts to have influence on crop growth. As capillary rise is neglected in this simulation (see above), <TK> was set at 0.

Max. number of layers: Concerns soil depth. One layer comprises 10cm. During the soil survey at the AOI, almost every profile proved to be deeper than 70cm. As a consequence the number of layers used for modelling was set to 10. Higher numbers would make no sense, since soil layers deeper than one meter usually have no influence on crop development. Some soils in the survey also showed shallow profiles due to encrustings. These were neglected when considering number of soil layers, because most of the encrustings can easily be destroyed

by ploughing. Soils with encrustings that can not be broken by a plough are generally of no interest, regarding crop cultivation.

Field capacity <Cm>: Here the data that were obtained from the soil analysis (see chapters 2.2.4.2 and 2.3.1.1) have been used. As the modelling was done in accordance to the existing soil units, the typical field capacity values of each soil units were used (see table 2-6). In case of the soils in the *Western mopane-pan mosaic*- and the *Mixed savanna on loamy to sandy soils*-unit field capacity values varied a great deal and it was impossible to define a typical value. Therefore, the values of soils that are of no interest for cultivation (due to high salinity, water-logging and/ or firm encrustings) neglected. The field capacity values of the remaining profiles were quite homogenous and the typical value could be determined.

Available field capacity <Ce>: see field capacity above

Table 2-6: Characteristic values of available Field capacity (aFc) and Field capacity (Fc) of each vegetation unit of the AOI, as applied in the modelling procedure

Vegetation unit	aFc	Fc
Mopane-Combretum savanna on sandy soils	17	21
Western sand plains	17	21
Mixed savanna on loamy to sandy soils	17	21
Cuvelai palms & fruit-trees on loamy sands	14	19
Mopane shrubs & low trees on loamy sands	17	24
Western mopane-pan mosaic	17	28

Plant parameters

The MARCROP software already holds the plant parameters of seven different crop varieties that can be selected (see chapter 2.4.2.2.2). For this study the parameters of the *"55 days"*-Tepary variety were selected.

2.4.3.2 Analysis of the MARCROP-output data

MARCROP displays the results of each single simulation in tabular and graphic form. The most interesting output parameters are the AET and the hydrature-values of the plant at each day of the vegetation cycle. The AET represents the calculated relative yield expectations under the defined seasonal water supply conditions. From the sequence of the hydrature-values conclusions can be made upon the specific environmental (here rainfall and soil-water) circumstances that were responsible for the calculated AET.

2.5 ADMINISTRATION AND PRESENTATION OF SPATIAL DATA/ GIS

For the analysis, display, storage and administration of spatial and attribute data concerning the AOI, the ArcView software by ESRI and several programme extensions were used. Together with a variety of other computer

programmes (e.g. MapInfo, ArcInfo, IDRISI, ArcGis) ArcView belongs to a group of computer programmes, which are known as *Geographical Information Systems* or simply *GIS.*

A large variety of literature on the theory and practical application of GIS has been published and is widely available. These publications are accompanied by a large number of sites on the World Wide Web. Therefore, the following annotations concerning GIS are intentionally kept very short.

"A GIS is a system comprising hardware, software, and procedures to collect, store, modify, analyse, model and present spatial data to support complex tasks in planning and management" (GOODCHILD & KEMP in GTZ, 1994, p.7)

Compared to traditional, printed maps a GIS represents a dynamic way to store and display spatial attributes and data. Apart from the ability of automated mapping and display of locations, a GIS provides a permanently expandable database to record and analyse spatial data and their associated attributes. *"For instance a GIS is capable of including not only a map of locations of roads but of combining this with further information through attributes. The advantage of a GIS is therefore the ability to interrelate multiple types of information from a broad range of sources. The different data are usually saved in* [so called] *layers"* (VOGT & WIESENHUETTER, 2001, p.5; see figure 2-5). After spatial (= topographical and geometric) data have been geocoded, they can be manipulated by overlaying or extracting the desired information. Another possibility is to add and/or interrelate various data derived from different sources.

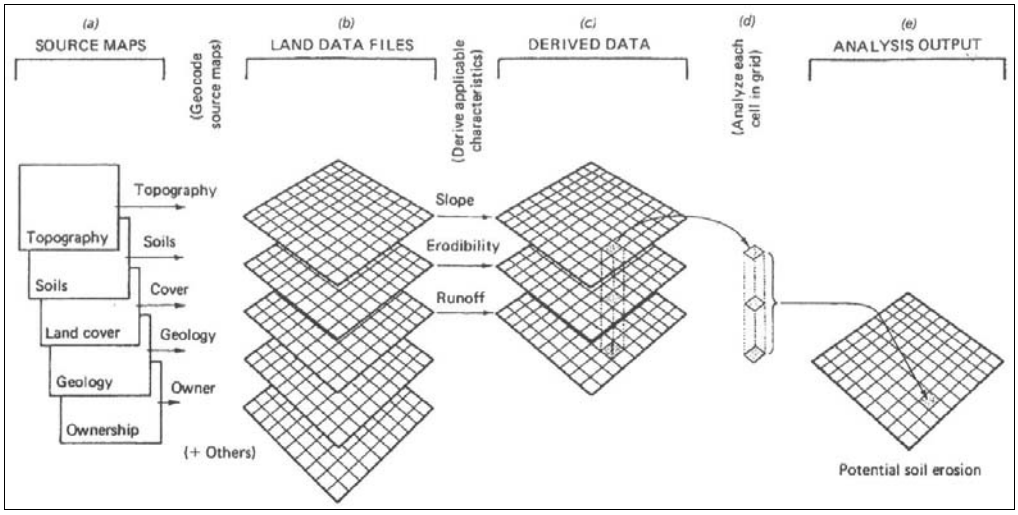


Figure 2-5: Schematic overview on a GIS analysis procedure at the example of an assessment of soil erosion potentials (Source: LILLESAND & KIEFER, 1994)

The decision to apply ArcView in this study was made because several institutions and organisations in Namibia had already compiled extensive data sets with this software. By using the same software, it was possible to build on these already existing data sets. On the other hand, these data sets can now be completed with the data that were created in context of this study.

3 GENERAL PROFILE OF THE AREA OF INTEREST (AOI)[1]

3.1 LOCATION AND GENERAL CHARACTERISTICS OF THE AOI

The AOI is situated in the north-west of the Republic of Namibia. It forms the central and western part of the *Omusati* region. Together with the *Oshana* region, the *Ohangwena* region and the *Oshikoto* region Omusati forms an area also known as *"north-central Namibia"*, "*North-central*", *"four Os",* "*Owamboland"* or simply "*Owambo*", because it is the traditional settlement area of the *Owambo* people (see annex, map 1). The AOI in particular is part of the area occupied by the *Ngandjera* -tribe.

The AOI has the shape of an irregular polygon and covers approximately 670 km². The northern boundary is a virtual line of ~12 km, running from 17,87°S / 15,02°E to 17,87°S / 15,13°E, close to where the Oshakati-Okahao road crosses the "*Etaka-channel"*. From here the eastern borderline runs down in a slightly south-easterly direction for ~70km towards 18,50°S / 15,23°E. Here the track from *Okahao* via *Amarika* ends up in another track running almost straight from the east to the west following the 18,50°southern latitude. This track is the southern demarcation of the AOI.[2] Its assumed western extension meets the gravel road no. C35 after ~98km, at 18,52°S / 14,30°E. This gravel road comes from *Kamanjab* and leads straight up north to *Ruacana*. For ~ 57km this road is the western border of the AOI. At 18,01°S / 14,28°E, about 12km north-west of *Amakange*, the boundary of the AOI starts to run in north-easterly direction. The course roughly follows the south-eastern demarcation of the proposed *Uukwaluudhi Forest and Wildlife Conservancy*, which lies to the north. Following this line, after ~79km the starting point of the boundary-line is reached again, close to the settlement of *Uukwalumbe* (see annex, map 2).

Because the AOI is part of the *Owambo* basin, which is a very old area of sedimentation, the relief appears fairly flat and uniform.

Regarding climatic aspects, the area is located within the region of the tropics, namely the "*semi-dry tropics with a short rainy season of 3-5 months"* (climate types according to CREUTZBURG-HABBE in KRAMER et al., 1989, p.27 f.). According to the *"effective climate-classification"* of KOEPPEN, the AOI is situated in the *"dry"* or *"B-climates"*, precisely the *"BS- or steppe-climates with summer rain"* (climate types according to KOEPPEN in HENDL & LIEDTKE, 1997, p.407 f.). The annual mean temperature of the Omusati region is 23°C, with a mean maximum of 32°C during summer months and 9°C in the winter months. Rainfall decreases towards the south-western and to the southern areas of the district, where the AOI is located. Central and south-western Omusati has a mean rainfall of 300-450mm (MENDELSOHN et al., 2000, p.9). The variability of average annual rainfall in northern Namibia is rated with 25-30% (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995, p.36). Potential evaporation exceeds 2500mm per annum

[1] For the present chapter literature and map information concerning exclusively the AOI has been used as far as possible. However, very little data is available on this level. Much more information exists on the Omusati region and the whole Owambo. Wherever this information was also representative for the AOI and no more detailed data was available, these sources have been used.

[2] The territory south of this line consists of the area of the proposed *Ongandjera forest conservancy* and the state-run quarantine camp *Omatambo-Maowe*.

(FRIEDRICH-EBERT-STIFTUNG, 1997, p.185). It is assumed that the climate in Owambo, apart from short periods of fluctuations towards drier and wetter conditions, has been like this for several million years (MENDELSOHN et al., 2000, p.9).

Closely related to the climate are soil development and vegetation. According to the FAO soil-classification, three main soil units are located within the AOI. In the north-east *orthic Solonetzs* and in the east and the central area *cambic Arenosols* are dominant, becoming *calcic Xerosols* in the western parts (FAO & UNESCO, 1972, sheet VI 3; FAO & UNESCO, 1977). However, reality is much more complex and chapter 3.2.4.1 and chapter 4.2 give a more detailed overview on soils.

Colophospermum mopane or *"Mopane"* (local name: *"omusati"*) in varying growth forms is the dominating feature of the vegetation almost all over the AOI. To classify the vegetation-zones, several authors use different terms that characterise the area. Quoting the labels used most often, the area is part of the *dry savanna-zone* becoming a *thorn bush* and *succulent savanna* towards the west. Towards the southern parts of the AOI, the savanna becomes increasingly open and grassy.

3.2 PHYSICAL ENVIRONMENT

3.2.1 Geology and Geomorphology

Like with most African regions, the geological history of the AOI is reaching far back in time. The AOI and the whole Owambo lie on a continental basement, which is 2600-1700 million years old, dating back to the days of the continent *Rodinia*. This so called *Pre-Damara basement*, made up by granites, gneisses and volcanic rocks, is located several thousand meters under the recent surface today. Above this basement, the so-called *Nosib group* is situated. It consists of 900-750 million year-old sediments, namely a 20m thick basal layer of conglomerates, followed by a sandstone layer and a 200-300m thick unit of quartzite with subordinate phyllite. It developed when an intensive period of rifting began about 1000 millions years ago, and the sediments of the *Nosib group* were deposited in the newly formed rift valleys.

About 750 million years ago, the rifting had caused the separation of landmasses into what is today northern Namibia and the territories north of it, and into southern Namibia and the regions south of it. An ocean filled the space between the two landmasses. In the course of time a shallow shelf formed on the southern fringe of the northern block and up to 7000m of dolomite and limestone, partly interlayered with phyllite, accumulated. They comprise what, today, is known as the *Otavi group* while the old sea shelf is identical with what is called the *Owambo basin*.

About 650 million years later, for a reason yet unknown, the direction of the rifting reversed, resulting in the formation of the super-continent *Gondwana*. During this process of continental collision, the sediments of the *Otavi group* were folded up along the rim of the Owambo basin. The so-called *Dolomite hills* in the south-west of the AOI are a result of these events. During the consolidation of Gondwana erosion caused the sedimentation of arenites, phyllites, siltstone/agrillite, quartzites and conglomerates into the Owambo basin. This whole sediment

block, which is topped with feldspathic quartz-arenite, is called *Mulden group*. In the south-west of the AOI (in-between the Dolomite hills) as well as in it's centre, the *Mulden group* almost reaches the present surface and is covered only by a relatively thin layer of unconsolidated and semi-consolidated sediments of the *Kalahari group* (see below). Together with the *Nosib group* and the *Otavi group,* the *Mulden group* is also called the *Damara sequence*.

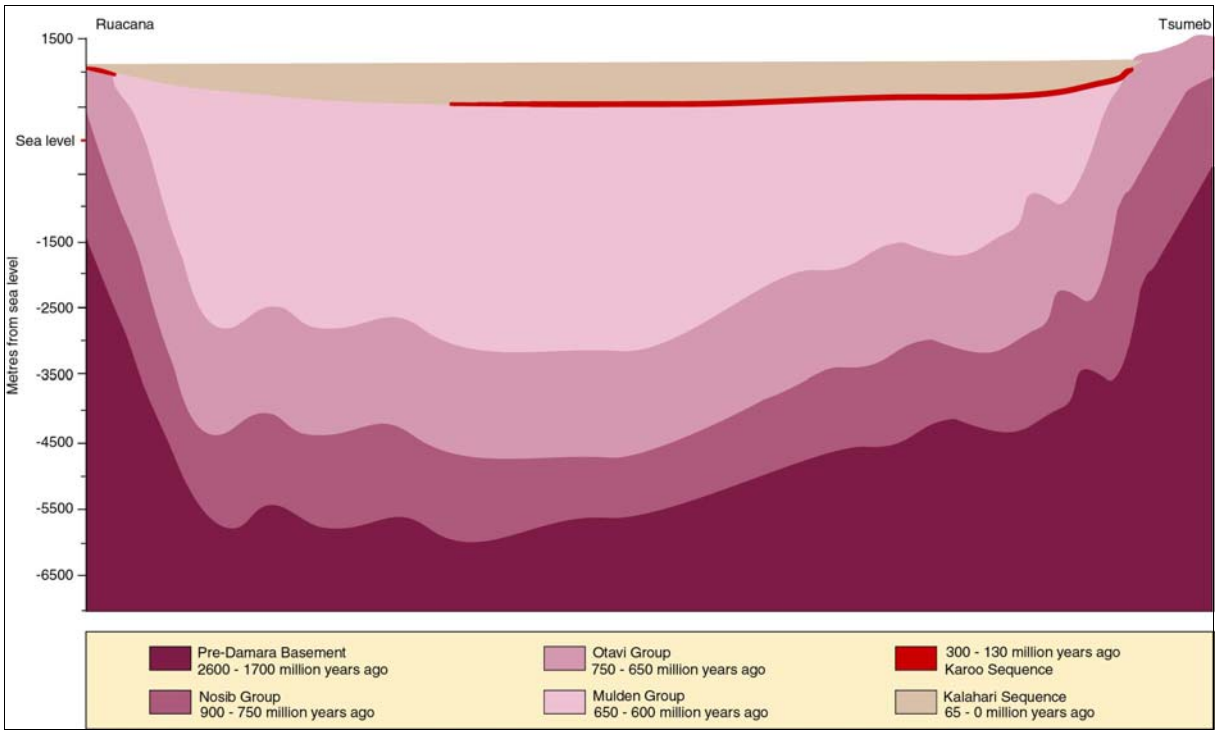


Figure 3-1: Sequence of geological deposits in north-central Namibia (Source: DEA, 2002)

In the following periods of continental erosion took place, starting around 550 million years bp., and coming to a halt around 300 million years bp. with the beginning of the *Dwyka glacial period*. The glaciations ended about 280 million years ago, leaving the basin covered with lakes and shallow seas. All that is left of that era is a shallow, discontinuous layer of shale, sandstone, limestones and beds of organic material, called the *Karoo sequence* (~ 280-150/ 130 million years bp.).

Around 150 million years bp. the seas had dried up, and vast areas of Gondwana had turned into a desert. The whole region came to be covered with dunes and wind-blown sand (MENDELSOHN et al., 2000, p.6).

Then, about 130 million years bp., Gondwana started to disintegrate. The margins of what today is southern Africa were lifted up, and intensive erosion started once again. Finally, 70 million years before now, the *Kalahari basin*, a depression in the centre of the southern-African subcontinent, formed. The much older Owambo basin became the western lobe of this newly formed depression.

During the last 70 million years the basin was filled up with clay, while silt and sand were washed and blown in from the higher surrounding regions. During more humid periods rivers drained into the basin, forming huge,

shallow lakes with clays and calcretes sedimenting down. These lakes all dried out and again sand was blown into the basin, partly mixing with the water-borne clays or covering these sediments completely.
Due to the hot climate, those "ancient" lakes often evaporated rapidly and salts could accumulate within the lake sediments. These accumulations are responsible for much of the groundwater in the AOI being brackish.
All the sediments that accumulated in the period starting 550 million years bp. are summarised under the name *Kalahari group*. They cover nearly every part of the AOI and are subdivided into three formations: The basal formation is called *Ombalantu,* consisting of red, semi-consolidated mudstone, sandstone and siltstone with interbeded white nodular limestone layers. It is overlain by a reddish brown conglomerate, sands and poorly consolidated sandstone called the *Beiseb formation*. The toplayer is called *Andoni formation* and "*consists of sands, clays, thin limestone layers and nodules of dolocrete and calcretes"* (MINISTRY OF MINES AND ENERGY, GEOLOGICAL SURVEY OF NAMIBIA, 2000, p.1).

Because of the geological processes described, the AOI shows a relatively flat and uniform topography today (figure 3-2).

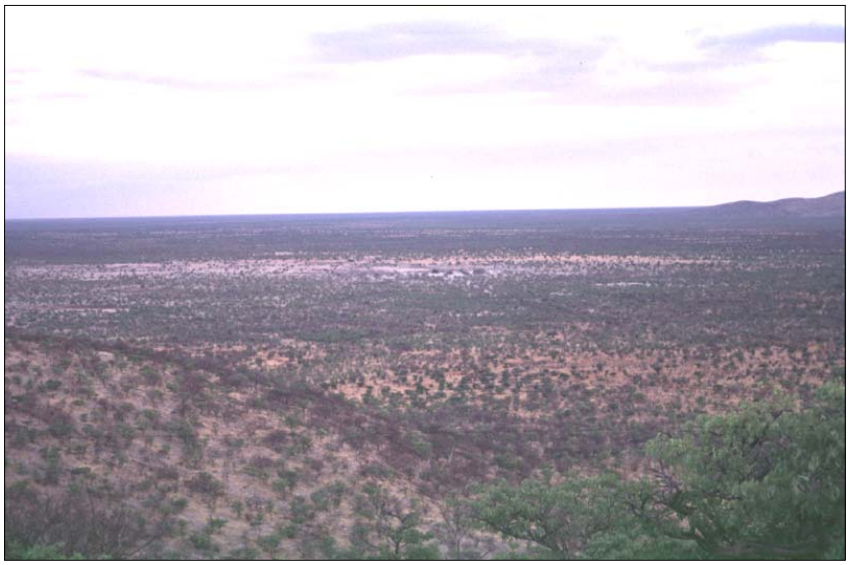


Figure 3-2:
View from the *Dolomite hills* into the AOI (Source: own photography, February 2002)

Two landscapes, commonly known as *Western Kalahari woodlands* and *Mopane shrublands,* cover most of the AOI (see annex, map 3; MENDELSOHN et al., 2000, p.8) today. The difference between the two landscapes is originated in their vegetation and in soil composition and not in their topography, which is virtually the same. They form a flat plain with an average elevation of ~1130m.a.s.l. that covers most of the area. Only towards the western border of the AOI the landscape slowly, almost imperceptibly, rises to elevations around ~1220m.a.s.l..
Around the southern border, the landscape undulates slightly over a vast area.[1]
In both landscapes, the ground is covered with more or less consolidated, sometimes saline, loamy or clayey, sand with only weak soil development.

[1] No remarks were found in literature, but the distances between the small elevations, their heights and inclinations give the impression of an old, more or less settled dune-field.

As today virtually no wide-ranging drainage system exists within the AOI (see chapter 3.2.5), it is mainly aeolian sedimentation and sometimes small, locally limited sheet-floods that form the present surface.

A truly conspicuous feature of the *Western Kalahari woodlands* and *Mopane shrublands* are the numerous salt and clay pans. Hardpans and calcrete outcrops are some other common features.

Salt pans are found in small depressions with an underlying basement of impermeable stone, e.g. limestone. Run-off water from areas with saline rock material, like e.g. the *Dolomite hills*, is trapped, leaving the salts behind after evaporation. Clay pans are smaller depressions in sandy areas. Here, run-off water can drain into the ground, leaving the suspended clay particles on the surface. Hardpans and calcrete outcrops occur where draining reaches calcrete-bearing geological layers. The calcrete is dissolved and brought to the surface with the stream of evaporating soil water.

As pans will hold the only available surface water after the rainy seasons, animal concentration is high in the surroundings of pans. The trampling of animals within and at the rim of the pans loosens the sediments, a factor not to be underestimated in context of erosion. Most of the eroded material is blown far away, but heavier particles sometimes form distinctive dunes at the edges of the pans (MENDELSOHN et al., 2000, p.7).

The north-western edge of the AOI is a small lobe of the *Cuvelai* landscape (see annex, map 3). The whole *Cuvelai* has an average elevation of ~1000m.a.s.l. (NGHITILA, 1997, p.3) and is slightly inclined to the south-east. As it is the inland drainage delta of the ephemeral *Cuvelai River system,* the whole area is characterised by a labyrinth of broad and shallow drainage lines called "*oshanas"*. One of the largest and partly reinforced *oshanas* is the *Etaka* or *Etaka channel*. The *Etaka* is the north-eastern border of the AOI.

During the rainy seasons the *oshanas* usually fill with water, often cutting into the underlying sediments of sand, silt, clay, limestone and sandstone. In heavy rainy seasons strong floods, called *efundja,* can occure in the *Cuvelai* and the flood waters bring in sediments from the Angolan highlands. In addition to the force of water, that constantly alters the landscape in the *Cuvelai*, wind erosion takes place throughout the whole region, especially during the dry season.

Due to low relief in the AOI, deep, linear water erosion is almost impossible and wind is almost exclusively the cause for erosion. In addition, human activities can intensify this process (MARSH & SEELY, 1992, p.12).

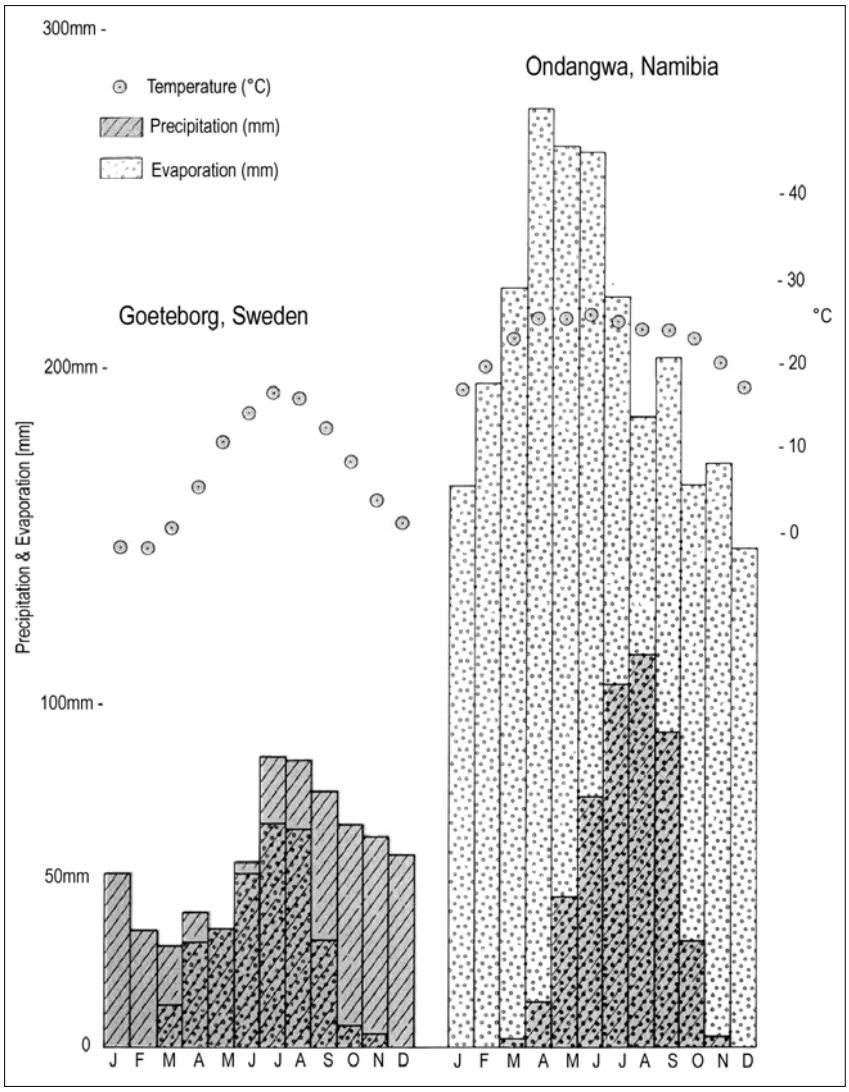
The only really outstanding and elevated topographical features of the region are the *Dolomite hills*. They are located adjacent to the AOI, in the far south-west of the region. This group of gently ascending hills reaches a maximum elevation of 1462m.a.s.l. at *Okonjota*. The hills are completely covered with dolomite cobbles and rocks. They are isolated representatives of the *Otavi group* and *Karstveld* landscape, that has its greatest extent south and west of the Etosha pan. Calcrete outcrops and shallow, loamy to sandy soils are characteristic in the area around the hills.

3.2.2 Climate

As was already mentioned in chapter 3.1, the AOI/ Omusati region is located in the semi-arid to arid tropics. As a consequence, the climate is characterised by low rainfall, a distinct rainy season, high rainfall variability, relatively high temperatures, low humidity, and high evaporation rates. The present chapter will describe these features in more detail.

3.2.2.1 *Temperature*

In FRIEDRICH-EBERT-STIFTUNG (1997) the mean annual temperature of the Omusati region is reported to be 23°C, with a mean maximum of 32°C during summer months and 9°C in the winter months. Unfortunately, it is not mentioned from which climate stations these data derived. For the AOI no temperature data is available. Nevertheless, the climate diagram of the station in *Ondangwa* (~ 100km east of the AOI) gives an impression of the annual range of temperatures in north-central Namibia (see figure 3-3).



During the winter months of June and July the average daily temperature is reported 17°C, but average minimum winter temperatures can drop to 7-8°C. In regions south of Ondangwa and in the *Etosha area*, occasionally even frosts are reported. From September to December average daily temperatures reach 25°C, with maximum temperatures between 30-35°C. The summer months from January to March are a little cooler due to the effects of cloud cover and rainfall.

Figure 3-3:
Climate diagram of Ondangwa (north-central Namibia; Source: MARSH & SEELY, 1992)

3.2.2.2 *Evaporation, Wind and Humidity*

Apart from temperature, vegetation cover, and solar radiation (on which no data could be found in context of this study), humidity and wind are important determinants of evaporation. Very little information regarding the AOI or Owambo was found on both factors. Several investigations on humidity and wind at the Namibian Weather Office as well as in different archives and libraries were of very limited success. The only useful data for this study were obtained from NNEP-data (DEPARTMENT OF ENVIRONMENTAL AFFAIRS, NAMIBIA, 2002), MENDELSOHN et al. (2000), MARSH & SEELY (1992) and were collected at Ondangwa station(~ 100km east of the AOI).

According to MARSH & SEELY (1992, p.7), the average humidity [relative?] in Ondangwa is highest in March with 50% and lowest in September with 17%. In contrast, GIS-data of the NNEP show a relative humidity of 10 - <20% during the *"least humid months"* and of 80 - <90% during the *"most humid months"*.

The main direction of wind during the rainy season is east to north-east and north. Apart from thunderstorms, the winds in the Owambo area *"are not very strong during most of the year"* (MARSH & SEELY, 1992, p.7). At Ondangwa the maximum mean daily wind speeds are reported in October with 6,5 km/h (see table 3-1) .

Table 3-1: Mean daily wind speeds (km/h) at Ondangwa (Source: DEA, 2002)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Speed	5,7	2,8	3,1	3,2	2,5	4,6	5,3	3,9	3,3	6,5	5,3	6,3

The average annual evaporation in north-central Namibia is about 2500mm and exceeds the total annual rainfall 4-8 times depending on the particular area. Usually evaporation rates are highest from September to November. During this period wind speeds are relatively high, the surface water has vanished and humidity has its lowest records.

No data on evaporation is available from *Ongandjera/ Okahao*-station, but for *Okaukuejo* (~ 185km south/ south-east) and *Mahenene* (~ 100km north) *Class-A-Pan* data were disposable.

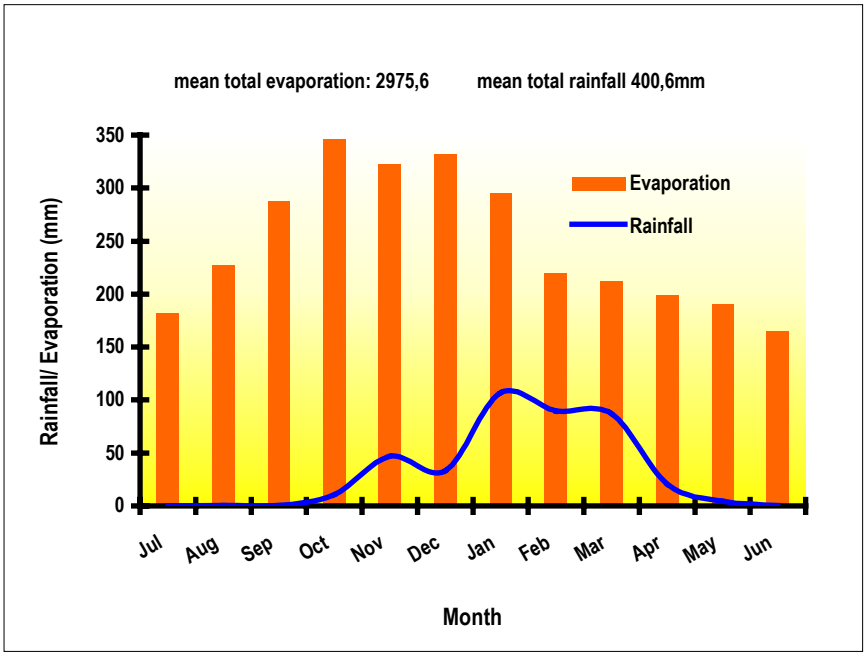


Figure 3-4:
Long-term mean monthly rainfall (mm, 1960-1989) and calculated mean monthly evaporation (mm) at Ongandjera/ Okahao

An interpolation of long-term (1951-1985) mean annual data (see chapter 2.3.2.2) resulted in an annual evaporation of 2975,5mm at Ongandjera/ Okahao. Figure 3-4 shows the calculated mean monthly evaporation at Ongandjera/ Okahao in relation to the mean monthly rainfall.

3.2.2.3 *Rainfall*

In Owambo, rain is usually caused by convection. Precipitation is relatively patchy and rainfalls often occur during thunderstorms. These storms can sometimes be so heavy, that they even have damage crops badly (MARSH & SEELY, 1992, p.6). Most of the rain-saturated air is originated in the Indian Ocean, reaching Owambo during the summer months (when a low-pressure system is developed in the region of the Kalahari basin) with winds of the north-east monsoon system. Therefore the winds that reach Owambo during the rainy season, usually keep an eastern to north-eastern or northern direction.

Because of the wind direction, the north-eastern parts of Owambo receive the rain earlier and with higher amounts than the south-western areas. In fact, there is a distinct rainfall gradient in north-central Namibia, that is reflected in the long-term means of the rainfall amounts in the region:

While the north-east (and the mountainous area around *Tsumeb*) receives an average of 550-600mm of rain, it is only about 200-300mm in the far south-west.

This gradient is also reflected in the AOI. According to maps in MENDELSOHN et al. (2000, p.9) an average of 450mm of rain falls in the north-eastern parts, declining to 300 in the far south-west. Figures derived from rainfall maps that consider the regional rainfall gradient (MENDELSOHN et al., 2000, p.9), show the mean monthly long-term rainfall distribution in mm during summer throughout (south-west to north-east) the AOI.

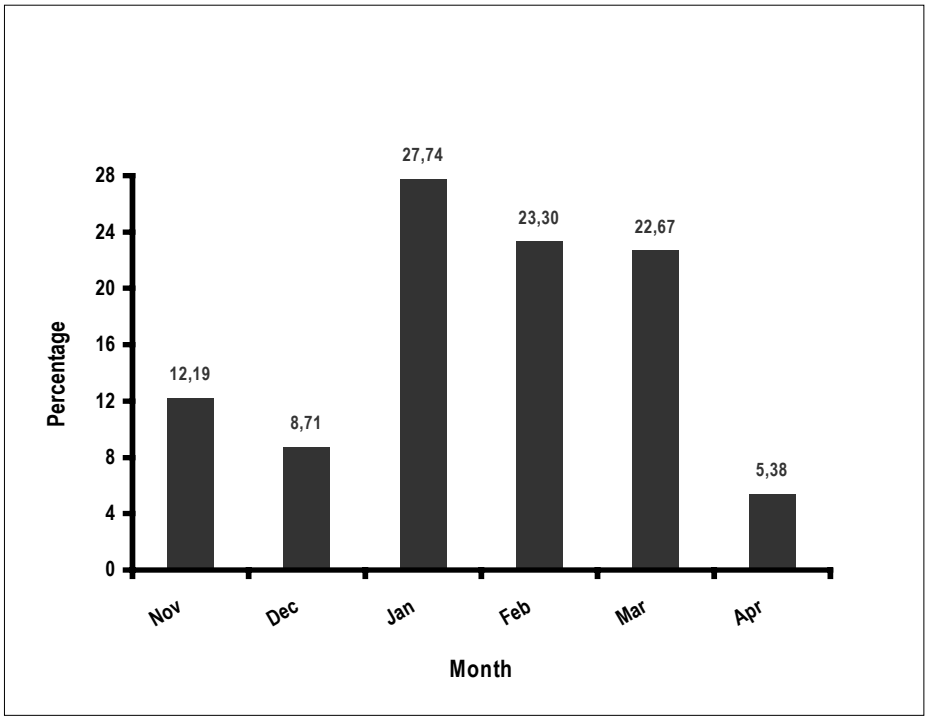
Table 3-2: Mean monthly distribution of rainfall from south-west to north-east at the AOI

Month	November	December	January	February	March	April
Mean monthly rainfall from south-west to north-east	30-50mm	20-40mm	80-120mm	70-120mm	80-100mm	20-30mm

The only station to report rainfall, that is found in the AOI is *Ongandjera/ Okahao* station, situated in the far north/ north-east of the AOI. Here the long-term (1960-1989) mean of yearly rainfall is 400,6mm (see figure 3-4). Unfortunately the station was closed in the beginning of the nineties.

3.2.2.3.1 Rainy season

"96% of all rains in north-central Namibia is falling during the 6 months from November to April, whereby two thirds of precipitation are concentrated in January to March" (MENDELSOHN et al., 2000, p.9). Formally "[Ovamboland´s] *beginning of rain season is defined as the date after November 15th when rainfall is accumulated over three consecutive days to at least 20mm and when thereafter no dry spell of more than seven days occurs within the next thirty days"* (KEYLER, 1996, p.35). So much for the definition.



In reality rainfall in Owambo is very erratic and only difficult to predict. Figure 3-5, derived from as set of daily rainfall data, shows the mean monthly rainfall distribution (%) at Ongandjera/ Okahao during rainy seasons from 19960/61-1988/89, while the real, highly variable situation is reflected in figure 3-6.

Figure 3-5: Mean distribution (%) of seasonal rainfall amounts in relation to month at Ongandjera/ Okahao

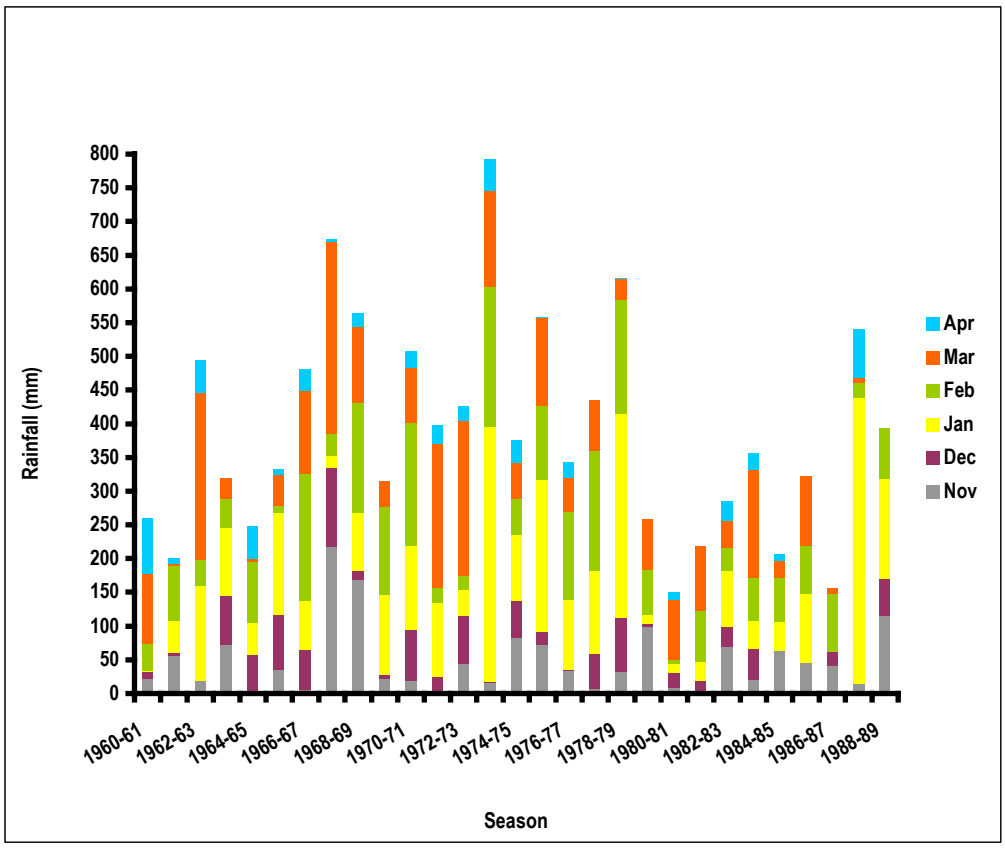


Figure 3-6: Monthly distribution of rainfall amounts per rainy season at Ogandjera/ Okahao (1960/61-1988/89)

3.2.2.3.2 Rainfall variability

A very distinctive feature of rainfall in northern Namibia, as in almost all regions of the semi-arid tropics, is high variability. The reason for this phenomenon is the way in which rainfall is generated in the outer tropics and sub-tropics. The rains are usually caused by convection within convection cells of relatively limited spatial extent. The occurrence of these cells is highly dependent on the seasonal shifting of the zone of inner-tropical convergence (ITC). Caused by temperature variations and other factors, the seasonal location of the ITC can vary from year to year within a range of +/- 200-300 km. As a result, the commonly expected rainfalls within a region may be very reduced or even fail completely from time to time.

The variability of average annual rainfall in northern Namibia is figured 25-30% (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995 , p.36). In seasons with good rains, the total rainfall amount can be 3-4 times as high as during dry ones. The mean seasonal variability at Ongandjera/ Okahao station during the period of 1960/61-1988/89 is 32,9%. Figure 3-7 displays the deviation of seasonal rainfall amount from the seasonal long-term mean.

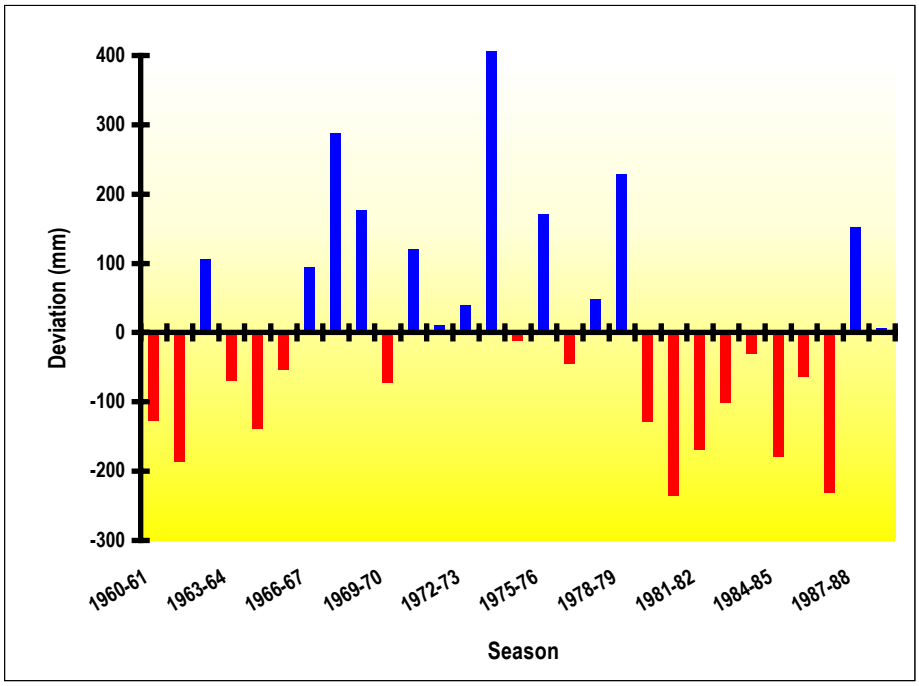


Figure 3-7: Deviation (mm) of seasonal (Nov-Apr) rainfall amount from the seasonal long-term mean at Ongandjera/ Okahao (1960/61 - 1988/89)

An analysis of data from 1940-1999 of four climate stations located in Owambo (*Okaukuejo*, *Tsumeb*, *Oniipa* and *Oshikuku*), done by MENDELSOHN et al. (2000, p.10), shows that during fifty-nine years each station has recorded at least one or two years with less than 200mm of total rainfall, but also had several exceptionally good years, with total amounts exceeding 700mm, sometimes reaching 1000mm. At Ongandjera/Okahao, three seasons with rains of 200mm or less and one season with rains exceeding 700mm were reported during 1961-1989.

Another striking feature of rainfall in Owambo is the variation of rainfall within the rainy season. An analysis of the climatic data of the Ondangwa station in MARSH & SEELY (1992, p.8), about 100km east of the AOI, has shown that of fifty-five recorded rainy seasons the highest rainfall of the recorded period occurred in 2% of the years in November, in 18% of the years in December, in 24% of the years in January, 30% of the years in February and in 25% of the years in March.

A similar pattern (see figure 3-8) was found, when rainfall data of Ongandjera/ Okahao station were analysed.

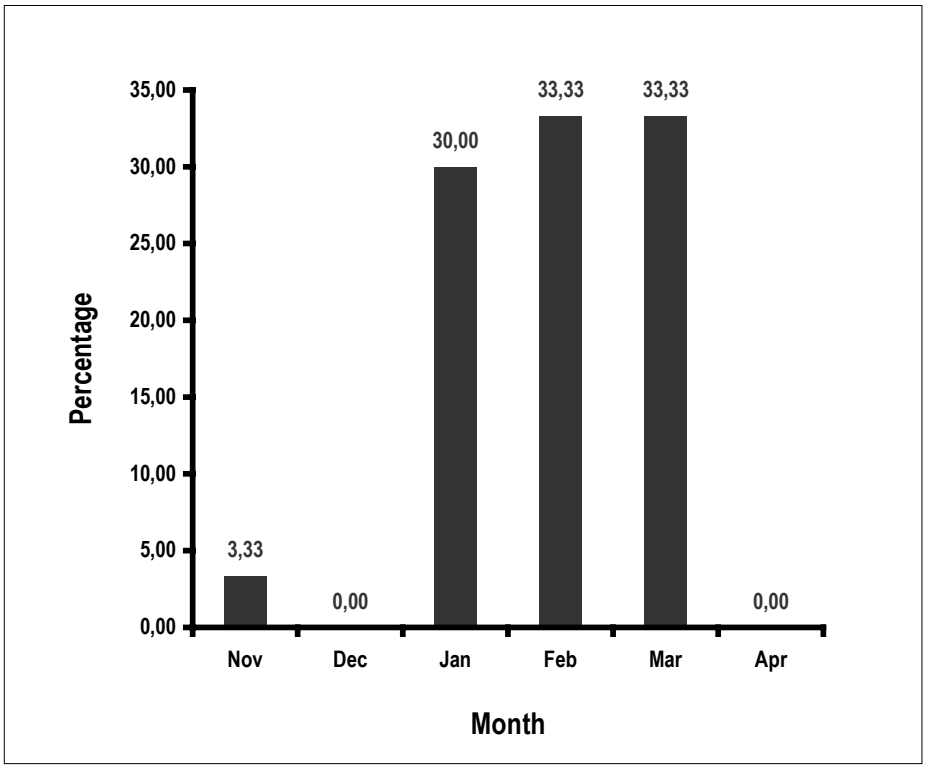


Figure 3-8: Innerseasonal mean long-term distribution (%) of rain-fall maxima at Ongandjera/ Okahao (1960/61 - 1988/89)

This *"inner-seasonal"* variability from year to year has a major effect on crop production, especially regarding the right moment of planting.

3.2.2.3.3 Productive rainfalls

"One measure of productive rain assumes that only falls of ten millimetres or more in one day will have noticeable effects on plant growth, especially the growth of crops" (MENDELSOHN et al., 2000, p.10).

MENDELSOHN et al. (2000) have done an analysis of days with productive rains for several stations in Owambo. For November and December, at each station six or less days per month, can usually be expected to have productive rainfall. From January to March these days are more frequent, but have a higher long-term deviation of numbers than in November, December and April. Figure 3-9 shows the monthly long-term(1940-1999) distribution of days with productive rainfall for three stations in Owambo-land.

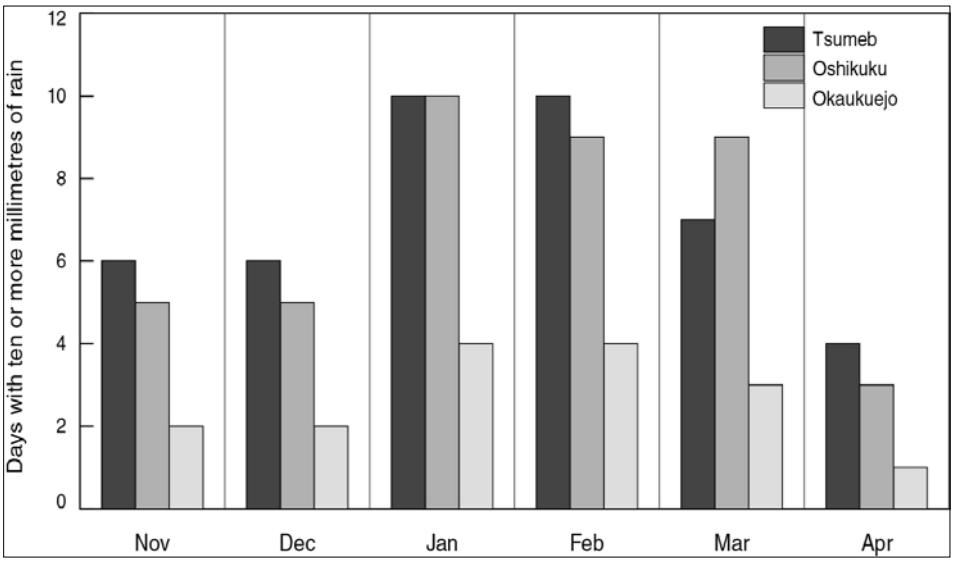


Figure 3-9: Monthly long-term (1940-1999) distribution of days with productive rainfall at Tsumeb, Oshikuku and Okaukuejo (Source: MENDELSOHN et al., 2000)

Looking at Ongandjera/ Okahao climate station, the long-term (1960/61-1988/89) mean number of days with productive rains is 12,7 days per season, with a mean of 1,6 days in November, 1,1 days in December, 3,3 days in January, 3 days each in February and March and 0,7 days in April. However, the seasonal variations are quite high, as it is shown in figure 3-10.

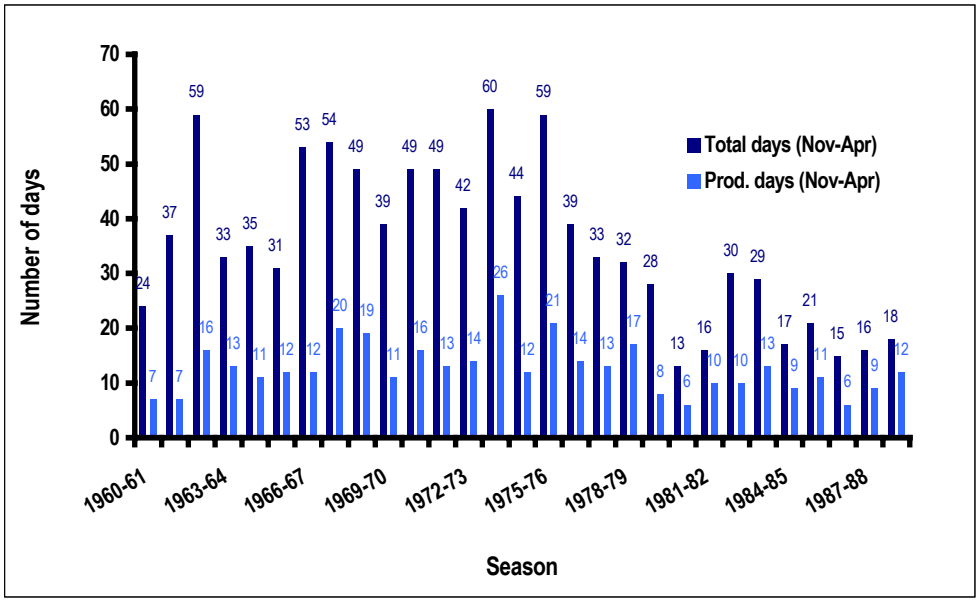
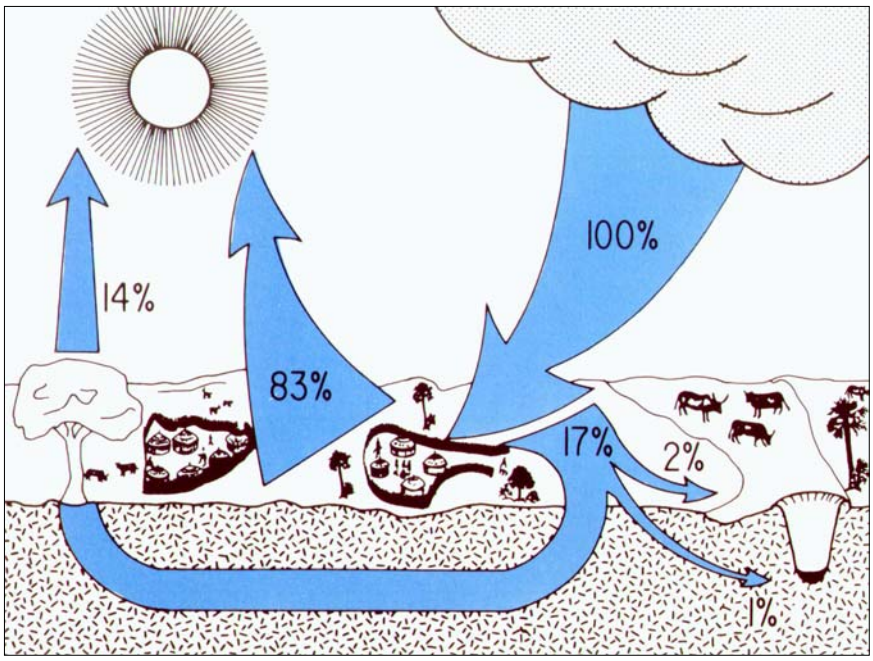


Figure 3-10: Seasonal numbers of days with rainfall and with productive rainfall (≥ 10mm) at Ongandjera/ Okahao (1960/61-1988/89)

3.2.2.3.4 Effective rainfalls

"Effective rainfall is that part of the total rainfall that is available to plants for growth and to recharge groundwater reserves" (MARSH & SEELY, 1992, p.7). No numbers on effective rainfall are available for the AOI or the Omusati region, but for the adjacent Oshana region, that borders Omusati in the east, such information exists.



It is assumed that 83% of all rainfall in Namibia evaporates soon after it falls. In Oshana, the remaining 17% are distributed as such: 2% remain as periodic surface water, 1% recharges the shallow groundwater aquifer and 14% are available for the vegetation (acc. to a report of the Department of Water Affairs, quoted in MARSH & SEELY, 1992, p.7).

Figure 3-11: Distribution of rainfall within the ecosystem of the Oshana region (Source: MARSH & SEELY, 1992)

An actual evaporation rate of 83% of the total rainfall would mean that the Oshana region would only receive an average annual amount of ~80mm effective rainfall.

In the generally drier AOI, even lesser numbers are to be expected. Yet, all these figures are quite speculative and generalised, and the whole atmosphere-soil-plant-water system is very complex.

It is not clear for example, if and to what extent water infiltration capacity of the soil, capillary rise of groundwater etc. are considered in the quoted numbers of figure 3-11.

3.2.2.3.5 Rainfall trend, drought and the effects of "El Nino", "La Nina" and "Benguela El Nino"

Rainfall trend

An analysis of rainfall data from a recording period from 1940-1999 of four stations in north-central Namibia (*Okaukuejo*, *Tsumeb*, *Oniipa* and *Oshikuku*) showed, that obviously cycles of ten years with increased, respectively decreased rainfall exist. While the fifties and seventies were decades with good rainfalls, the sixties and eighties were remarkably drier. It was also found, that the number of days with productive rains (>10mm) between January and March were roughly 25-50% lower in the eighties and nineties than they were in the seventies (MENDELSOHN et al., 2000, p.10).

Figure 3-12 displays the seasonal rainfall amounts and the rainfall trend at Ongandjera/ Okahao from 1960/61 – 1988/89.

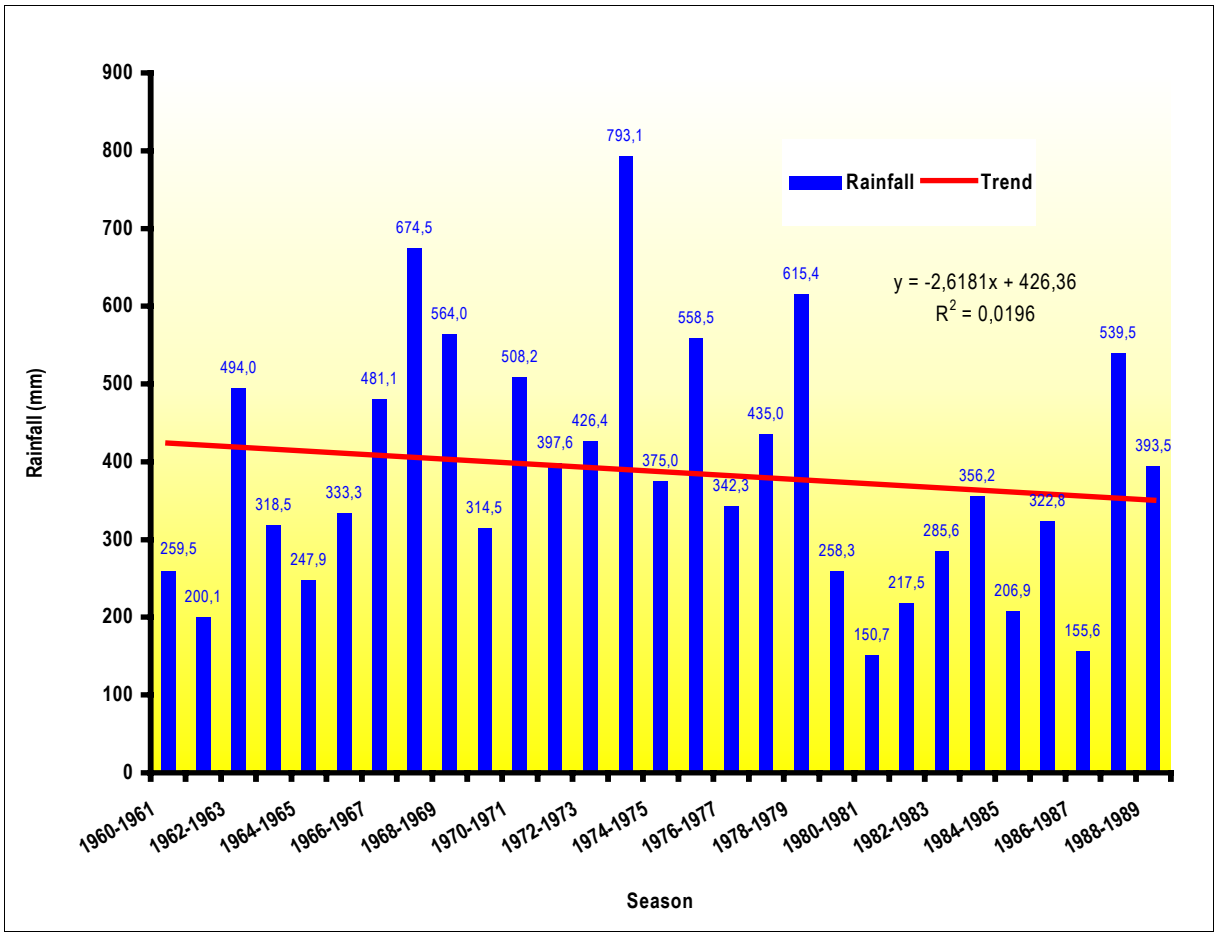


Figure 3-12: Seasonal rainfall amounts and the rainfall trend at Ongandjera/ Okahao from (1960/61 - 1988/89)

A trend analysis of numbers of days with productive rainfall/ season (1960/61-1988/89) at Ongandjera/ Okahao also proved a decline in numbers of days with productive rainfall (see Figure 3-13). The trend that is shown in this figure is very weak and should not be regarded very representative. Apart from that, the numbers show a similar distribution as the stations that were analysed by MENDELSOHN et al. (2000).

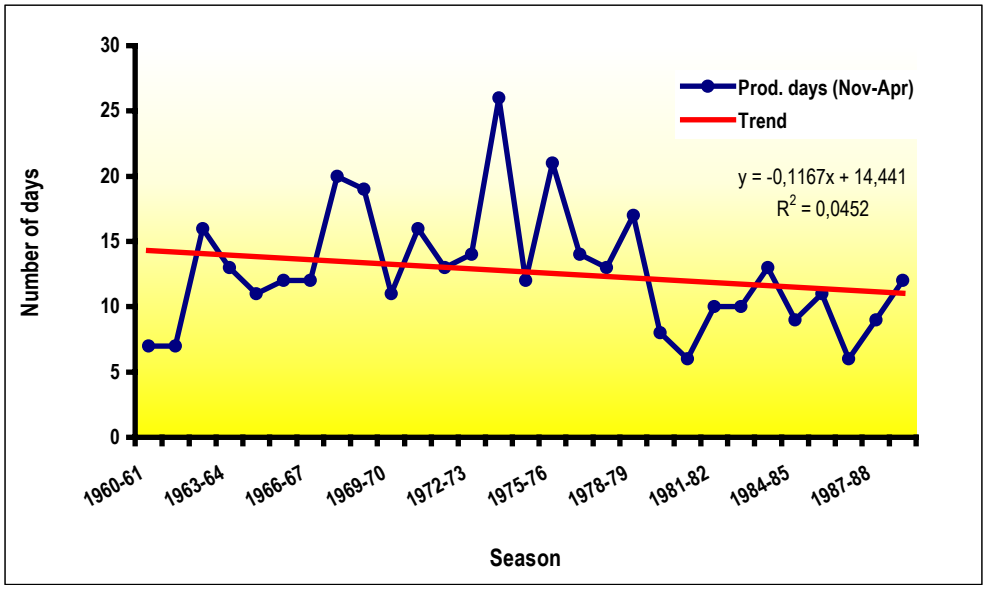


Figure 3-13: Number of days with productive rainfall (≥ 10mm) per rainy season at Ongandjera/ Okahao (1960/61-1988/89)

In KEYLER (1996, p.2) also a decline of the average annual rainfall in Owambo by at least 10mm over the last 20 years and the increased occurrence of droughts during the last 10 years [mid-eighties to mid-nineties] are mentioned.

Drought

For several reasons it is not easy to address the topic of drought and the determination factors. A great problem e.g. are the many ways and different methods how drought is defined (see MAINGUET, 1991 and SEELY, 1999). Meteorologists and hydrologists for example usually define a drought statistically. For them a drought is a negative deviation of the mean average rainfall amount of a certain region. Unfortunately, it seems that no common threshold exists, which specific grade of deviation defines a drought.

Agronomists usually do not consider rainfall statistics exclusively to define a drought. They consider the availability of soil moisture during plant sensitive phases and the results of deficits of soil-water during these phases (also see chapter 1). This is why a *meteorological* and/ or *hydrological drought* does not automatically mean the occurrence of an *agricultural* and/ or an *edaphic drought* and vice versa.

To do a basic analysis of the climate of the AOI (represented by the 1960-1989 climate data of Ongandjera/ Okahao) with respect to drought, a meteorological definition applied by the SOUTHERN AFRICA REGION CLIMATE OUTLOOK FORUM was used. Here, *"above-normal rainfall is defined as within the wettest third of recorded precipitation totals in each region over the period 1961-1990; below-normal rainfall is defined as within the driest third of precipitation totals; near normal is the third centred around the climatological median"* (SOUTHERN AFRICA REGION CLIMATE OUTLOOK FORUM, 1997).

With this term of reference, each rainy season can be rated at least meteorologically. Regarding this definition, the rainy seasons at Ongandjera/ Okahao from 1960/61-1988/89 can be rated as followed:

The 1960s and 1980s are characterised by a more or less equal distribution of seasons with below-normal (partly with extreme, say >50%, negative deviations of the median) and normal to above-normal rainfall. The 1970s in contrast, were a decade with favourable rainy seasons. Only one season had below-normal rainfall, while four had normal and five had above-normal rainfall.

This classification was done on the background of twenty-nine reported seasons and the seasonal rainfall amounts between November and end of April, with a median of 356,2mm. For the detailed data, including the extreme values, see annex 3-1.

It is not easy to identify seasons with *agricultural droughts* at the AOI. As rainfall is not only very erratic in north-central Namibia, but also very patchy, there is *"a great deal of small-scale geographic variation"* (J. MENDELSOHN, e-mail correspondence 25th of October 2002) concerning rainfall yields and hence the occurrence of drought. In addition do crop failures, which are a characteristic feature of agricultural droughts, not exclusively depend on the rainfall pattern of a whole rainy season. The choice of the cultivated crops and the farmers decision on the planting day is also of great influence (see chapter 4.3.2.3).

Nevertheless, to get a rough idea about the situation regarding agricultural droughts at the AOI, the rainfall data of Ongandjera/ Okahao were analysed, by using a definition in SEELY, 1999 (p.3): *"Crop droughts refer to insufficient rain for at least part of the growing season. In Namibia this has been identified as no rain for 10 days after the last productive [≥10 mm] fall."* It seems reasonable to apply this definition in context of this study, as an agricultural drought is characterised by a failure or a sufficient deficit of rainfall and plant available soil-water that is necessary for the development of crops and natural vegetation (see MAINGUET, 1991, p.32 f.).

For the analysis of the rainfall data it was assumed, that planting in Owambo traditionally occurs between January and March and that crops usually need at least ~50 days from the day of planting, until they reach the ripening phase. Therefore, the analysis concentrated on rainfall events during January to the end of April. The results showed no or only low risks of agricultural drought during most of the rainy seasons during the 1960s and 1970s. Only during the 1961/ 62 and the 1963/ 64 seasons the risks were high. During the seasons of 1965/66, 1971/72 and 1972/73 the risk depended much on the choice of the planting date. In the 1980s the situation has changed significantly. During most of the rainy seasons in this decade, the risk of crop droughts was very high. Only in the 1981/82 and the 1985/86 season, the risks were low. In the 1982/83 season the risk was depending on the choice of the planting date. A detailed list of the classification results is shown in annex 3-1.

It has to be emphasised, that the findings concerning drought and drought risks at the AOI should be interpreted with care. They only reflect the situation at Ongandjera/ Okahao, where the rainfall data was collected. In addition, the definition of crop drought (see above), on which the analysis is based, refers only to dry spells of ten or more days following the last productive rainfall events. It does not consider the actual rainfall amount of such a productive rainfall event that was preceeding a dry spell, nor the local soil characteristics regarding water holding capacity.

Effects of El Niño, La Niña and Benguela El Niño

The regional effects of El Niño, La Niña on climate are discussed worldwide, sometimes not without controversy. In the Namibian context the phenomenon of Benguela El Niño is included in this discussion. This additional phenomenon should not be understood as a mirror image of the Pacific El Niño. While the offshore Pacific event usually coincides with the austral solstice in December, *"the Atlantic event occurs at least six weeks (during February to March) after the solstice."* (OLSZEWSKI, 2001a). What is observed in the Atlantic is that *"the upper ocean layers along the Angolan-Namibian coast* [become] *anomalously warm with temperatures in places up to 8°C above that usually found in the region. The maximum temperature differences were found at depth of 30-50m reflecting the deepening of the thermocline."* (GAMMELSROED et al., 1995).

While the Pacific El Niño occurs at the latitude of the equator, the Atlantic event extends from south of 5°S [16°S according to OLSZEWSKI, 2001a] to at least 24°S off central Namibia (see GAMMELSROED et al., 1995). The mechanisms causing the phenomenon are not fully understood yet, but according to GAMMELSROED et al. (1995) *"the Benguela El Niños seem to be associated with a positive subsurface salinity anomaly (~ +0,5 psu) in Namibian waters and a negative (~ -4 psu) surface salinity anomaly in Angolan waters."*

According to OLSZEWSKI (2001a), *"1925, 1934, 1944, 1954, 1956, 1963, 1974, 1976* [1995, see GAMMELSROED et al., 1995] *and 2000 were years with a marked Benguela event".* During each of these years, *"increased rainfall* [was] *observed inland."* Further analysis of climate data, mentioned by OLSZEWSKI (2001a), also lead to the assumption, that the coincidence of a Benguela El Niño and a La Niña lead to a constellation, that can result in remarkably wet rainy seasons in Namibia. This assumption could be confirmed by statements made by the INTERNATIONAL RESEARCH INSTITUTE FOR CLIMATE PREDICTION (IRI) and J. MENDELSOHN of the DEA in Windhoek. The IRI mentions, that La Niña usually *"included relatively wet conditions over much of Indonesia and parts of Australia and southern Africa"* (see INTERNATIONAL RESEARCH INSTITUTE FOR CLIMATE PREDICTION, 1999). During an own analysis, MENDELSOHN also found, that in south-east Namibia, in Kavango and eastern Owambo *"chances of higher rain are much greater in La Niña years"* (J. MENDELSOHN, e-mail correspondence 12th of October 2002).

In the analysis MENDELSOHN also found, that in the same regions *"the chances of high rains are much lower in El Niño years".* OLSZEWSKI (2001b) mentions, that the four most recent El Niño events of 1987, 1992, 1995 and 1998, each terminated the analogue rainy season, which had started very promisingly. According to him, each season saw an early start of rains, which to him is a *"local hall-mark of an El Niño season".*

Noteworthy in this context is also a statement of F. UIRAB, Deputy Director of the Namibia Meteorological Service: *"…an El Niño episode in Namibia is usually associated with normal rainfall over the most parts of the country, however, even during a strong El Niño year some parts of the country have been observed to receive normal rainfall"* (URIAB in GOUVERNMENT OF NAMIBIA, 2002).

A comparison of seasonal rainfall amounts reported from 1960/61-1988/89 at Ongandjera/ Okahao with reported El Niño, La Niña and Benguela El Niño events shows the following results:

During the period of record, eight El Niño events occurred. Using the definition of meteorological drought of the SOUTHERN AFRICA REGION CLIMATE OUTLOOK FORUM (1997, see above), three of them were associated with below-normal rainfalls, four with normal rainfalls and one with above-normal rainfalls. In the same period three single La Niña and two accompanied by a Benguela El Niño occurred. Of the single La Niña events one was associated with below-normal rainfall, one with normal and one with above-normal rainfall. The two La Niña/ Benguela El Niño events were both associated with above-normal rainfall, with the 1973-1974 event showing an extreme positive deviation of 104,89% of the mean average. During the 1962-1963 season a single Benguela El Niño occurred, associated with above-normal rainfall, too. For the exact figures, see annex 3-1.

An examination of the number of days with rainfall and with productive rainfall from beginning of November to end of April during years with reported climatic phenomena, shows a situation very similar to that of the rainfall amounts. To rate the number of days with (productive) rainfall, the total numbers of each season were classified in the same way as the rainfall amounts (see above). Afterwards the results were analysed for relations with the climate phenomena. The findings of the analysis were very inhomogeneous: During the eight El Niño events, the number of rainy days was one time below-normal, six times normal and one time above-normal. Regarding numbers of days with productive rainfall they were below-normal during two seasons and normal and above-normal during three seasons each. In the three seasons with a single La Niña event, the number of days with rainfall and with productive rainfall was one time below-normal, one time normal and one time above-normal. During the two seasons with a La Niña/ Benguela El Niño and during the single Benguela El Niño event, the number of days with rainfall and with productive rainfall was above-normal in each season.

Because of the small number of these results and the sometimes slightly different statements of the cited sources, assumptions regarding the effects of El Niño and La Niña events on rainfall amounts and number of rainy days in the AOI seem not very useful. Only the rainfall reports that are associated with a Benguela El Niño event may permit the assumption that chances of normal to above-normal rainfall are good during such events.

With the whole discussion about the effects of such extraordinary events, it must not be forgotten, that temporal and spatial variability of rainfall is a natural characteristic of arid regions and does not exclusively depend on events like El Niño and La Niña. Extremely dry or wet years also occur regardless of such phenomena, as it is documented in annex 3-1.

3.2.3 Vegetation (mainly according to MENDELSOHN et al., 2000)

The Omusati region has its name for a good reason. *"Omusati"* is the local term for *Colophospermum mopane* or simply "*mopane*". Mopane is found almost all over the region and especially within the AOI. Depending on its habitat, it appears as low and small shrub, as dense bush exceeding 2m or as a tall tree within a typical tree savanna. For the local people the plant is of great value, as it provides medicine, building and fire material. Tools are also made out of the hard wood.

The vegetation of the Omusati region can be roughly classified in accordance to four characteristic physiographic regions of the North-central:

In the north and north-east the *Etaka-Cuvelai system* is located, an area largely covered by a palm savanna. The open grassy drainage channels (*oshanas*) are lined with Makalani palms *(Hypaena ventricosa)*, mixed with Mopane trees and several shrubs. The soils in the *oshanas* and the neighbouring lowlands are composed by silt, clay limestone and sandstone. In the higher parts saline *Kalahari sands* may occur, supporting Mopane shrubs.

The so-called *Western Sandveld* makes up most of the western Omusati. The landscape is extremely flat and only rarely undulating gently. It gets more arid towards the west and thus carrying a bush savanna or an open tree savanna rather than densely growing trees. Mopane, intermixed with grassland, dominates the whole area. From south to north, towards the woodland of Ruacana, the number of species increases. Mostly deep Kalahari sands form the soils, but plenty of small, clayey pans are found, too.

Seasonally flooded grasslands, the so-called *Ekuma Grassveld*, characterise the south-east of Omusati. The grassy vegetation is interspersed with patches of Mopane and Acacia species, which become denser towards the south. Soils are composed similar to the *Etaka-Cuvelai system*, but are generally more sandy and saline.

The south-western and north-western areas of the district comprise the undulating *Karstveld*. The vegetation appears as open shrub savanna with grass cover and variegated shrubs, mainly Acacia species and Mopane. Soils types and textures cover a wide range, including loams, clays, turf clays, and calcareous soils.

Especially in areas with high population density, along roads and drainage channels, "*the vegetation has been severely modified by man over the past century, with the rate of change having accelerated over the past two decades as a result of population pressure and consequently the growing numbers of domestic stock"* (FRIEDRICH-EBERT-STIFTUNG, 1997, p.185).

Looking at the AOI most of it is part of the *Western Sandveld* landscape or, according to MENDELSOHN et al. (2000), the *Western Kalahari Woodlands* (see annex, map 3). In the south-east it borders a relatively small area carrying *Karstveld*-vegetation, where hills of the *Otavi Group* are situated. In the north-west of the AOI, vegetation of the *Western Kalahari Woodlands*-vegetation changes towards vegetation of the *Etaka-Cuvelai*, or *Cuvelai* type (MENDELSOHN et al., 2000). Finally, the eastern parts are characterised by the so-called *Mopane shrublands*, a region of transition from the dominating *Western Sandveld* into the *Ekuma Grassland*.

Concerning the AOI, the three occurring vegetation types (*Western Sandveld* / *Western Kalahari Woodlands*, *Etaka-Cuvelai* and *Mopane shrublands*) can be subdivided into several vegetation units (see annex, map 4):

3.2.3.1 Vegetation units of the Western Sandveld/ Western Kalahari Woodlands

- ***Western sand plains*:** A large flat area with brown to red sands and relatively few calcrete outcrops, pans and a few drainage features. The vegetation is characterised as *"a mixture of woody species in a monotonous savanna with low cover"* (MENDELSOHN et al., 2000, p.25).
  - Predominant species:
    - ***Trees:***[1] *Acacia reficiens, Acacia erioloba, Terminalia sericea, Lonchocarpus nelsii*
    - ***Shrubs:*** *Catophractes alexandrii, Grewia flava, Acacia mellifera, Croton gratissimus*

[1] In some vegetation units, depending on the habitate conditions, trees, e.g. *Acacia hebeclada* and *Colophospermum mopane*, may occur as shrubs rather than trees.

- ***Grasses:*** *Schmidtia kalahariensis, Aristida stipoides, Aristida meridionalis, Eragrostis porosa, Enneapogon cenchroides, Stipagrostis uniplumis, Stipagrostis hirtigluma*

- ***Mopane-Combretum savanna on sandy soils*:** Partly acidic, quite coarse and in depressions more clayey red sands form the basis for an open savanna.
  - Predominant species:
    - ***Trees:*** *Colophospermum mopane, Terminalia prunoides, Combretum apiculatum, Terminalia sericea, Loncho-carpus nelsii, Dichrostachys cinerea*
    - ***Shrubs:*** *Croton gratissimus, Rhizogum brevispinosum, Commiphora spp.*
    - ***Grasses:*** *Schmidtia kalahariensis, Schmidtia pappophroides Aristida stipoides, Aristida meridionalis, Eragrostis porosa, Enneapogon cenchroides, Stipagrostis uniplumis, Stipagrostis hirtigluma, Pogonarthria fleckii*
- ***Western mopane-pan mosaic*:** *"This is a spectacular mosaic of thousands of small pans and some larger ones, surrounded by higher ground supporting copses of woody species"* (MENDELSOHN et al., 2000, p.25). Loams and loamy sands with high salt concentrations are located here.
  - Predominant species:
    - ***Trees:*** *Colophospermum mopane, Acacia reficiens, Acacia nebrownii, Acacia luederitzii, Terminalia prunoides*
    - ***Shrubs:*** *Commiphora mollis, Catophractes alexandrii*
    - ***Grasses:*** *Eragrostis porosa, Eragrostis annulata, Stipagrostis uniplumis, Stipagrostis hirtigluma, Willkommia sarmentosa, Monelytrum luederitzianum, Sporobolus tennelus, Odyssea paucinervis*
- ***Mixed savanna on loamy to sandy soils*:** Sandy to loamy soils, usually covered loosely with calcrete rocks provide the ground for a relatively dense savanna with a variety of plant species.
  - Predominant species:
    - ***Trees:*** *Colophospermum mopane, Sesamothamnus guerichii, Terminalia prunoides, Acacia reficiens, Acacia luederitzii, Combretum apiculatum*
    - ***Shrubs:*** *Catophractes alexandrii, Acacia nebrownii, Leucosphaera bainesii, Petalidium engleranum, Euclea pseudoebenus*
    - ***Grasses:*** *Schmidtia kalahariensis, Eragrostis porosa, Eragrostis annulata, Enneapogon cenchroides, Stipagrostis uniplumis*

3.2.3.2 Vegetation units of the Etaka-Cuvelai

- ***Cuvelai palm and fruit-trees on loamy sands*:** This unit covers an area that is slightly elevated above the surrounding territories, densely populated and under intensive cultivation. The soils are loamy sands and not as sodic as elsewhere in the *Cuvelai-system*.

- Predominant species:
  - ***Trees:*** *Hyphaene petersiana, Sclerocarya birrea, Berchemia discolor, Diosporus mespiliformis, Adansonia digitata* and in disturbed areas especially *Pechuel-Loeschea leubnitziae, Acacia arenaria* (see MENDELSOHN et al., 2000, p.20)
  - ***Shrubs:*** usually cleared
  - ***Grasses:*** *Schmidtia kalaharensis, Odyssea paucinervis, Sporobolus tenellus, Willkommia sarmentosa, Tricholaena monachne*

3.2.3.3 Vegetation units of the Mopane shrublands

- ***Mopane shrubs and low trees on loamy sands*:** The AOI´s share of this unit lies west of the *Etaka channel*, where the soils are sandier than east of it, where they tend to be loamier. Most of the whole unit is covered with Mopane growing up to 4 meters. Nevertheless, due to the differences in soil texture, the area that is located in the AOI is showing much denser and less tall Mopane vegetation.
  - Predominant species:
    - ***Trees:*** *Colophospermum mopane, Terminalia prunoides*
    - ***Shrubs:*** *Colophospermum mopane, Catophractes alexandrii*
    - ***Grasses:*** *Schmidtia kalaharensis, Eragrostis porosa, Eragrostis annulata, Stipagrostis uniplumis, Enneapogon cenchroides, Aristida ascensionis*

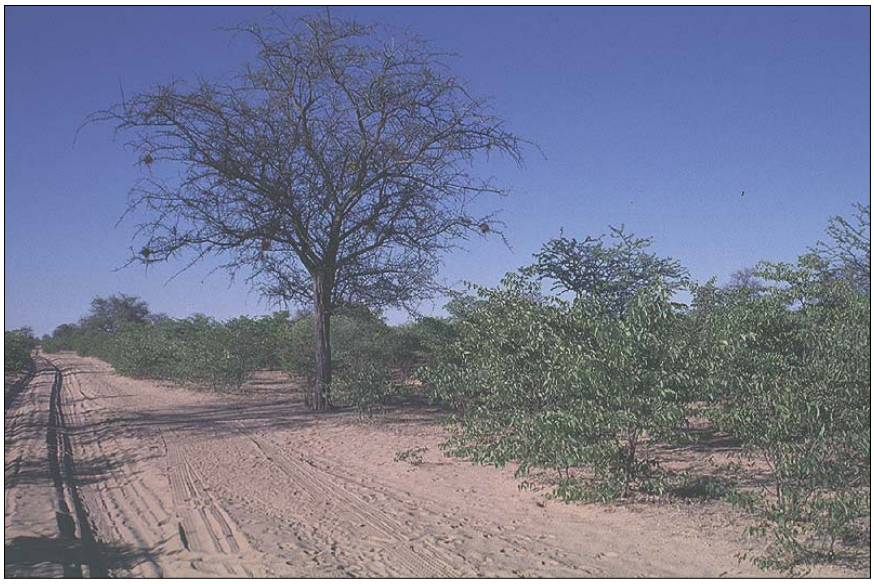


Figure 3-14:
Bush track in the area of the *Mopane shrubs and low trees on loamy sands* – vegetation unit (Source: own photography, January 2002)

3.2.3.4 Alternations of natural vegetation

At least two aspects alternate the appearance of the natural vegetation at the AOI: human influence and rainfall variability. Especially the area of the *Cuvelai-palms and fruit-trees on loamy sands*, the *Mopane shrub and low trees on oshanas* unit as well as the unit of *Mopane shrubs and low trees on loamy sands* has been altered by man to a great extent. It is a region of comparatively high population density with people living on small-scale farming. Therefore, most of the original vegetation has been cleared, apart from a number of useful fruit trees like

e.g. Marula trees *(Sclerocarya birrea)* and Makalani palms *(Hypaena ventricosa)*. Yet, even in the more inaccessible western and south-western parts of the AOI vegetation is increasingly cleared. To a large extent, new farm land is prepared, but plenty of trees, especially *Colophospermum mopane, Terminalia sericea* and *Terminalia prunoides* are cut down, because they are used as building-, fencing- and fire-material. There are no numbers available for the AOI, but during the 1991 census 84% of the households in the Owambo indicated wood as their prime building material and 96% used wood for cooking purposes (MENDELSOHN et al., 2000, p.26).

Grazing and high stocking rates (see chapter 3.3.7.2) also influence the composition of the vegetation (esp. on grasses and shrubs) throughout the AOI.

Figure 3-15:
Effects of grazing on vegetation cover – the area in the back of the picture is protected from grazing by a fence, whereas the area in front is used as pasture (Source: own photography, January 2002)

High rainfall variability is another effect that can change the condition (e.g. vitality, density and biomass) of vegetation rapidly (MENDELSOHN et al., 2000, p.28).

3.2.4 Soils

According to the FAO "1:5 000 000 Soil Map of the World" (FAO & UNESCO, 1977) north-western and north-central Namibia is characterised by three major soil types: *calcic xerosols*, *cambic arenosols* and *orthic solonetzs*. The *calcic xerosols* are accompanied by *calcic cambisols* as well as *cambic arenosols* and *chromic luvisols*.
The *cambic arenosols* are associated with *albic arenosols*, *calcic xerosols*, *solonchaks*, *vertisols* and *regosols*, while alongside *orthic solonetzs*, *luvic* and *cambic arenosols* occur.
On-site the AOI this characterisation proves to be quite inadequate, which is of no surprise, considering the scale of the FAO map. For this reason, local Namibian sources and own findings are used in this section to describe the soils. This classification may not exactly match with the FAO classification system, but nevertheless it provides a fairly good overview on the soil situation in the AOI,.

3.2.4.1 General soil characteristics

Almost the whole Owambo, including the AOI, is situated on a fundament of *Kalahari sandstone*. In the south-west of the AOI there is a transition towards bedrock of *dolomites* from the *Otavi group*. Almost all the sandstones and dolomites are covered by a +/- 3m thick layer of loose sands, that are aeolian deposits of the *Tertiary*. In

some places all over the AOI, but especially in the eastern and north-western parts, silts and loams also occur. Typically they are found in and near pans of varying sizes. There are two types of pans to be found all over Owambo: clay pans and salt pans. Yet, pans showing both characteristics are also possible. Clay pans are usually found in sandy areas, where wind erosion has formed small depressions. During the rainy season the silts, clays, and loams are laid down in these depressions by run off water. Salt pans on the other hand, are situated in regions where layers of limestone (e.g. formed by run off from mountains of the *Otavi group*) trap water that consequently has to evaporate, leaving the suspended salts behind on the ground. The *Etosha pan* in north-central Namibia is a famous representative of such a salt pan.

The permanent reworking of the sediments by wind and to a limited extend by water, greatly hinders the development of well structured soil profiles, as they are known from temperate climate zones. The long dry season that prevents chemical weathering and the decomposing activities of soil organisms, as well as the comparatively low plant cover are additional factors for the limited soil formation.

As a result of the environmental conditions, the soils of the AOI show the typical characteristics of semi-arid and arid soils:

- Slow soil formation, shallow profiles and/ or not very distinctive soil horizons
- Low sorption capacity
- Low contents of organic matter and humus in the top-soils
- Deficiency of nutrients and therefore a low fertility
- High local concentrations of (alkaline) salts, resulting in neutral or alkaline pH-levels
- Accumulation of calcium carbonates

The reason for the low sorption capacity of soils in semi-arid and arid regions is the reduced soil formation. Thereby only a small amount of sorption-complexes, such as clay minerals and humins, are formed (GANSSEN, 1963, p.98). The low contents of organic matter, humus and nutrients are the result of the already mentioned reduced weathering and biological activity, the low plant density and the weak sorption capacity. GANSSEN (1963, p.38 & p.88) analysed seventeen samples of northern Namibian soils, which he labelled *"soils of dry forests"* and *"brown soils of the semi-desert"*. The results showed humus contents of 0,5-2,0%, total nitrogen contents of 0,03-0,13% and C/N-ratios between 8-13. The findings made in the context of this study (see chapter 4.2) are quite similar to the results of GANSSEN (1963).

The salinity found in plenty soils within semi-arid zones is an effect of repeated sequences flooding and evaporation, leaving the dissolved salts of the water behind. The accumulation of calcium carbonates in semi-arid environments is usually not a result of ascending calcareous groundwater, but of the slowed hydrolysis of

bedrock that contains calcium-aluminium-silicate compounds (GANSSEN, 1963, pp.27-29). This process is described as followed:

$CaSiO_3 + 2H^+ + 2OH^- \rightarrow Ca(OH)_2 + H_2SiO_3$

$Ca(OH)_2 + 2CO_2$ (from atmosphere) $\rightarrow Ca(HCO_3)_2$

$Ca(HCO_3)_2 \rightarrow CaCO_3 + H_2O + CO_2$ (reaction driven by evaporation)

In temperate and humid zones the calcium carbonates, which are formed by this chemical process, are easily dissolved again by soil-moisture, whereas in semi-arid areas they fall out and remain in and on top of the soils.
In the course of time, the accumulation of calcium carbonates and salts can result in the formation of hard crusts within the profile or on top of the soils. This phenomenon can be observed at various sites throughout the AOI. In addition, the soils within the AOI show also hard layers of baked sand and substrate, so called *fragipans*, a feature typical for soils in Owambo. They are usually found at a depth between 20-100cm (MARSH & SEELY, 1992, p.10). Another distinctive attribute is the low water retaining capacity of the soils (MARSH & SEELY, 1992, p.12), that is easily explained with their predominantly sandy texture.

MENDELSOHN et al. (2000) distinguish the soils of north-central Namibia into nine categories and areas of their occurrence (MENDELSOHN et al., 2000, p.18): *silts*, *sodic sands*, *deep Kalahari sands*, *loams and clays*, *loams*, *clayey sodic sands*, *sands and loams*, *clayey sands* and *dolomite sands*. Three of those types occur within the AOI: *sands and loams*, *deep Kalahari sands,* and *silts* (see annex, map 5).
The sands and loams cover the north-east, the east, the north-west, parts of the northern fringe of the AOI, as well as an isolated patch within the AOI. Wind and, partially, water rework these substrates permanently, resulting in a mixture of different textures. Apart from areas around Okahao, these soils tend to be saline (MENDELSOHN et al., 2000, p.18). Especially in the western parts of the AOI rock outcrops are also common. Sands and loams are site for the *Cuvelai palms and fruit-trees on loamy sands*-, *Mopane shrubs and low trees on loamy sands*-, W*estern-mopane-pan mosaic*- and *Mixed savanna on loamy to sandy soils-vegetation* units (see chapter 3.2.3).
Deep Kalahari sands cover the largest area of the AOI. They are found throughout the centre and in the south and south-west of it. These reddish-brown, sometimes yellowish sands are still shaped by strong. In depressions the texture tends to be loamier. The typical vegetation these soils carry is *Western sand plain*- plant societies and *Mopane-combretum savanna on sandy soils*- plant societies (see chapter 3.2.3).
Silts are found in and around the numerous pans that exist throughout the AOI. Especially in the south-west and western parts, they are frequent. The *silts* are deposited in depressions, which were formed by wind erosion. Typically, they form soils that are dark brownish to greyish with surface cracks, increased salinity and calcrete outcrops.
Of course this description, which is based on the classification by MENDELSOHN et al. (2000), is still quite general and the occurrence of different types of vegetation indicate, that the real situation is far more diverse, because *"the types of plants that grow there are largely a product of the kinds of soil present. This is particularly*

true on a local scale where differences in soils explain much of the local variation in plant life. Climatic factors…also have major impacts on plant life, but these effects are usually more wide-ranging than those on a local scale" (MENDELSOHN et al., 2000, p.18). This factor was considered during the research for this study, where the soils were analysed in accordance to the occurring vegetation types. Therefore, chapter 4.2 provides a more detailed overview on the soils of the AOI in accordance to the occurring vegetation type.

3.2.5 Hydrology and water

A look at a topographical map depicting the AOI proves the complete absence of perennial rivers within the AOI (see annex, map 2). Even the whole Omusati district has no such feature. Only in the north-eastern part it borders the western fringe of the *Cuvelai-system* or *Cuvelai*. Even without being located within the AOI, this non-perennial drainage system should be introduced briefly, because it is a major source to recharge the shallow groundwater aquifer for almost the whole of Owambo, including the AOI.

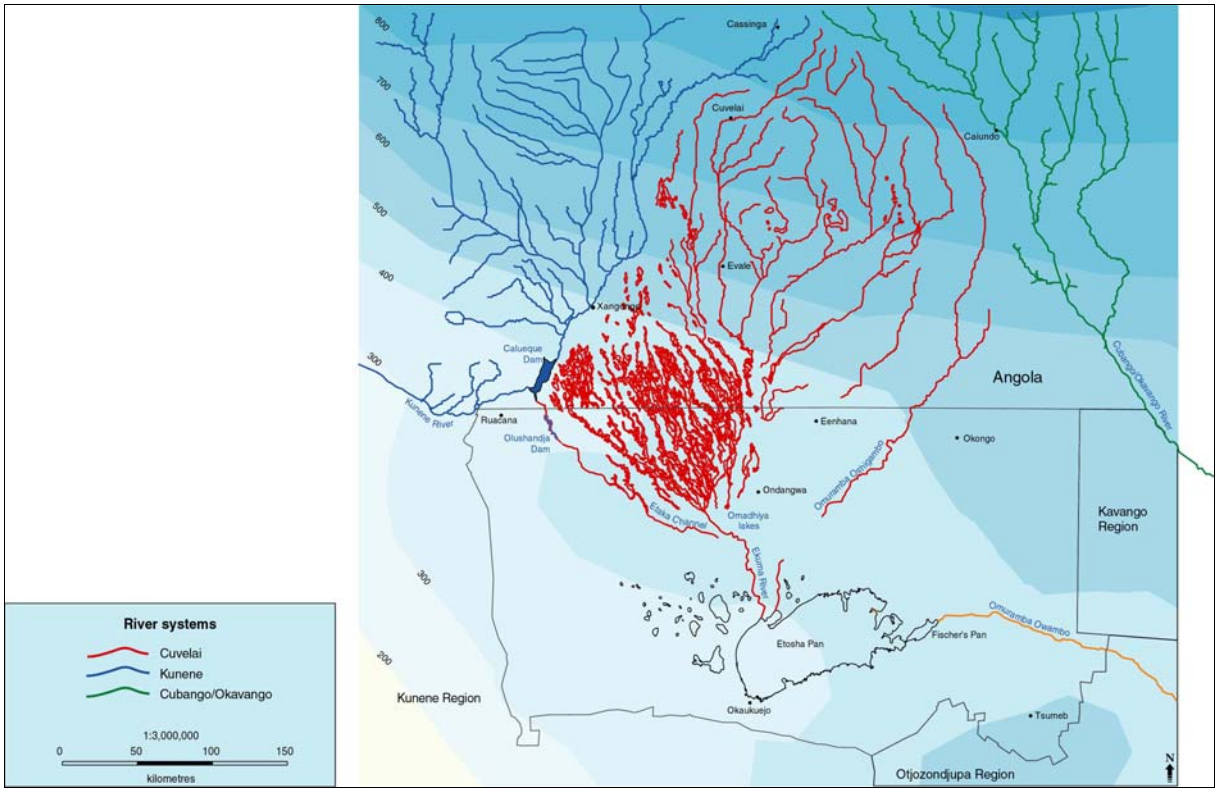


Figure 3-16: The *Cuvelai*, and neighbouring *Kunene* and *Cubango/ Okavango* drainage systems, and zones of annual average rainfall (mm, Source: DEA, 2002)

The *Cuvelai* is a system of hundreds of shallow, relatively broad, meandering drainage lines called "*oshanas".* Those are interlinked with each other, forming a huge inland delta. Around the area of *Lake Oponono,* in the centre of the Oshana district, the *oshanas* converge. Depending on the amount of rainfall, the system is flooded during the rainy season and for several weeks afterwards. In the course of the year, it will fall dry until the next rainy season. The whole system is originated in southern Angola, the catchment area lies between the *Kunene-*

system in the west and the *Cubango/ Okavango-system* in the east. Most of the water within the *Cuvelai* comes from Angola, some of it as far as from the *Highlands of Encoco*. However, part of the water also originates from local rains in Owambo. In years with sufficient rainfall, a flood called "e*fundja"* may occur, filling the whole system, but the flow of water in the *oshanas* rarely exceeds a velocity of 0,5 m/ sec (NGHITILA, 1997, p.3). In statistically eight times in twenty years some of the flood waters even reach the *Etosha pan*.

As already mentioned, the AOI itself has no share of the *Cuvelai*. It does not even have distinct non-perennial drainage lines. Only a few very small lines, rarely exceeding 5km in length, lead towards the greater pans in the west of the AOI. The only exception is found on the north-eastern border of the AOI, the so-called *Etaka* or *Etaka channel*. Most authors refer to it as the western fringe of the *Cuvelai*, but is more likely that the *"Etaka…may represent the remains of the main course of the Kunene river when it apparently drained into the region up until about two million years ago"* (MENDELSOHN et al., 2000, p.13). Not far south of the Angolan border the *Olushandja Dam* has been erected to dam the Etaka. From time to time water is released into the channel to be used for the livestock that is kept along the course of the *Etaka*.

The only surface water to be found in the AOI is rainwater caught in pans, but it evaporates quite fast. Therefore, the water supply for people and livestock has to be covered mainly by groundwater.

Three main aquifers within a complex groundwater system that is not fully understood yet, are identified in the AOI, respectively Owambo. Two of these main aquifers are located within the sediments of the *Kalahari sequence* (see chapter 3.2.1):

The first is the most shallow one, called *discontinuous perched aquifer* (DPA).[1] It depends completely on rainfall and the *Efundja* too keep it charged. The water drains through the toplayer of sand and is trapped by an underlying layer of clay or other heavily permeable material. Ever since people settle in Owambo, they tap this aquifer with the help of shallow, hand-dug wells, called "o*mithima"*. However, in the course of the dry seasons these wells may fall dry, due to evaporation and the percolation of water through the underlying sediments, which are not completely impermeable.

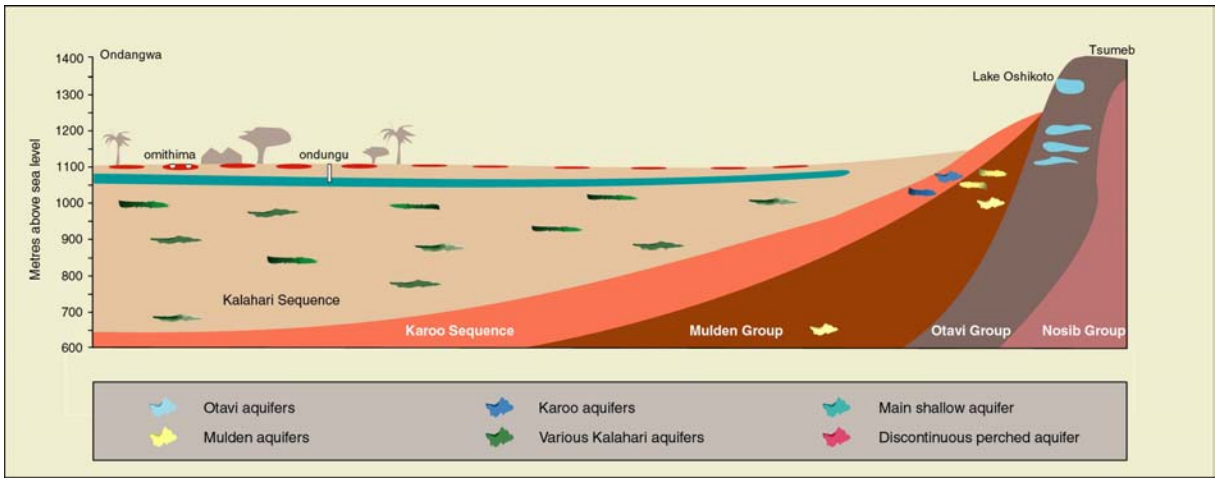


Figure 3-17: Cross section, showing the main aquifers of north-central Namibia (Source: DEA, 2002)

[1] *Discontinuous* because it is not found all over the region, *perched* because it lies on top of a less permeable sediment layer.

A little deeper than the DPA, between ~ 20-40m the *main shallow* (or *saline*) *aquifer* (MSA) is located. It is exploited with the help of so called "*oondungu"*, deep hand-dug wells. Normally the *oondungu*, like the *omithima*, are found in groups, with every well belonging to a particular family. The quality of the water gained from the MSA is of great variety. Especially in the south-eastern Omusati, it is often too saline even for livestock. However, if water from rainfalls or out of the *oshanas* is able to percolate down into the MSA it forms freshwater lenses of good quality, floating on the denser salt water.

Underlying the *Kalahari sequence* is the *Karoo sequence,* which is followed by the *Damara sequence* (see chapter 3.2.1). In these deep sediments a complex system of aquifers is found, which is known as *saline deep aquifer* (SAD). Within the SAD, water is located in depths ranging from 30m down to 670m. Most of the water is more or less brackish but can be used for drinking.

To supply the population with fresh water, numerous boreholes have been drilled in addition to the traditional wells. A pipeline system bringing fresh water down from the *Kunene* now also reaches into the AOI a far as Okahao (see annex, map 7). All these efforts are part of a government plan to guarantee every household access to potable freshwater within a distance of 2.5 km. Nevertheless, especially within the AOI some of the small and scattered settlements have to bring in some of their freshwater with the help of water tankers.

3.3 SOCIO-CULTURAL, DEMOGRAPHIC AND SOCIO-ECONOMIC CHARACTERISTICS

3.3.1 People of the AOI – history and culture

The AOI is part of a region known as Owambo or Owamboland, the traditional settlement area of the Owambo people. With ~50% (MALAN, 1998, p.10) of the total population, the Owambo represent the major ethnic group in modern Namibia. As most of them still settle within Owambo, this is also the most densely populated area within Namibia (see figure 3-18).

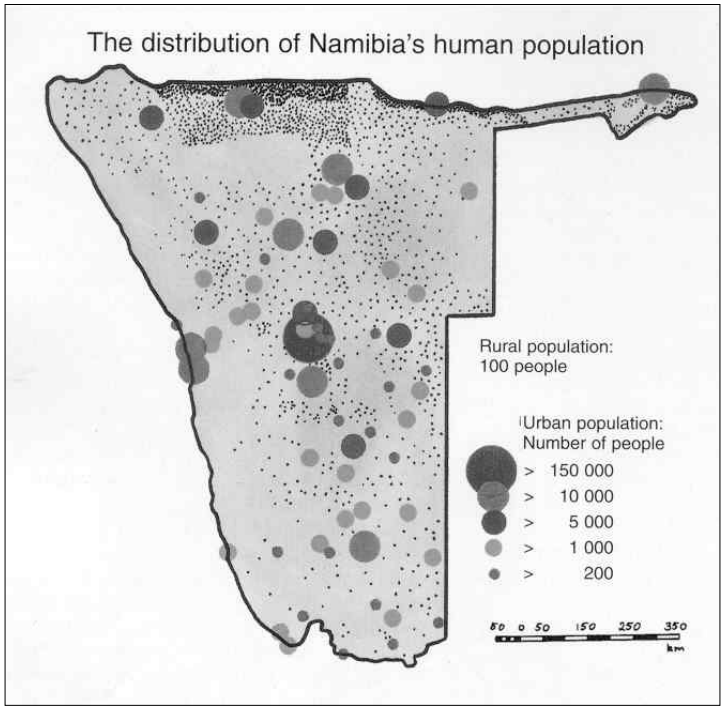


Figure 3-18:
Population distribution in Namibia (Source: TARR, 1995)

The Owambo living in Namibia, are distinguished into eight, by some authors into nine, different tribes: The *Kwaluudhi*, *Kwanyama*, *Ndonga, Ngandjera, Kolonkadhi*, *Kwambi*, *Mbalantu*, *Eunda* and *Mbandja*.[1] Eight closely related tribal languages exist, but no lingua franca has developed. Generally, *Oshindonga* and partially *Oshikwanyama* are widely accepted as written languages.

The Omusati region in particular is the tribal area of the *Eunda, Kolonkadhi*, *Kwaluudhi*, *Mbalantu* and *Ngandjera*, with *Ngandjera* representing the largest group living within the AOI (MENDELSOHN et al., 2000, p.46).

Apart from language, the tribes differ in some of their traditions, e.g. tribal governance and wedding ceremonies. Yet, they also have very much in common, so most of the literature that was reviewed in context of this study, is referring to the Owambo as one ethnic group.

The Owambo belong to the *south-west Bantu*, but their origin is thought to be in the area of *"some lake in the eastern region of central Africa"* (MALAN, 1998, p.21). Culturally, they show tight relations to the farming cultures of central Africa, but unlike the neighbouring tribe of the *Okavango,* they are not typical *Bantu*-farmers, as they have a strong tradition in livestock (esp. cattle) breeding. It is supposed, that on their move from central Africa they have followed a branch of the *Kavango river*, which formed several lakes on it's way to into the *Etosha-pan*. This river is thought to have ceased a long time ago, due the effects of an earthquake. First, the Owambo settled around a lake called *Osimolo*, now vanished, providing the people with plenty of fish. Several disputes, esp. about fishing rights, may have caused the formation of the different Owambo tribes. In the 16th century, the Owambo seem to have finally settled in the extensive plain that is situated north of *Etosha* and reaches far into southern Angola; an area that has previously been occupied by the *Hei//om*, a tribe of the *San*. Here, they established their typical agro-pastoral culture. As their economy provided a production surplus, they were also able to develop a class of political leaders taxing the people, as well as professions like potters, woodworkers, salt gatherers, metalworkers and traders. Especially the *Kwanyama* are known to have traded cattle for iron from the *"Cassinga"* area in Angola, while the *Ndonga* traded cattle for salt and copper from the *Etosha/ Tsumeb* area.

Besides farming, trading, the keeping of cattle that are driven to seasonal grazing areas, the storage of agricultural products in large woven containers (called *lighandi*), hunting, the gathering of wild fruits and fishing during the rainy season were and still remain strategies to cope with periods of crop drought and crop pests.

In 1851, the Owambo had their first documented contact with European colonialists. From 1860 on, they are known to have had trade relations with the European traders and in 1870 missionising started. With traders from *Walvis Bay* and especially with the Portuguese in Angola, the kings of the Owambo traded cattle and slaves (to work in the portuguese-angolian plantations) for industrial products, alcohol, and weapons. After slavery had been abolished in 1875, contract labour was exported to Angola.

When Namibia, then "*German South-west Africa*", became a German colony in 1884, the Owambo area was not directly included in the German administration and remained more or less independent. Nevertheless, the presence of colonists in the region accelerated acculturation, and by 1907 a strong migrant labour system had

[1] The *Mbandja* tribe is not separately annotated in every publication.

developed, with Owambo men moving to the south, working in the mining areas and the related industries, and on commercial farms.

In retrospect it has to be stated, that the arrival of Europeans in the region had a deep, sometimes fatal impact on society and the natural environment in Owambo: "*Along with the severe stresses imposed by higher taxes and the selling of slaves, several other upheavals were to come upon the people during the last few decades of the 19th century. Substantial social changes were caused by the expansion of Christianity. There where repeated years of drought, locust attacks on crops and, as the final straw, the rinderpest epidemic in 1896-98 when up to an estimated 90% of all the cattle in the region died. Further ills were to befall the region in the early decades of the 20th century, when repeated crop failures and famines killed tens of thousands of people. The introduction of direct rule and taxation by the Portuguese in southern Angola led to an exodus of 40.000 refugees from there into Owambo, adding considerable demands on the resources available for crop and livestock production. By the end of the 1800s, the production system in Owambo had essentially collapsed, and people grabbed the opportunity of adding new source of income to their diminished resources: salaries from contract labour"* (MENDELSOHN et al., 2000, p.63).

In addition, the old (and still valid) colonial border between Angola and the former German South-west Africa divided the settlement area of the Owambo. Apart from the tribes of the *Ndombothola*, *Mbadya*, *Kwamatwi*, *Kafima* and *Vale* about one third of the *Kwanayama* population are Angolan citizens today.

With the defeat of Germany in the First World War, German South-west Africa was turned into a South African mandate territory by the former League of Nations, and a system of commissioners with limited administrative and juridical powers was introduced in Owambo. After consultations between the South African administration and the tribal authorities, Owamboland officially received a central government and self-administration in 1968. Nevertheless, de facto the territory was still influenced by South African authorities.

Already eleven years before 1968, the *Owamboland People's Congress* (OPO), later *South West Africa People's Organisation* (SWAPO), was founded. In 1966, SWAPO launched an armed struggle to gain independence from the South African apartheid regime. During the struggle, combat action mainly took place in Owambo and southern Angola. The war forced several thousands of people into exile and had effects on demography, settlement patterns (e.g. it hindered the expansion of settlement areas into unoccupied areas), and economic activities (e.g. the establishment of a commercial farm sector) in Owambo (MENDELSOHN et al., 2000, p.1). Finally, after more than three decades of struggle, the country now called *Namibia* became independent in 1990.

In the course of the subsequent political and administrative re-arrangement, Owamboland has been turned into four administrative regions: *Omusati*, *Oshana*, *Ohangwena* and *Oshikoto* (see annex, map 1).

3.3.2 Social structures and settlement structures

The Owambo society is traditionally a *matrilinear* society, which means every newborn belongs to the mother's line of descent. Therefore the oldest brother of the mother, and not the natural father, is the most important authority for a child, next to the mother. If this particular uncle dies and has no brother, it is the children of his

sister that will inherit most of his possessions, esp. his livestock. A matrilinear society must not be confused with a matriarchate. In the Owambo society, like in most other matrilinear societies, men are the keeper of power.

After the marriage of a young couple, they have to establish their own homestead, which preferably should be located close to the home of the husband's uncle (= *avunu*-local settlement). Traditionally, the Owambo live in a round, palisade protected homestead called o*ngandjo*. The palisade usually is made of trunks, branches, millet stems or bushes. Today, these materials are sometimes not available and substituted by scrap material (see figure 3-19). The o*ngandjo* has a diameter between 15-50 m, clearly defined living and working areas and contains several huts made of clay, wood and millet stems. The *kraal* (called *oshigunda*) where the livestock are kept at night, and usually the woven grain containers, called *iighandi*, are situated outside the palisades. Traditionally, the homestead is surrounded by fields, which belong to the household. This is the reason, why the traditional Owambo culture has developed no villages, but dispersed settlements.

Figure 3-19:
Traditional homestead (*ongandjo*) surrounded by fields (Source: MARSH & SEELY, 1992)

Due to acculturation/ cultural change, environmental change and modern infrastructure, e.g roads, the settlement structures are increasingly altered. Especially wealthy households often show modern building structures, such as brick houses with windows and zinc roofs, as they can afford the building material. Today, also *neo-local* settlement is becoming more dominant, because families that are engaged in retail or other business, prefer to settle along main roads or frequently used bush tracks. Another important reason for neo-local settlement is the lack of arable land, so people have to move to areas where unoccupied space is available. One destination of this movement is clearly the AOI. Here settlements, e.g. *Amarika*, established only in the last decades are found, showing village-like structures, brick houses, school buildings and so called *Cuca-shops*[1].

Figure 3-20:
***Cuca-shop* in north-central Namibia (Source: own photography, February 2002)**

[1] *Cuca shops* are small shops, selling alcohol, soft drinks and good of daily need.

Older places of settlement, like *Eholongo*, show more traditional structures. Nevertheless, despite the modern housing structures, private infrastructure in Omusati remains still fairly poor. Of all households, only 15% had access to safe water, 1% had electricity, 53% owned a radio and 93% still used the bush as toilet in 1993 (CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION, 1994).

Another obvious feature in the AOI is, that fields often do not surround the homesteads anymore. Instead, they are a little further away and frequently are very large, compared to the rest of Owambo. Mostly they are fenced off with wire.

3.3.3 Demographic characteristics

In 1993, a system of regional governments was established in Namibia and in administrative terms, the research area is part of the Omusati region since then. In 1998, an administrative re-organisation was done. During these reforms, the borders of the Omusati region, as well as the ones of the neighbouring Oshana and Oshikoto region, and of some constituencies within the regions, have been changed. As a result, today there is still some confusion about the exact boundary lines and the limits of some constituencies. However, according to the 1991 census, the Omusati region comprises an area of 12.552 km² with a population of 189.919 people, making up 13,5% of the country's total. The people were distributed to 30.882 households in 1991, which means an average household size of 5,9 persons. According to the 1991 census, 100% of Omusati´s population live in rural areas.

In 1991, 48% of the population was younger than 15 years, 46% were aged between15-64 years and only 2% were older than 64 years. The average fertility rate dropped from 5,7 children/ woman in 1991 to 4,9 in 1996 (MENDELSOHN et al., 2000, p.40). Average life expectancy at birth was 63,0 years for males and 66,9 years for females in 1993 (CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION, 1994, p.20) According to MENDELSOHN et al. (2000, p.36), the number of population in Omusati in 2000 was expected to be 240.900. Compared with the numbers given in the 1991 census this would mean an increase in number of ~26.8% within 9-10 years. For the AOI in particular no exact population data is available. But, as it comprises large areas of the Okahao constituency, with a population of 29.100 people in 1998 (MENDELSOHN et al., 2000, p.45), a number between 10-15.000 inhabitants might be realistic. The southern part of the *Ruancana* constituency is also part of the AOI, but in this constituency, most of the population is concentrated in the northern parts, lying outside the AOI.

Average population-density in Omusati is 15,1 persons/ km², but in fact, the northern part of the region is more densely populated than the south, where the AOI is located. According to a map in MENDELSOHN et al. (2000, p.38 or 44), most of the AOI has a population of less than ten persons/ km², whereas the biggest portion of land has even less than one inhabitant/ km². Almost all the people are concentrated in Okahao and the growing outskirts, or in the scattered, small settlements and cattleposts throughout the AOI.

3.3.4 Present settlement dynamics

Steady population growth at a high level is not only observed in the Omusati region but all over Owambo. The increase in numbers of people also has effects on the settlement patterns. With increasing population, arable areas are getting rare. Despite the fact, that some families turn towards settlements with modern housing structures along the main roads or in towns like *Okahao*, *Oshakati* and *Ondangwa*, where they are engaged in non-agricultural business, the need for arable land is still high. Often even families that own houses in towns, still have a homestead with a field somewhere in the countryside (O. AMAMBOO, interview).
The shortage of suitable land results in four processes:

- Condensation of settlement in the northern and central parts of Owambo: Compared with old homesteads, the newly established ones are smaller. Usually the sizes of the fields of newly established households are also smaller.
- Establishment of settlements and villages in the southern and south-western parts of Owambo. Originally, these areas are reserved for communal grazing. This reservation makes perfect sense, in regard to the reduced and unreliable rainfalls, which put agriculture at risk. An example of a new village in such areas is *Onkani* in the south-western part of *Uuvudhiya* constituency/ Oshana district. According to O. AMAMBOO (interview), this village developed in the last third of the last century. Many people living in Onkani have no origin in this area, but descend from areas further north and north-east. Today the village is surrounded by large fields and people try to practice agriculture with varying success (O. AMAMBOO, interview; own observation and discussions with local farmers).
- "Illegal" land reservation/ occupation in the communal areas, by rich/ influential persons (see chapter 3.3.6.3)
- Increasing urbanisation: More and more people try also to settle in the larger towns and cities of Owambo. Especially young people try to find non-agricultural employment there. As not all people can afford proper housing, locations with simple zinc huts develop at the fringes of the towns (O. AMAMBOO, interview; L. SHIAPAKA, interview; own observations).

3.3.5 Governance

3.3.5.1 Government authorities

Like any other Namibian region, Omusati is administered by a governor, a number of councillors representing the different constituencies of the region, as well as a chief executive officer with administrative staff. The administration of Omusati is located in the regional capital of *Outapi*. Subordinate to the regional government are the local governments and authorities. They are responsible for the affairs of any larger town or municipality.[1] No

[1] Towns receive government funding, while municipalities are self-funding bodies.

larger town or municipality is situated within the AOI. The largest settlement within is Okahao, a community that has been declared a development area and should be developed into a town (in administrative terms) within the coming years.

3.3.5.2 Tribal authorities

Alongside government authorities, each of the Owambo tribes has its own tribal authority. These authorities have jurisdiction over their specific tribal area. The *Kwaluudhi*, *Kwanyama*, *Ndonga* and *Ngandjera* are each ruled by a king in conjunction with councils of senior headmen. The *Kolonkadhi*, *Kwambi*, *Mbalantu* and *Mbandja* are ruled by councils of senior headmen only. The position of the king is passed on within his *matrilineage*. The position of the headman is supposed be passed on in the same way, but due to cultural changes it is increasingly passed on within the *patrilineage*. The kings and/ or the councils of senior headmen are not legally in possession of the tribal land but are seen as trustees to appoint districts of the tribal land to senior headman. The senior headmen do not own the land but have a lifetime commodity. They divide their districts into several wards called *omikunda*, which are sold to headmen at the amount of about six cattle or an equivalent in cash. After the death of headmen the right of disposal falls back to the senior headman in charge.

In 1994 a survey has shown, that more than 2000 headmen were in charge in Owambo, each one having jurisdiction over an average of forty-eight households and four-hundred people. In reality however, sizes of districts and wards vary a lot and a ward may comprise only ten homesteads and their farmland.

The area of a homestead an the accompanying farmland can be rented for a lifetime from a headman at the amount of approximately two pieces of cattle or more, depending on the size of the fields. After the death of a head of family, the right of disposal and all buildings on the unit traditionally fall back to the headman. The successor of the head of family, though, has the right to rent everything anew, usually at the old price.

In case a complete field remains unprepared for more than a year, it can be expropriated by the headman and will be rented out anew.

Apart from the decisions on where people may farm and establish their homes, the tribal authorities administer all tribal affairs. They are responsible for the resolution of major conflicts and allocate grazing rights.

Today the tribal authorities loose more and more of their influence. There is an increasing number of wealthy and/ or politically influential people who tend to disregard the tribal authorities. These people also play role models for imitators. As a result, increasingly tribal conclusions are ignored, and land allocations (present and past ones) are questioned. In addition, there is increasing government control undermining tribal authority, too.

3.3.6 Land and land tenure

"Land is much more important than any other natural resource. People cannot grow crops, they cannot collect wood to build their homes and cook their food, and they will not have pastures on which their livestock can graze if they have no access to land. Over and above those tangible values, land also provides people with a sense of permanence, a feeling of security that comes with having rights over land." (MENDELSOHN et al., 2000, p.45)

The quotation gives an impression of the high values attached to land in a rural society. This and a growing population in need of space to live and farm, results in a strong demand for land all over Owambo. Even people that are already in possession of land want more, for it provides more options of income and more security. In addition to the high demand of land, issues of who owns, who controls and who uses the land often become very difficult in Namibia and especially in Owambo:

There is land in Namibia, which is owned and controlled by just one single person or body. This applies e.g. to National Parks like the *Etosha National Park*. The same is true for so-called *commercial farmland*.[1] In this case the farmer usually has the title of the land on which he farms.

On the other hand, there is land owned by one body, but controlled and used by one or many other persons. This applies for most of the so called *communal land*.[2] It is property of the government, supposedly controlled by regional governments and tribal authorities but used by individual farmers.

In the AOI, there is no ground under direct government control. Neither is there commercial farmland and almost all over rural Owambo people still remain unable to legally own land. However, there is land used by small scale farmers around the area of Okahao and the vast area to the south-west and west of Okahao, that is open for communal grazing. (see annex, map 6)

Adjacent to the AOI, there are three areas, which are reserved for special utilisation. In the south and in the north-west of the AOI there are plans to transform two large areas of communal grazing territory into a forest, respectively a forest and wildlife conservation area, which should be managed by local communities. In the south, it is the so-called *Ongandjera Forest*, in the north-west the *Uukwaluudhi Forest and Wildlife Conservancy*. Up until now these plans have not yet been realised, as tribal disputes between the *Ongandjera* and *Uukwaluudhi* (see SHIVUTE, 1998), as well as informally established, fenced off farms (MENDELSOHN et al., 2000, p.74) prevent the implementation of the projects so far. A third area, which is located at the southern/ south-western border of the AOI, is occupied by the *Omatambo-Maowe*-quarantine camp, which is maintained by the government.

3.3.6.1 Small-scale farms

The *small-scale farm* is the typical form of the agricultural production system all over rural Owambo. *"Almost all of the 85.000 rural households in Owambo are surrounded by small fields for farming."* (MENDELSOHN et al., 2000, p.49) Usually farming is a family affair. However, the farmer is not in legal possession of the land, as it is allocated to him by his headman. In most cases, the farmland surrounds the farmers homestead and is divided into two areas. One is reserved for cultivation, while the other part, the so-called *uuyanda*, is a separate area of

[1] Commercial farmland: The label commercial refers to the market orientated production systems of those farms.

[2] Communal land: The term communal describes and ownership system, in which the government is the legal owner of the land. Most of the production on communal land is used for domestic consumption. *"The most important assumption guiding state ownership of communal ground is the intention for those lands to be available as a safety-net for the poorest people, those who could not afford to buy land if a system of titled ownership was in place. It is also assumed that poorer people will have ready access to common-property resources…. however, those kinds of assumptions barley hold in the north-central region, where areas that remain truly communal in terms of common-property resources are dwindling very rapidly".* (MENDELSOHN et al., 2000, p.45)

pasture and/ or woodland. The size of farms can vary a lot because several factors determine the extension of small-scale farms:

The first determinant is the overall availability of land. Farms are smaller in densely populated areas, like the north-central of Owambo (see figure 3-21). There, the suitable farmland has been occupied for plenty of years. Consequently, recently established farms are forced into the small plots that are leftover or the families have to migrate to previously unoccupied areas.

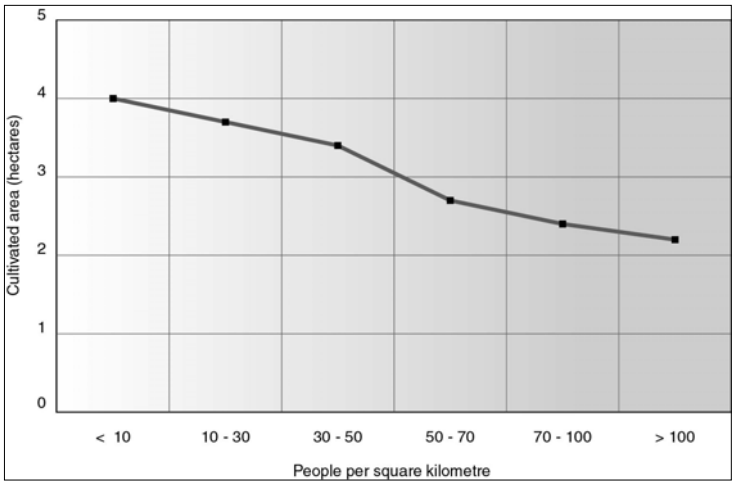


Figure 3-21:
Cultivated area in relation to population density (Source: DEA, 2002)

The second important determinant is wealth. Because the land is allocated by headmen, there is a relation between farm size and the amount of money/ number of cattle that is paid to the headman in order to receive a piece of land. In addition, poorer farmers can't afford to fence of large areas off land and may not be able to pay additional labour to cultivate all the land. Therefore, only the wealthy people can afford large estates.

Over the last decades, the area of land used for farming has increased all over Owambo. Figures by MENDELSOHN et al. (2000, p.50) show an increase of 3% between 1964-1970 and of 2% from 1970-1996 in the areas of *Tsandi* and *Okahao*, both part of the Omusati region. Data of the *Agricultural Survey* (table 3-3) give an additional impression of the expansion of farmland within the Omusati region :

Table 3-3: Development of cultivated area in the Omusati region (1996-1999, Source: CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION, 2001)

Omusati region	1996/ 97	1997/ 98	1998/ 99
Area (ha) planted by cropping season	74,286	77,039	80,577
Number of fields planted	21,886	22,34	23,351
Average size (ha) of fields	3,39	3,45	3,45

A comparison of aerial photographs from 1970 and 1996 done in context of this study, also gives clear evidence of an increasing number of homesteads and cleared farmland south-west and west of Okahao, as well as around some other settlements located in the AOI (see chapter 4.1).

The main reason for the increase of small-scale farming areas is the growing population. The number of new households in the Tsandi and Okahao area grew at a rate, correlating with the area of farmland newly occupied in

that region. This correlation is easily explained, as existing farms in Owambo are rarely divided and every new household/ family is supposed to establish a new farm.

Another reason for the growth of farmland not to be forgotten, is the wish for expansion by wealthy farmers, who already own a farm: *"…almost every farmer has a deep-seated desire to have more land, thus increasing his or her assets and options."* (MENDELSOHN et al., 2000, p.49).

3.3.6.2 Communal grazing areas

Apart from small-scale farms around Okahao, most of the research area is consists of land declared *communal grazing land* by the relevant tribal authority (see annex, map 6). It is considered to be under the direct control of traditional leaders. Yet, the decree of the tribal authorities has only formal character, because the land has always been used primarily for communal grazing and is property of the government.

Lack of rainfall and shortages of potable water in these areas make it difficult to settle on a permanent basis. Nevertheless, where water is available by traditional ways of gaining water (see chapter 3.2.5) or by modern boreholes[1] (see annex, map 7) some permanent settlements with farming activities, e.g. *Amarika*, could be established.

3.3.6.3 "Illegal" fencing

In the recent years the practice of so-called *"illegal fencing"* has become an issue all over Owambo.

As already mentioned, most of the land in Owambo is owned by the government, but allocated to the people by the traditional leaders. This is the traditional practice. At present, especially wealthy people, who can afford the fencing material, start to disregard the decisions of headmen and fence off much more land than they are entitled to. Normally these "illegal" areas comprise more than 10ha, sometimes reaching up to 100ha. Usually the people do not use all this land for farming. They just keep the land, maybe for their children[2] or they graze their animals there during times of drought when no more fodder is found on the communal pastures (O. AMAMBOO, interview).

Generally, this practice is called *"illegal fencing"*, because it breaks traditional laws. Despite this fact, there is no legislation in Namibia in place yet, to give that practice a really illegal status. *"Perhaps the only illegitimate aspect is that all these* [illegal] *farms infringe on the customary rights of people in communal areas, rights giving them and their cattle access to traditional grazing areas and water resources. These are water sources in natural pans and boreholes installed at government expenses, many of them drilled to provide water during the 1992/93 drought"* (MENDELSOHN et al., 2000, p.49).

According to a survey by the NNEP (D. DAVIES, interview), it is estimated that all over Owambo at least 7.900 km² have been fenced of that way. "Illegal" farms in the Omusati region make up only a relatively small portion of this number, due to the lack of water in most of the still unoccupied areas in the region. Nevertheless, the

[1] Many boreholes were installed by the government in reaction to the 1992/93 drought.

[2] Due to changes in social and settlement habits of the matrilinear Owambo society, recently the relations between children and their natural father become more and more important and strong.

statements of several interview-partners (O. AMAMBOO, D. DAVIES, M. KALUNDUKA) and own observations lead to the assumption that the process is progressing in Omusati, too: *"… new farms will in all likelihood be established once wealthy people have their own boreholes drilled"* (MENDELSOHN et al., 2000, p.49). However, while this study is in progress a communal land bill is being discussed in the Namibian parliament, hopefully to address the problem of illegal fencing amongst other aspects.

3.3.7 Socio-economy

In several publications the economy of the Owambo tribes is called a *subsistence economy*, classically not focused on maximum production and market sales, but to provide the needs of the family. This view is only partially correct. Fact is, that so far there has been no great commercial orientation within the agricultural system of the Owambo. There are several reasons for this situation, e.g. animal diseases, and an under-developed traffic infrastructure (partly an effect of the civil war) that makes it hard to reach markets, (see chapter 3.3.7.3.1). Another reason may be seen in the long period of civil war, hindering structural changes and the development of a commercial agricultural sector.

Nevertheless, it is wrong to call the Owambo society a pure subsistence society, for it has a diverse and vigorous economy with a long tradition of trade and migratory labour (MENDELSOHN et al., 2000, p.62; also see chapter 3.3.1)

Yet, it is true that almost every Owambo family is somehow engaged in some agricultural activity. In 1996, 53% of the people in Owambo aged 15 or older even stated that they depend mostly on farming activities and have no other source of income (MENDELSOHN et al., 2000, p.64). This should apply especially for the extremely rural Omusati region and shows the remaining importance of agriculture within Owambo.

3.3.7.1 The Farming system of the Owambo

The typical farming unit in Owambo is the small scale-farm. Nearly every rural household in Owambo is engaged in that kind of farming activity. Traditionally the fields of a household surround the homestead of the particular family. Only 6% of the farmers in Owambo own more than one field (MENDELSOHN et al., 2000, p.54). The average size of the fields in the Omusati region was 3,45 ha in 1998/ 99, but in reality the sizes of fields can vary a lot in Owambo.

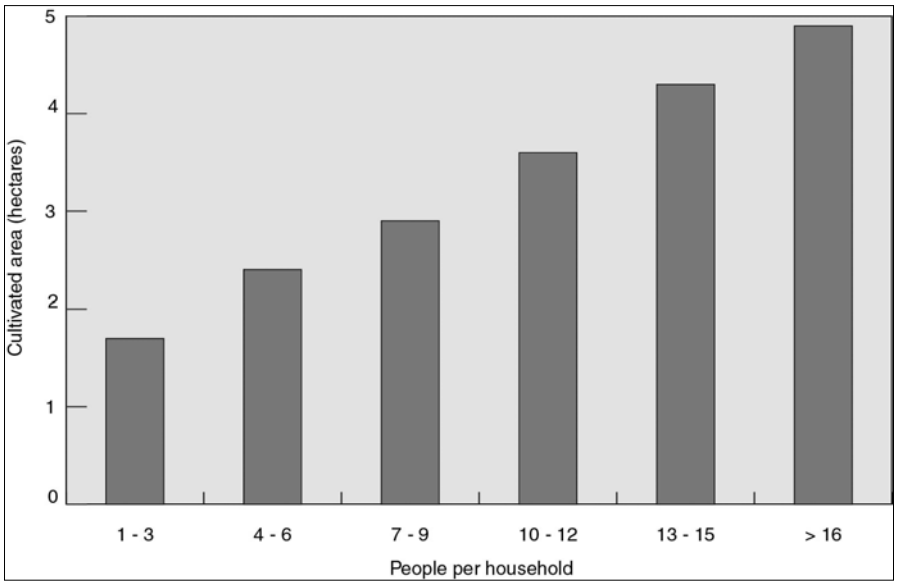


Figure 3-22: Relation between cultivated area and household size (Source: DEA, 2002)

The field has to be rented from the headmen (see chapter 3.3.5.2) and there has to be enough labour available to prepare the fields; therefore, it is the wealth and size of the family that determines the actual field size. Usually a large family is also regarded as rich, because normally at least one family member is engaged in some paid labour activities (other than agriculture), providing some money influx into the household (see chapter 3.3.7.3.2).
Figure 3-22 (MENDELSOHN et al., 2000, p.54) gives an impression of the relation between field and family size in Owambo.

Another influential factor on field size is population density: In highly populated areas, less space is available and the fields therefore are smaller (see figure 3-21).
As already mentioned, traditionally the ground around a homestead is divided into two parts. One is reserved for cultivation, while the other part, is a separate area of pasture and/ or woodland. In fact this separation has rarely been seen in the AOI during the fieldwork of this study. Apart from the area around Okahao, the fields at the AOI are often not even located around the homesteads. Sometimes homesteads also made way for village-like settlements, e.g. in *Amarika*. The fields at the AOI are often even quite large (up to 10 ha; own observation, confirmed by O. AMAAMBO, interview), compared to the rest of Owambo and sometimes they are fenced off with wire. This might be a sign that the area has been only turned into farmland during recent years. Observations of large new clearings within the Mopane bush in the southern parts of the AOI may also back up this assumption.

Farming in Owambo is very labour intensive and women contribute 62% of the labour input, while men contribute 33% and children younger than 15 years 5%. The high proportion of women has three main reasons:

- A high percentage of households (~38%) have no male head of household that could help with fieldwork.
- Many men often are engaged in off-farm employment and away during the farming season.
- Men are traditionally less involved in crop production but concentrate more on livestock husbandry and off-farm employment

Before the fields are ploughed, most of the farmers apply some kind of fertiliser. During the cropping season 1998/99, 77% of all farmers in Omusati were using manure or compost for fertilisation. About 11% had also used chemical fertilisers. However, chemical fertilisers are not very popular, as they are expensive and the effects are doubtful, because the mostly sandy soils have only a low capacity for fixation and the chemicals are drained rapidly. Another 12% of farmers did not use any fertiliser at all, mostly because they did not own any livestock to produce manure (CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION, 2001, p.13).
After fertilisation it takes approximately thirteen workdays for a single person to plough 1ha by hand with the traditional hoe. With the help of draught animals (oxen or donkey) it will take only four days, whereas a tractor needs only 2-3 hours. In 1998/99 about 71% of all families engaged in planting in Owambo were in possession of their own plough, but only 19% had their own oxen for draught (MALAN, 1998, p.10).

Tractors are slowly becoming more popular. They can be rented from private entrepreneurs for about 120 N$/ ha or from government agencies for approximately 40 N$/ ha. However, as the government service did not pay off well, most of the tractors were privatised during the last 2-3 years. Despite the high costs to rent a tractor, it seems that this is still cheaper than to rent draught animals (MENDELSOHN et al., 2000, p.52). All over Owambo only about 30% of all households can afford to rent a tractor (KEYLER, 1996, p.40), but this number will decrease most likely due to the rising costs through privatisation of the service (O. AMAMBOO, interview). Consequently most families still have to prepare their fields by hand and where labour is short, hired labour or labour exchange is common. According to KEYLER (1996, p.31) ~14% of households in Owambo have to practice labour exchange or hire labour.

After ploughing, it takes about eight days for a single person to plant one hectare. The seeds used for planting are traditionally selected from the farmers own production. During the growth season another twenty-seven workdays/ ha are required, because the fields have to be weeded 2-3 times until harvesting. When the crops turn ready for harvesting, they also have to be protected against clouds of the *"red-billed quela"* (*Quelea quelea*) bird. Because of these birds, most of the trees around and within the fields have been cleared, so the birds won't find space to rest and nest (O. AMAMBOO, interview). Harvesting usually occurs during May-July, and a single person needs about seven workdays to harvest 1 ha.

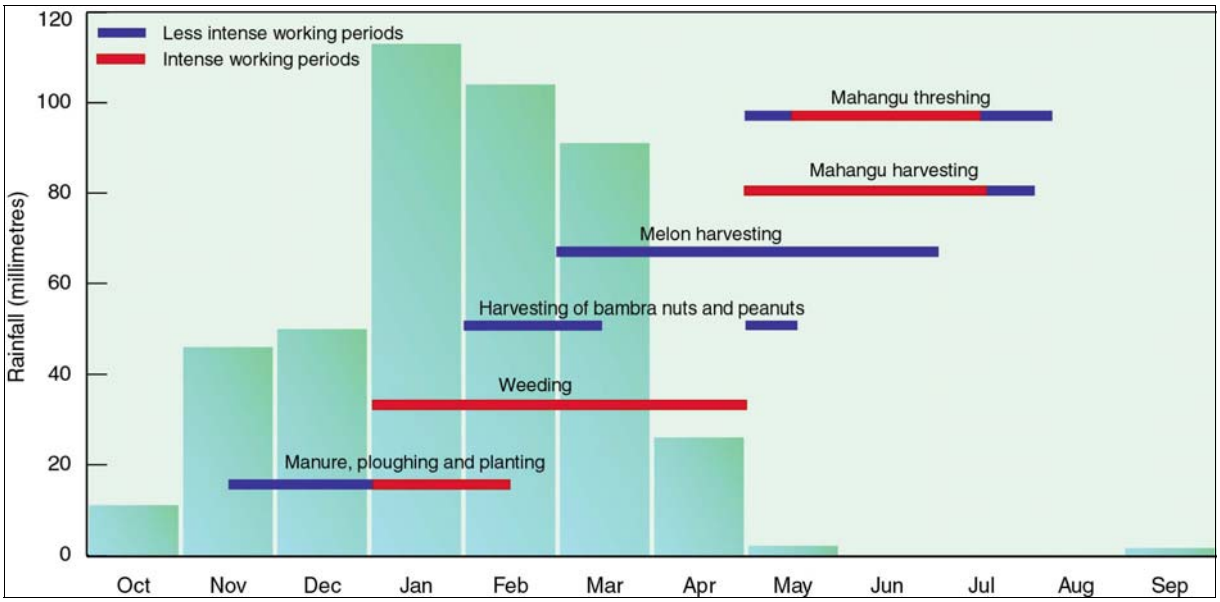


Figure 3-23: This figure gives an overview of the labour sequences in farming throughout the year. (Source: DEA, 2002)

A paper on the Namibian millet producing sector defines the start of the rainy season in Owambo like this: "[Ovamboland´s] *beginning of rain season is defined as the date after November 15th when rainfall is accumulated over three consecutive days to at least 20mm and when thereafter no dry spell of more than seven days occurs within the next thirty days"* (KEYLER, 1996, p.35). This definition though, sounds very theoretical and the beginning of the rainy season does not automatically mean the beginning of planting. In fact, *"January, February and March…are usually the only productive months with enough rain for crop and pasture growth."*

(MENDELSOHN et al., 2000, p.9). Talking to several farmers in central and western Owambo, the planting season *"usually can begin in January, with high rainfall over at least three days and then the rains must not fail for longer than seven days. Sometimes you also have to wait up to February or March, before you can start planting."* Seemingly it requires quite some experience in local weather phenomena, to find out about the best moment for planting. However, *"...still you never know. It begins with good rain, you plant and then - no more rain"* (Mr. SHIAPAKA – local farmer, interview).

To address the problem of erratic rainfall, the farmers in Owambo have developed their own strategy. Although some of them practice dry sowing, which means that the seed is placed before the beginning of the rains, most of them do not apply this technique. Usually, after some days of good, consecutive rainfall their experience tells farmers that the productive season might have started and they start sowing. However, usually they don't plant the whole field at once. As the rains in Owambo are highly variable, they plant gradually and over weeks, sometimes even months, depending on the climatic conditions. This strategy minimises the risk of a total loss of seed material in case of a sudden dry spell after the beginning of the first rains.

Fallow is not common in Owambo anymore, for there is not enough space left and people cannot afford to leave a plot uncultivated (O. AMAMBOO, interview; Mr. SHIAPAKA, interview). But, usually the patches that are used for the cultivation of different crop varieties are rotated from season to season within the field.

Yet, sometimes farmers are unable to cultivate the entire area they have planned to prepare. Reasons are a lack of family or paid labour, shortage of seeds, lack of draught power and sometimes also a lack of land (KEYLER, 1996, p.63).

Other problems farmers have to face in Owambo are crop pests, e.g. a fungus called *"pearl millet smut*". The fungus affects the head of the millet ears and cannot be removed once it is there. In addition, soil aspects are of further concern: The soils in Owambo, and especially in the AOI, have very low levels of nitrogen, phosphorus and potassium contents. On the other hand, cropping is intense and it is the general view of interviewed farmers that soil fertility is declining, although there is no scientific prove available yet (MENDELSOHN et al., 2000, p.52). Furthermore, most of the soils are extremely sandy and have a bad water retention and a rapid drainage. Often the soils are also saline or there are underlying layers of water logging clay or calcrete, whicht are hard to plough.

The most important crop species used for cultivation in Owambo are local breeds of pearl millet, called *"mahangu"*. Threshed *mahangu* can be stored for several years in the traditional woven containers called and therefore is the main staple food. After milling, the flour is used to prepare a stiff porridge called "*oshifima*", the basic food of the Owambo people. A survey amongst farmers has shown that of an assumed field size of 3 ha, usually 2,7 ha are planted with *mahangu* (MENDELSOHN et al., 2000, p.54). The remaining 0,3 ha are used to grow sorghum, the second most important crop all over Owambo. Sorghum is usually used to prepare non-alcoholic and slightly alcoholic beverages.

In addition to millet and sorghum 85% (acc. to MENDELSOHN et al., 2000, p.50) – 95% (acc. to KEYLER, 1996, p.29) of all households grow a varying mixture of beans, Bambarra groundnuts, peanuts, melons, pumpkins,

tomatoes and (rarely) cowpeas. These crops are cultivated planted on separate patches, or they are intercropped with the millet. Sorghum and millet are never intercropped.

3.3.7.1.1 Mahangu

Pearl millet (*Pennisetum glaucum*) is a very common crop in India, the Near East, the southern USA, and in the African savannah zones. The origin of this erect (6-15 feet in height), annual grass is unknown, but it is known to be cultivated in Africa and Asia since *"prehistoric times"* (MARTIN & LEONARD, 1967, p.526). The plant is protogynous, largely cross-pollinated and partly self-sterile.

Sandy loams suit the millet plants best, but they also grow on sands with bad water retention and poor nutrition. However, millet does respond well to heavy fertilization (see KEYLER, 1996, p.527).

In addition, the crop is adapted to high temperatures and is relatively drought tolerant, e.g. it "*takes roots again after a dry period"* (MENDELSOHN et al., 2000, p.51).

In Owamboland, millet is supposed to have been introduced by the early Owambo settlers. During the long period of cultivation it was continuously improved by selection and cross breeding. Today *mahangu* is the most important staple food of north-central Namibia. 80-90% percent of the calories that are produced in the region stem from pearl millet, and about 90% of the cultivated area is used to grow it.

Figure 3-24:
Mahangu field in north-central Namibia (Source: MARSH & SEELY, 1992)

The whole vegetation cycle from germination to ripening takes about five months. The average yield lies between 200-300kg/ ha, but it can vary from 100kg/ha up to 500-600Kg/ ha, depending on factors like farming techniques, soil quality and rainfall, which is the most determing factor. During the 1996/97 rainy season with comparably good rains about 30% of households in Owambo were able to produce enough *mahangu* to cater for their nutritional needs, while this number dropped to 16% during the 1997/98 period with lower rainfall (see MENDELSOHN et al., 2000, p.53). Analyses quoted in MENDELSOHN et al. (2000, p.53) and KEYLER (1996, p.2), proved a general decline in rainfall amounts since the beginning of the eighties, a trend that affects yields seriously. To encounter this development, improved millet varieties were introduced in Namibia by the end of the eighties in co-operation with ICRISAT. The best known is the *Okashana1*-variety, with a vegetation period of only three months and a higher yield expectancy. According to CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (2001), 14% of all farming households in Omusati were using improved millet varieties exclusively, while 36% still used traditional seeds and 50% applied a mixture of both in the season of 1999/2000. According to MALAN (1998), there are several reasons why improved millet varieties have not really asserted themselves: The yields of *Okashana1* outperform traditional ones only in short rainy seasons, when the local

varieties do not reach full maturity. During average and good rainy seasons it is the other way round, because traditional *mahangu* can make better use of the available water and nutrients due to its longer growth period. In addition, good soil nutrition is a general precondition for high yields of *Okashana1.*

Another reason why local varieties are preferred, is storage and surplus plant material. The common way to store *mahangu* in large woven baskets. There the kernels can be stored up to eight years. A single basket can contain more than a ton of kernels. The peel of kernels of improved millet is softer than the one from traditional varieties. Therefore, it can be cracked by its own weight during storage and then the kernels can be affected by beetles and other parasites. Traditional varieties also produce longer stems and more leaves than improved varieties. This material provides valuable fodder and building material and is less available from the improved millet. Other reasons why many farmers still rely on local varieties is because their flavour is preferred. Shortage of seeds from improved varieties is also a problem sometimes. Especially during seasons where the productive rains start late, the demand of seeds can be higher than the supply, because in those seasons farmers would prefer *Okashana1*, for the shorter vegetation cycle.

A problem for both, traditional and improved varieties, are crop diseases caused by bacteria and fungi (e.g. *Tylopospori*um *penicillariae*, known as *pearl millet smut*), rodents, insect epidemics (e.g. *Acantoplus speiseri* or *armoured cricket*), and birds (*Quelea quelea* or *red billed quella bird*), which can cause dramatic yield loss.

3.3.7.2 Livestock keeping

Livestock breeding is almost as important as farming in the Owambo culture. Besides cattle and goats also donkeys, pigs, and sometimes sheep and horses are kept. Despite the important role of livestock though, especially most of the cattle is owned by only a small portion of people: ~80% of all cattle in Owambo belongs to only ~20% of all households, while ~60% of the households do not own a single cow. Approximately 30% of the households don not even possess goats, because they cannot afford them. The large and rich families, who usually have an additional source of income through paid labour, own the highest numbers of livestock (MENDELSOHN et al., 2000, p.55 & 66).

Generally, cattle numbers are lower in densely populated areas, due to lack of pasture. Nevertheless, livestock numbers have continually increased over the past decades and there seems to be a correlation to population development. While in 1935 an estimated 135.000 pieces of cattle were kept in Owambo, it was about 580.000 in 1998. In addition, there was almost a fourfold in numbers of goats (1.1mio in 1998), donkeys (107.000 in 1998), sheep (37.000 in 1998) and pigs (81.000 in 1998) over the past thirty years. Only during times of pests and droughts, animal quantities have declined temporary. During the 1992/93 drought for example, approximately 25% of the cattle was lost.

Cattle numbers are particularly high in the Omusati region, respectively in the AOI. Table 3-4 gives an overview of the livestock increase in Omusati from 1996-1999.

Table 3-4: Development of livestock numbers in the Omusati region (1996-1999, Source: CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION 2001)

Omusati region	1996/97	1997/98	1998/99
Cattle	113,819	164,199	225,610
Goats	265,587	283,164	328,577
Donkeys	35,851	58,213	51,059
Sheep	16,753	21,315	23,172
Pigs	18,172	20,890	24,494
Poultry	179,636	228,278	222,376

J.S. MALAN calls the way the livestock [cattle, goats and sheep] is kept by the Owambo a system of "*semi-transhumanz*" (MALAN, 1998, p.32) with two major movements every year: By the end of summer (end of March – May) the animals move towards the highly populated areas with the permanent settlements. There they will find pasture, as the grass has grown during the rainy season and they can also feed on the *mahangu* stubble after harvesting. After these grazing areas are depleted by August – September, the herds move back to the traditional and freely accessible grazing areas with cattleposts in the east, south and west of Owambo (see figure 3-25).

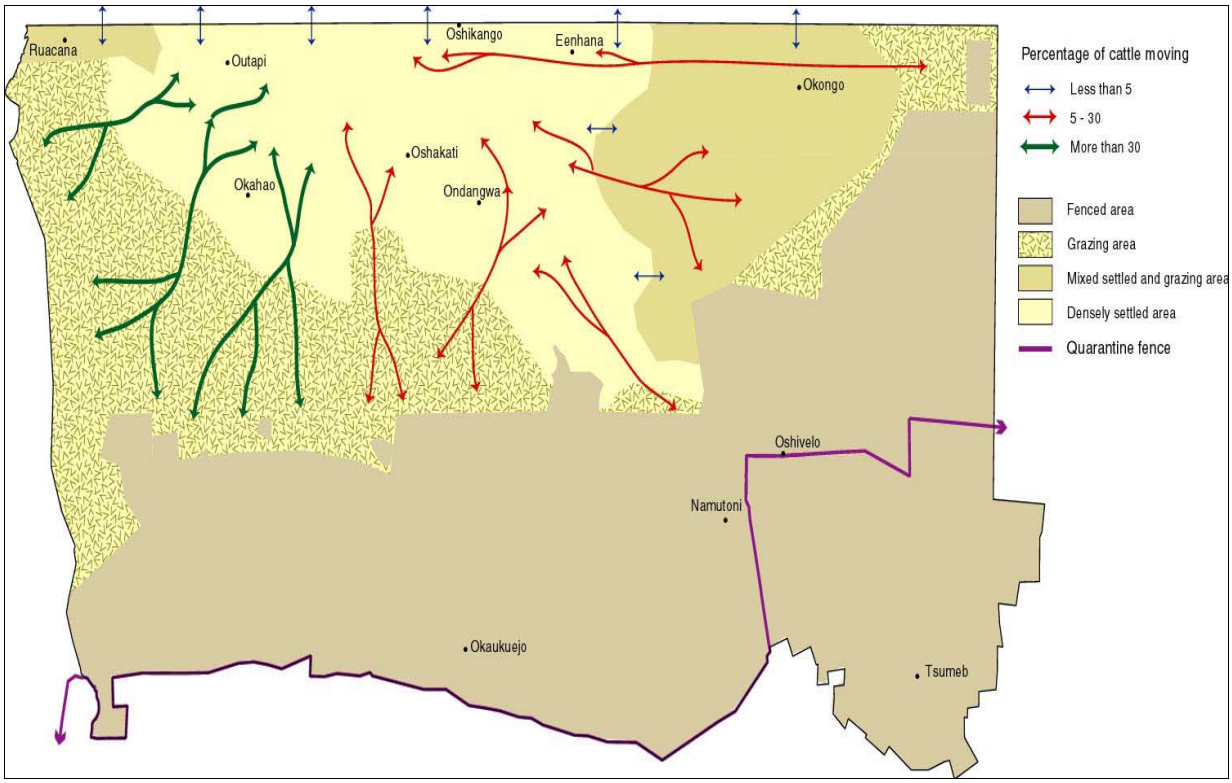


Figure 3-25: Seasonal cattle movements in north-central Namibia (Source: DEA, 2002)

Lactating animals, calves, as well as draught animals are hardly ever moved and are kept in the *kraal* by the homestead. In the old days, the movements occurred not only to exploit more grazing areas, but also to conserve

the sparse water supplies in the settled areas. Today, with a [relatively] good water supply by means of boreholes and pipelines, especially in the central and northern Owambo, the animals have to be moved only for grazing reasons. Usually the movements happen within the tribal boundaries, but distances are longer than in the old days, because unoccupied space is getting sparse (MENDELSOHN et al., 2000, p.57). A relatively new problem are the large herds of rich families. They do not find enough space for grazing in the populated areas anymore. As a result, they are kept in the communal grazing areas throughout the year. If pasture there gets sparse, the animals are often moved to illegally fenced areas, where fodder will still be available. This practice contains lot of conflict potential, because as these areas are no longer accessible to all, other families can not profit from that land, which often includes public boreholes, too.

Furthermore, livestock numbers in Owambo are a general problem. The centre of the AOI for example shows a density of >30 large stock units (LSU)[1/] km² during summer and between 20-30 LSU/ km² for the rest of the year, while a maximum of 10 LSU/ km² is recommended for the sustainable utilisation of occurring kind of vegetation (MENDELSOHN et al., 2000, p.59).

Despite the high stocking numbers, cattle is only rarely slaughtered, mostly only on special occasions, e.g. wedding ceremonies or funerals. It is also rarely sold (see chapter 3.3.7.3.1) and the main reasons of keeping high numbers of cattle have to be seen in status and the strategic value during times of drought.

3.3.7.3 Income structure

No detailed data on the income structure of the AOI in particular was available for this study. Nevertheless, publications on the Omusati district and on the whole Owambo can give an impression that should also apply for the situation of the AOI quite well. MENDELSOHN et al. (2000) mention, that the image of the Owambo society as an exclusively subsistence economy is generally wrong. In fact, the Owambo have a long tradition of trading, craftsmanship, and since the beginning of colonisation, also in migratory labour. Nevertheless, agriculture has always been and presently remains the fundament of the Owambo society, as well as a very important source to provide livelihoods. However, as the risk of drought and seasonality (and therefore of crop failures) is high in north-central Namibia, households also strive to find other sources of income in addition to agriculture. According to SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA (1995), the importance of this strategy was shown during the dry spell of the 1992/93 rainy season, where only food aid kept many poor rural families alive. Characteristically these “poor, rural families” were households that had no other source of income than agriculture.

3.3.7.3.1 Incomes generated by agricultural activities

According to CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1999) 23.032 households, with a population of 204.106 persons, had planted crops in Omusati during the 1998/99 season. 149.800 persons were engaged in these activities full or part time. 28% of the farming households reported, that they had no other source of income than agriculture.

[1] LSU in the Namibian context: 1LSU = 1 head of cattle or 8 goats

Looking at the whole Owambo, 50% of all households had no wage earner, and 53% of all people aged 15 or older depended mostly on farming and had no cash income through paid labour or business (figures from 1996, in MENDELSOHN et al., 2000, p.64).

The typical agricultural production unit in Owambo is still the small-scale farm. About 40% of the farming households can afford to keep cattle in varying numbers and 70% own goats in varying numbers/ household. The farming products are usually consumed by the family and are only rarely sold. Livestock is also rarely sold: only about 18% of the goats are slaughtered per year, mostly for own consumption. Concerning cattle, ~7% are slaughtered, 5,5% for own consumption and 1,5% for sale. At the bottom line only between 3-7% of the cash income in Owambo is generated by farming activities and livestock breeding.

According to MENDELSOHN et al. (2000) and other sources, the are several reasons for this fact:

- There is no real national market for *mahangu*. Millet that is (informally) traded, is often produced in Angola, where production costs are less.
- The marketing of fresh products such as tomatoes, melons and pumpkins is almost impossible due to the bad traffic infrastructure (O. AMAAMBO, interview; farmers at Onkani, interview).
- The cereal production is often inadequate, due to bad rainfalls and/ or cultivation conditions. Especially small farmers produce no or only little surplus. This surplus has to be stored for security reasons, in case the next harvest fails. Despite this strategic stock, nearly all farming households have to buy additional food every now and then.
- Most livestock owners consider their animals as a strategic resource in case of droughts and food shortages.
- Especially cattle are objects of prestige. They represent wealth and are rarely sold.
- The veterinary cordon fence *("red line"*) in the south of Owambo hinders the free formal trade of cattle. Yet, farmers can sell their cattle to MEATCO nowadays, but before any meat is allowed to pass the red line towards the markets in the south, the cattle has to stay at one of the three government controlled quarantine farms. The farmers have to bear the costs of transport to and from the quarantine farms, which makes sales to MEATCO unattractive to many farmers.
- In Owambo informally traded meat has to compete with cheaper meat from Angola. Approximately 70% of all meat that is traded at Owamboland´s most important informal meat market in *Outapi*, is coming from Angola.
- People find easier ways than farming and livestock breeding to generate cash income to support the household.

3.3.7.3.2 Other sources of income

It was mentioned that in 1998/99 28% of all households in Omusati had no other source of income than agriculture. This means, that 72% had other/ additional sources of income: According to CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1999), 45% of all households mentioned pensions as

source of revenue and 27% mentioned remittances, wages and business avails as sources of cash money. Unfortunately, it was not listed to which extent these revenues contribute to the household livelihoods.

A major source of income is migratory labour. Especially young men, and increasing numbers of women, seek jobs outside Owambo, e.g. as employees in the tertiary sector, the government administration, as mining and industrial workers, or on the commercial farms in the south.

Other ways to provide incomes are the growing informal sector, as well as trading/ retail business. *Cuca-shops* (see chapter 3.3.2) are found all over north-central Namibia and represent a very typical form of trading enterprises in Owambo.

Nevertheless, almost every Owambo household and almost every Owambo still seems to be somehow involved in agricultural activities. Be it the successful businessman, who is based in Windhoek most of the time, but still owns a farm somewhere in Owambo, or the innumerable migrant labourers, who return to Owambo during Christmas/ New Years holiday, to support the agricultural activities of their families.

3.3.8 Infrastructure

3.3.8.1 Physical infrastructure

„*The physical infrastructure* [of the Omusati region] *is generally poorly developed"* (FRIEDRICH-EBERT-STIFTUNG, 1997, p.186). This is especially true for the south-west of the region, where the AOI is located. The primary need in Omusati is definitely the provision of potable water, which is only available to 15% of the households. Many people in the region still depend on water from hand-dug wells. Very often, especially at the end of the dry season, this water is very saline and not potable anymore. There is a network of channels and water-pipelines in Owambo, and the north-eastern part of Omusati is linked to it. But as far as the AOI is concerned, most households still have to rely on traditional wells or, being a little better off, on deep boreholes with pumps (see annex, map 7) that reach potable groundwater. Apart from Okahao and the surroundings, the mentioned pipeline system does not reach into the AOI. During the field work for this study, when the rains of the 2001/02 rainy season had not yet started, one could meet members of the small communities within the AOI, who had to go as far as Okahao to collect potable water by means of pick-up trucks and water tanks.

The road network of Omusati is also relatively poorly developed. There exists only one asphalted road, linking Oshakati in the Oshana region with Okahao, including a short branch towards Onaanda. At present, this road is extended from Okahao towards Tsandi, to displace the existing gravel road. Another well maintained gravel road runs along the western border of the Omusati region, connecting Kamanjab with Ruancana. Within the AOI, only unmarked bush tracks exist. They are often difficult to pass, due to soft sand or during the rainy season. According to O. AMAMBOO (interview) the lack of easily passable roads is a great problem for farmers who want to sell fresh products, e.g. vegetables, at the larger settlements like Okahao, Tsandi or Oshakati. Railroads do not exist throughout the Omusati region.

Another great need in Omusati and the AOI is the development of extensive electricity and telecommunication networks. Only 1% of all households in the region have access to electricity for lightning and only 53% own a radio to receive basic information.

3.3.8.2 Institutional and touristic infrastructure

In Omusati, *"facilities such as schools, hospitals, clinics, police stations, postal services and magistrates´ offices are partly well developed and partly neglected"* (FRIEDRICH-EBERT-STIFTUNG, 1997, p.186). Concerning the AOI, the last is true. Only in Okahao the full range of facilities is available, including a small hotel, an agricultural development centre, a milling and seed selling service and a veterinary service. Another veterinary service is also available in the south of the AOI at *Uutsathima*. Secondary and combined schools in the AOI are also only available in and around Okahao, while in the rest of the area only primary schools are located. Nevertheless, the literacy rate is already at pleasant 78% in Omusati and ~85% of the population aged between 6-24 years were enrolled at school (CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION, 1994, p.8). The pupil/ teacher-ratio of the region is 36,2 (FRIEDRICH-EBERT-STIFTUNG, 1997, p.186).

High-grade health services are also only available in Okahao, while a few small clinics or only daily-occupied outreaches are scattered over the AOI (see annex, map 7). Because of the relatively poorly developed infrastructure in the AOI, diseases like malaria and diarrhoea are still a serious problem. HIV/ AIDS is generally a serious problem all over Owambo and the number of infected people still seems to increase.

Throughout the whole Omusati region, touristic infrastructure and recreation areas are non-existent, resulting in more or less no tourism in the region. An exception is the famous *Etosha National Park*, which comprises the southern parts of Omusati, Oshana and Oshikoto. Yet, at present the park is only accessible from the south and no official gates exist on its northern boundary so far, it has no commercial or touristic effects on Omusati. However, there is the proposal to establish the *Uukwaluudhi Forest and Wildlife Conservancy* just north-west of the AOI in the forthcoming years. It is also planned to open up a new gate at the northern border of the *Etosha National Park*. Maybe these projects will contribute to make Omusati and the whole Owambo more attractive to tourists.

4 RESULTS

4.1 FINDINGS OF AERIAL PHOTO INTERPRETATION (INCLUDING OBSERVATIONS DURING THE FIELD WORK)

In the analysis, pictures of September 1996 and September/ October 1970 flights that cover the central Oshana and the complete Omusati region, were used (see chapter 2.1.3.1).

The pictures were only analysed in a qualitative and non-quantitative way, but the condensation of settlement areas, especially around the o*shanas*, in the central Oshana region was obvious. The open space between single homesteads has dramatically declined from 1970 to 1996. It also seems, that the sizes of homesteads and the surrounding fields have become smaller. The size of areas with trees and shrubs also has been reduced significantly. Apart from the condensation in central Owambo, the settlement area is extending south-, south-east and westwards. Especially from *Okahao* and *Tsandi* (where the settlement structures also were condensed in 1996) new settlements reach towards the south-west. New settlements also have emerged along the *Etaka-channel*. The sizes of homesteads close to Okahao also seem to be reduced, compared with the ones that already existed in 1970.

Very remarkable is the increase of bush tracks in central and western Omusati. Especially the number of tracks caused by cattle has grown. Many of these tracks lead towards Okahao and end close to an area of numerous homesteads where all the natural vegetation, apart from some singular trees and palms, appears to have gone. Within the AOI the size of settlements already existing in 1970 (*Amarika*, *Okekolongo*, *Okashishi*, *Onamatanga*) has increased. Only in *Uutsathima* there was apparently no remarkable change, while Okashishi seems to have grown rapidly. This might be the result of a structure looking like a borehole, which is to be seen on the 1996 pictures, but not in 1970. in the period between the two flights also a settlement called *Ekolongo* has developed.

The decrease of natural vegetation is conspicuous in several areas, e.g. around Okashishi. Great clearings could also be observed in the south of the AOI. They do not exist on the 1996 pictures, but should be mentioned here, as they were observed during the fieldwork for this study.

Figure 4-1:
Clearing in the south of the AOI (Source: own photography, February 2002)

Large fields and fenced off areas have also become a striking feature of the AOI. In the 1970 pictures, only the typical fields close to the homesteads can be observed. In the 1996 pictures large, most probably fenced, wooded areas and large, rectangular fields have emerged. Their number is relatively small, but must have increased since 1996 because new areas with fencings were observed during the fieldwork in 2001.

Figure 4-2:
Large field close to the settlement of Amarika (Source: own photography, January 2002)

4.2 FINDINGS OF SOIL SURVEY

The general characterisation of the soils is given in chapter 3.2.4, while the following section will describe the soils more detailed in accordance to the prevailing vegetation units and on the background of the results of the soil survey.

The results of the analysis proved, that all the general characteristics of dry soils are reflected in the soils of the AOI (see chapter 3.2.4.1). Apart from that is the soil situation within the AOI quite inhomogeneous. Only at the level of vegetation units, the profiles within a unit are relatively homogeneous – a fact that supports the assumption, that soil and vegetation characteristics are very closely related in the AOI. Therefore, the subsequent sections will give a summary of the soil characteristics of each vegetation unit in the AOI. The detailed data of the findings are documented in annex 4-1 to 4-7.

4.2.1 Soils of the *Cuvelai palms and fruit trees on oshanas -vegetation* unit

In the area of the *Cuvelai palms and fruit trees on oshanas* -vegetation unit the soils of five profiles were described and analysed.

Typical for all of the profiles was their brownish-greyish to yellowish-greyish colour. One profile was an unstructured C-profile, while three of them were A/C-profiles, with a very small A-horizon of minor organic/ humic content. Another profile also showed a weakly developed/ initial cambic B-horizon. Apart from one silty soil, close to a small pan, the rest of the profiles had a texture of middle sand with a fine sandy component. The sands are quite deep and loose, so space for rooting was usually greater than 72cm. The bulk density (Bd) was very low to low all over. Only in one profile with a fragipan and in saline C-horizons of two profiles it was rated medium. The electric conductivity (EC) ranged from 0,46-83,12 mS/cm² at the five sample sites. In effect, two profiles showed high to very high salinity. In one case the full profile was affected, in another only the C2-horizon. PH-levels

ranged from 6,20-6,95 in non-saline profiles, while saline horizons showed levels of 7,25-7,85. Calcrete was not found at any site, but outcrops were seen on several occasions within the unit. Field capacity (FC; in mm, at pF >1,8) and plant available field capacity (aFc; in mm at pF between 1,8 and 4,2) were rated 19, respectively 14,5 all over. An exception was the silty profile with Fc 24 and aFc 17,5.

Two samples were analysed for plant available potassium (K_2O), plant available phosphorous (P_2O_5) and total nitrogen (N_t) contents. The K_2O concentrations were medium and P_2O_5-levels low. Average N_t and C contents were 0,018%, respectively 0,162%, resulting in an average C/N-ratio of 9.

For the detailed data of each soil profile see annex 4-2.

4.2.2 Soils of the *Mopane shrubs & low trees on loamy sands* -vegetation unit

In the zone of *Mopane shrubs & low trees on loamy sands* the soils of six profiles were studied.

The colours of the soils varied from reddish-brown to brown and rarely to greyish-brown. The profiles were a mixture of C-, A/C- and A/B/C-profiles (two each). The A- and B-horizons were only initially developed. One of the C-profiles showed a fragipan and calcrete nodules. At all other sites no encrustings or calcrete accumulations were observed. EC ranged from 0,81-1,25 mS/ cm², which means the soils showed only low salinity. PH-levels varied from 6,1 - 7,15, most of them were around 6,5. The textures consisted exclusively slightly silty sand, except one profile had middle sand with a fine sandy component at a depth >29cm. The fragipan had a medium Bd, in all other profiles Bd was rated very low to low. Soil depth usually was greater than 72cm. Fc/ aFc was rated 24/ 17,5 all over, except in the middle sandy profile with Fc/ aFc 19/ 14,5.

Three samples were analysed for K_2O, P_2O_5 and N_t contents. While P_2O_5 -levels were all low, K_2O concentrations ranged from low to medium to extremely high. There was no obvious reason for the extremely high concentration in that one profile, but the phenomenon was found at other profiles in the AOI, too.[1] Average N_t and C contents were 0,021%, respectively 0,202%, resulting in an average C/N-ratio of ~9,6.

For the detailed data of each soil profile see annex 4-3.

4.2.3 Soils of the *Mopane-Combretum savanna on sandy soils* -vegetation unit

In the *Mopane-Combretum savanna on sandy soils* the soils were studied at sixteen sites.

Apart from one profile with A/B/C-horizon structure, all others were A/C-profiles. Colours were reddish-brown mostly and sometimes brown to blackish-brown. The A- and B-horizons were all only weakly developed. In none of the profiles crusts could be found and calcrete nodules existed only in one profile. EC ranged from 0,51-3,58 mS/ cm². Eleven samples showed very low to low and five samples moderate salinity. PH-levels varied from 6,3 to 7,65, most of them were between 6,5-7,5. The soils at each site were deeper than 72cm and Bd was generally very low to low. Three soil samples had a texture of slightly silty sands; all others were fine sands with a component of middle-sized sand or vice versa. Fc and aFc were rated 19-24, respectively 14,5-17,5.

[1] McDONAGH and HILLYER (1999) mention a similar observation during a soil survey in more eastern regions of northern Namibia.

Six samples were tested for K_2O, P_2O_5 and N_t contents. P_2O_5 -levels all proved to be low, K_2O concentrations ranged from low (one sample) to medium (four samples) to extremely high (one sample). Average N_t and C contents were 0,025%, respectively 0,231%, resulting in an average C/N-ratio of ~9,2.
For the detailed data of each soil profile see annex 4-4.

4.2.4 Soils of the *Western sand plains* -vegetation unit

Eighteen soil profiles were described in the region of the *western sand plains*.
The soil colours were all reddish-brown to brown. In the south of the AOI the soils sometimes were yellowish-brown. Seventeen profiles were A/C-profiles and one was an A/B/C-profile. This profile also had a hard crust with a high to very high Bd at 70cm depth and calcrete accumulations were also found. Three of the other profiles also showed calcrete nodules, but the Bd was generally very low to low. The A- and B-horizons all were only weakly/ initially developed. The majority of soils had a texture of fine sand with a component of middle-sized sand or vice versa. A small portion also had a thin top-layer of coarse sand with a component of fine sand. Two samples had a texture of slightly silty sand. Apart from the encrusted A/B/C-profile, every profile was deeper than 72cm.

Figure 4-3:
Typical soil profile in the area of the *Western sand plains* – vegetation unit, exposed in the PUERCKHAUER-Bohrer (Source: own photography, February 2002)

All soils had a low conductivity, except for one with a very low conductivity. The range was from 0,71-1,92 mS/ cm². PH-levels varied from 6,2 to 7,95, most of them were between 6,5-7,5. Fc ranged from 19-35 (35 only in one top-layer of heavy silty sand), but at most sites it was 21. The aFc-values were between 14,5-26,5 (26,5 only in one top-layer of heavy silty sand), but mostly it was 17,5.
K_2O, P_2O_5 and N_t contents of seven samples were analysed. P_2O_5–levels were all low and so were two of the K_2O samples. The remaining five K_2O samples showed medium concentrations. Average N_t and C contents were 0,027%, respectively 0,193%, resulting in an average C/N-ratio of ~7,1.
For the detailed data of each soil profile see annex 4-5.

4.2.5 Soils of the *Western mopane-pan mosaic* -vegetation unit

In the area of the *Western mopane-pan mosaic* seven profiles were studied.

The soils were olive-blackish to blackish-brown in the upper parts, while all profiles became yellowish-grey to brownish-grey further down. All soils had A/C-profiles and showed calcrete accumulations. The A-horizons all were only weakly developed. Five profiles had weak to strong encrustings or cementations. Apart from one profile all were very saline in one or throughout all horizons. EC ranged from 2,29-25,93 mS/ cm² within A-horizons and from 20,15-27,80 mS/ cm² in C-, C1- or C2-horizons. PH-levels varied from 6,8 to 8,2. Most of them were situated between 7,0-7,5. Soil depth differed from 30cm to more than 72cm, but even in deep soils the salt accumulations may lead to shallow root development. The Bd was usually very low to low, rising to medium and high in encrusted horizons. Regarding the soil textures, they showed a mosaic of slightly silty sands, sandy silts, pure silts and loam with strong sand and clay fraction. Accordingly, Fc/ aFc also had a great variation: Fc ranged from 24-48,5, but mostly it was 39-39,5. The aFc-values varied from 17,5-28,5.

Three samples were analysed for nutrients. P_2O_5 –levels were all low, two samples had medium and one had very high K_2O-concentrations. Average N_t and C contents was 0,028%, respectively 0,3%, resulting in an average C/N-ratio of ~10,7.

For the detailed data of each soil profile see annex 4-6.

4.2.6 Soils of the *Mixed savanna on loamy to sandy soils* -vegetation unit

A real mixture are the soils of the *Mixed savanna on loamy to sandy soils*.

Seven profiles were described, four of them proved to be A/C-profiles, two A/B/C-profiles and one a C-profile. Colours were dark (blackish-brown, black) at the surface and turned to reddish-yellowish brown or grey deeper down in the profile. The A- and B-horizons all were only weakly developed. Five profiles had calcrete accumulations, four were more or less encrusted and two had a medium, respectively a high salinity. Considering all profiles, EC ranged from 0,17 mS/cm² - 11,36 mS/cm² and pH-levels from 6,70-9,04, but most of them were lying between 7,1-7,7. Space for rooting sometimes comprised more than 72cm, but in encrusted profiles it was reduced to 18-50cm. Great was also the variety of textures: fine sandy soils, lightly silty sands, medium silty sands, slightly sandy loams, silty loams and heavily sandy loams were found, while Bd ranged from very low to high. This resulted in Fc-values between 19,5 – 43,5 and aFc-values from 16,5–23.

K_2O, P_2O_5 and N_t contents of three samples were analysed. P_2O_5 –levels were all low and so was one of the K_2O samples. The two remaining K_2O-levels showed medium, respectively very high concentrations. Average N_t and C contents were 0,022%, respectively 0,244%, resulting in an average C/N-ratio of ~11,1.

For the detailed data of each soil profile see annex 4-7.

4.2.7 Mineralisation rates

An important factor for plant nutrition is the mineralisation of organic N, as plants only can absorb mineral N in form of ammonium or nitrate. Despite extensive literature reviews, no statements on N mineralisation rates in Namibian soils were found. The analyses that would be necessary to determine mineralisation rates at the AOI could also not be made in context of this study. Therefore, only very general statements can be made.
The good aeration of the sandy soils at the AOI, their almost neutral or slightly alkaline pH-levels, their C/N-ratios around 10, and the warm temperatures of the region should permit a fast mineralisation of organic N in the AOI. On the other hand will the dry conditions throughout most of the year limit microbiological activity and confine mineralisation almost completely to the rainy season. However, G. WARREN of the Department of Soil Science, University of Reading/ United Kingdom mentions that *"several reviewers have noticed that the proportion of soil total N that is mineralised in one season is remarkably constant. It is between 1% and 3% for most soils in the tropics and temperate regions, although there are some exceptions"* (e-mail correspondence, 16th of September 2002).

4.3 FINDINGS OF THE MODELLING PROCEDURE

The complete modelling results (= scenario A and B x ninety-eight planting dates distributed to twenty-nine seasons x four different soil units) regarding Tepary bean cultivation are documented in annex 4-8 to 4-15.
These results could be analysed in two different ways, *statistical* and *agro-ecological*. The purely statistical results only show the frequencies of the different calculated, relative yield classes (= agro-ecological types) throughout the modelling period. The agro-ecological analysis of the modelling results on the other hand tries to show the relations between the calculation results and planting dates, soil types as well as rainfall amount and temporal rainfall distribution throughout the vegetation period.

4.3.1 Results of the statistical analysis

In conducting the statistical analysis of the simulation results, only the best calculation result of each season was used, which means that the statistical data reflect the maximum possible relative yield of Tepary beans per season.
To give a basic overview on the complete results, the original agro-ecological types that were calculated by MARCROP, were re-classified into three new classes: favourable yield, marginal/ minimal yield and total crop failure.
These three classes comprise the following agro-ecological types:

- Favourable yield: Type 1 (optimum), type 2 (sub-optimum), type 3 (average)
- Marginal/ minimal yield: Type 4 and 5 (marginal), type 6a (minimal)
- Total crop failure: Type 6b-d (total crop failure)

Table 4-1 shows the percentage of occurrence of the three new classes during the twenty-nine simulated planting seasons in relation to the modelling scenario and the soil unit.

Table 4-1: Occurrence (%) of reclassified calculated yield classes from 1960/61 – 1988/89 in relation to soil unit and modelling scenario

Scenario:	**Scenario A**				**Scenario B**			
Soil unit:	***Unit I***	***Unit II***	***Unit III***	***Unit IV***	***Unit I***	***Unit II***	***Unit III***	***Unit IV***
Favourable yield	62,07	62,07	62,07	58,62	62,07	62,07	62,07	58,62
Marginal/ minimal yield	17,24	13,79	10,34	6,90	13,79	13,79	6,90	3,45
Total crop failure	20,69	24,14	27,59	34,48	24,14	24,14	31,03	37,93

Table 4-1 demonstrates, that in the area of soil unit I (= area the *Mopane-Combretum savanna on sandy soils*-, the *Western sand plains*- and the *Mixed savanna on loamy to sandy soils*- vegetation units) favourable yields can be expected in app. six out of ten seasons, no matter if the more humid scenario A or the drier scenario B is concerned. Regarding marginal/ minimal yields and total crop failures, the results differ between the two scenarios: In scenario B the risk of total crop failures is 3,45% higher than in scenario A.

The simulation results of soil unit II (= area of the *Mopane shrubs & low trees on loamy sands* vegetation unit) show no differences at all between scenario A and B. Favourable yields are expectable in app. six out of ten seasons, while total crop failures may occure during about two to three seasons out of ten.

In the area of soil unit III (= area of the *Western mopane-pan mosaic* vegetation unit) the chance of favourable yields in both scenarios is as high as in soil unit I and II. However, the risk of total crop failure in soil unit III, app. in three out of ten seasons, is higher than in the other two units.

The highest risk of total crop failures exists in soil unit IV (= area of the *Cuvelai palms & fruit-trees on loamy sand*-vegetation unit). Crop failures have to be expected in three to four out of ten seasons in both scenarios, while the chances of favourable yields are reduced in comparison to the calculation results of soil units I-III.

However, table 4-1 shows only the general trend, because of the re-classification of the MARCROP-output data.

All detailed outcomes of the statistical analysis, regarding scenario, soil type, planting season and calculated agro-ecological types are documented in the tables of annex 4-11and 4-12 There the frequency of each yield class is not only listed for the total modelling period (1960/61 – 1988/89) but also for each decade, as the modelling results varied a lot from decade to decade. In the wet seventies for example, favourable yields were at least twice as frequent than the were during the eighties.

4.3.2 Agro-ecological analysis of modelling results

As already stated in another part of this thesis (see chapter 2.4.1.1) rainfall and soil-water are the most influential factors concerning crop cultivation in arid and semi-arid regions. Regarding the issue of rainfall, two aspects are

of importance: Rainfall amount and temporal rainfall distribution throughout the vegetation period of the specific crop. Depending on the particular characteristic, every species needs a minimum amount of water to maintain its vitality and to complete the full vegetation cycle. Furthermore it is not only the total amount of rainfall that guarantees the success of a plant, but also the temporal distribution of the water supply, because the water demand varies within different phases of the vegetation cycle.

Especially if temporal distribution of water supply is concerned, another factor, apart from rainfall events, is of importance: The ability of soils to store water and provide it to plants during dry spells between two rainfall events.

The succeeding sections will try to analyse the modelling results of Tepary beans with respect to these factors, as they occure in the AOI. All statements were made by looking at certain significant seasons and their modelling results and therefore can only show a general trend. No absolute statements, e.g. on minimal water demand of Tepary beans, minimal number of rainfall events or the spatial limits of cultivation, can be made. Too many factors, like soil texture, amount of rainfall during a certain rainfall event, temporal sequence of rainy days and phase of crop development interact with each other and have effect on the final modelling result, respectively the actual yield of a crop.

4.3.2.1 Relations between soil and calculated relative yields

It does not matter whether one looks at the modelling results of scenario A or B (see annex 4-13 and 4-14), it is obvious that there is a clear effect of the soil types of the AOI on the expectable yields. For example, the typical soil water characteristics that are found in the area of soil unit I, resulted in 55,17% of the 29 calculated seasons in optimal yield for Tepary beans. For the soils of the soil unit II, the calculations resulted only in 48,28% in optimal yield. The soils of soil unit III had a result of 31,03% in the optimum yield class, while for soil unit IV optimum results were calculated in 37,93% of the seasons (all cited figures are related to scenario A; for scenario B the results are similar and the details are documented in annex 4-9, 4-12 , 4-13 and 4-14).

Soil unit I, II and III all show the same average values regarding plant available water, expressed by an aFc of 17mm. This means that theoretically the soils of these three units can provide the same amount of water to the plants. The value aFc = 17mm was applied to run the simulations of each of these three units. Therefore, it may be surprising, at first sight, that there are differences in the modelling results of some seasons between these three soil units. The issue of available soil-water becomes even stranger by recognizing that in some seasons the modelling results of soil unit IV are better than those of soil unit III. This is despite the fact that the soils of unit IV, with an aFc of 14mm, can provide less water to plants than the soils of unit III, with an aFc of 17mm. In addition, the soils of unit IV are more coarse than those of soil unit III.[1] This means, that the soils of unit IV drain better and faster and therefore may even fall dry earlier, than those of unit III. On the other hand it might be exactly the more coarse soil texture of unit IV, that caused the better modelling results of unit IV in some of the seasons.

[1] The comparably lower Fc and aFc are an expression of the more coarse soil texture in unit IV.

Within the modelling period this simulation results of unit IV were better than of unit III during four seasons: 1968/69 (scenario A and B), 1969/70 (scenario A), 1976/77 (scenario A and B) and 1983/84 (scenario A and B). By looking at the rainfall data of those seasons one can find, that the rainfall amounts vary a lot between the four seasons. They range from 307,0mm during 1976/77 to 177,7mm during 1983/84 and therefore, allow no conclusion regarding the phenomenon. What is conspicuous about the rainfalls during these four rainy seasons, is their relatively even distribution throughout the vegetation period of the Tepary bean. Rainfall events with only little (< 5mm) rainfall are quite frequent and long dry spells do not occure. Looking at the course of the hydrature-phases of Tepary beans[1] it becomes clear, that Tepary beans can make better use of the small rainfall events on the coarse soils of unit IV than on the finer soils of unit III. It seems plausible that the reason for this fact may lie in the different drainage qualities of the two soil units: Small rainfall amounts are endangered to evaporate on the soil surface, before roots can make good use of the water. The risk of evaporation is minimised, if the water can drain into the soil layers easily and quickly, where roots can absorb it.
Assuming this conclusion is right, it would explain why in years with a relatively good and even rainfall supply and with comparably frequent small rainfall events, the coarse soils of unit IV produce better modelling results than the soils of unit III. Furthermore, it would also explain, why the results of the soil units I-III differ, despite their identical aFc of 17mm: The assumption above implies, that plant water supply is not only depending on the water holding capacity of soil, but also the drainage quality of the soils. In fact, the soils of units I-III have different drainage qualities indeed, as it is reflected in their different Fc values. The soils of unit II e.g. have mean Fc of 24mm, while the soils of unit III have mean Fc of 28mm, which means that the soil of unit II have a better drainage - and in fact, the simulation results of unit II in total are better than those of unit III. In soil unit I the Fc (21mm) of the soils is even lower than in unit II and the modelling results are better than those of unit II.

As a conclusion of the analysis of the simulation results of the four soil units, the following can be stated:
Throughout every season within the simulation period the best results were achieved in soil unit I. This seems to be a consequence of the combination between drainage quality, reflected in an Fc-value of 21mm, and plant available soil-water, represented by an aFc-value of 17mm.
From a purely statistical point of view, the soils of unit II had the second best results, followed by soil unit IV on the third rank and unit III on the last. Anyway, in the units II-IV the results depend a lot on the rainfall amount and temporal distribution throughout the season. The soils of unit IV could bring good results during seasons with relatively small, but evenly distributed rainfall events. In years with more erratic rainfall better results are achieved in unit II and III.

4.3.2.2 Relations between calculated relative yields, rainfall amount and temporal rainfall distribution

The following considerations on rainfall amount and distribution were mainly made on the basis of the modelling results of scenario B. The reason for this decision is that scenario B seems more interesting, because compared to scenario A it represents the more extreme modelling scenario, regarding lower rainfall amounts and an

[1] The sequence of hydrature-values during the simulated vegetation periods can be checked in the MARCROP-output files.

increased evaporation. In addition the results of scenario B are identical with those of scenario A in most of the seasons and where there are differences, they are usually only gradual (see annex 4-10). Regardless, seasons in which the results of scenario A and B differ from each other are also considered in the following section.

Concerning rainfall amount, the simulation results of the season 1969/70 at the planting date of 4th of February are quite interesting. In this case optimum yield was calculated for soil unit I in Scenario B with the lowest amount of water available during the simulation period from 1960/61 – 1988/89: 155,6mm. This amount was distributed to 17 days with rainfall. Noteworthy in this case is also, that during the late flowering phase from day 40-55 no more rain was falling. The last rains only fell from day 32-38 of the vegetation cycle, with a total amount of 36,6mm.
For the soil units II-IV the calculation of scenario B resulted in average yield. Here, the comparison with the results from scenario A is mentionable. Concerning the results for soil unit I-III, they were identical with those of scenario B, but for soil unit IV, optimum yield was calculated in scenario A. This difference to scenario B must be caused by the higher rainfall amounts and lower evaporation rates that are used to calculate scenario A. Looking at the output files of MARCROP it becomes obvious, that this difference in rain amount and evaporation only becomes effective during the days 15-38 of the vegetation cycle and that it is only 4,1mm of available water that caused the difference between optimum and average yield.
The season 1981/82, with the planting date at 12th of February is a good example for conditions that resulted in a calculation of sub-optimum yield in the soil units I-III, in both scenarios. Looking at scenario B, 137,1mm of rainfall were available until day 37 of the vegetation cycle. The rainfall was distributed to a total of nine days, which were distributed quite evenly. The end of rainfall at day 38 caused a step-by-step decrease in hydrature conditions from class 1 to 3-4, reached on day 51, which is responsible for the sub-optimum yield. Regarding soil unit IV, the result was only average yield, because due to the comparably limited water storage capacity of these soils, hydrature phase 4 was already reached on day 50.
Representative of conditions that lead to marginal yield is the season of 1980/81. These results were achieved in both scenarios, in the soil units I-III. The planting date was set to 5th of March. Throughout the vegetation cycle 99,5mm of rain were available, but distributed to six days only. The rains occurred on day 1 (18,1mm), day 17 (19,6mm), day 18 (17,7mm), day 23 (28,5mm), day 24 (4,4mm) and on day 36 (11,2mm). After day 36 the rainfalls had stopped, before the plants could even reach the late flowering and fruit building phase. As a consequence of the end of rainfalls, the hydrature values dropped to class 4 on day 45, right in the middle of the yield-sensitive late flowering phase. But even before day 36, hydrature had repeatedly dropped to 3 and 4 in other phases of the plant development, due to the erratic rainfalls and the long sequences without rain. In soil unit IV it became obvious again, that these soils are not very suitable during years with long dry spells. The modelling result was a total crop failure, because during the long dry spell at the beginning and at the end of the vegetation cycle the hydrature values of the plants fell to class 5, as soil water supply was exhausted too early.
A good example that Tepary beans can cope with only few days of rainfall under certain conditions is the season of 1960/61. The planting date of the simulation was set to 3rd of March and 184,7mm (scenario B) of rain were distributed to only eight days within the vegetation cycle. The rain fell on day 1 (42,2mm) day 2 (2,0mm), day 5

(23,6mm), day 9 (1,5mm), day 14 (9,3mm), day 27 (2,9mm), day 29 (14,7mm) and last on day 33 (85,4mm). With this amount and distribution of rainfall the modelling resulted still in optimum yield for the soil units I and II. The results of unit III and IV were only average yield. The soil conditions of unit IV could not provide water long enough after the rains had stopped past day 33, while the soils of unit III could not trans-locate the water of the smaller rainfall events, as fast as the soils of the other units.

An impressing result is the one of season 1972/73, when planting date was laid on 2nd of March. 249,2mm (scenario B) of rain were well distributed over 18 days with rainfall, but from day 36 on, close to the end of the early flowering phase and 20 days before the end of the vegetation cycle the rains had failed. With few daily exceptions of value 1-2, the calculated hydrature conditions were class 1 throughout all soil units in both scenarios until day 35. After day 35, with a last rainfall of 12,3mm Tepary could still remain a hydrature of 1 for a while, until it finally dropped to 2 (soil unit I and II), respectively 2-3 (soil unit III and IV). Despite the long dry spell of twenty days at the end of the vegetation cycle Tepary was still able to achieve the optimum yield class. A similar season was 1966/67, with the planting day set to 6th February. During this cycle a dry spell of 9 days occurred at the end of the vegetative phase and another one of 12 days at the beginning of the late flowering phase, but the calculated yields still reached the optimum.

The season of 1967/68 illustrates to what extent differences in rainfall amount and evaporation between scenario A and B can play a role. With the planting date laid on 1st of March, optimum yield was calculated for the soil units I-III in scenario A. The results of the corresponding soil units in scenario B were one class lower than those of scenario A. Until day 45/46 of the vegetation cycle, the MARCROP-output data show no difference in the sequence of hydrature values between scenario A and B. Then the hydrature values in scenario B dropped from 2-3 to 3, just one day before the same happened in scenario A. The only difference between the scenarios is the amount of rain with which they are calculated. Evaporation has no influence in this case, because for March the evaporation values that are used in the simulation are identical.[1] The last rainfall in this particular simulation example occurred on day 37 of the vegetation cycle. The hydrature values of both scenarios only start to differ 8 days after the last rainfall, which means that the reason for the difference has to be found in the amount of that last rainfall event.[2] The rainfall amount of day 37 in scenario A was 3,7mm, in scenario B 3,6mm. It seems that it was this 0,1mm difference, that has caused the different calculation results between the two scenarios.

Regarding conditions that result in a total crop failure, the simulation results show a quite clear picture: In most of the simulated seasons with a total crop failure, the failure was caused by a unfavourable temporal rainfall distribution during the vegetation cycle and not by low total rainfall amounts. One of the most illustrative examples in this regard is the season of 1987/88, with the planting date laid on 10th of January. 422,1mm (scenario B) of rain, distributed to nine days were available during the vegetation cycle, but most of the rainfall events occurred during the initial growth phase between day 1 to 7. Afterwards the rains failed completely. Another example is the

[1] The evaporation values are derived from the interpolation, which is described in chapter 2.3.2.2. In case of March the evaporation values of scenario A and B are identical, because the results of the interpolation had to be rounded to one decimal place for the MARCROP application.

[2] The second last rainfall event occurred 8 days before the very last rainfall on day 37 and brought only about 15mm. It should have had no influence on the difference of the calculation results.)

season 1963/64, planting date 4th of January. 122,4mm (scenario B) of rain, distributed to 11 days were available during the vegetation cycle. During the phases of initial growth (day 1-7) and late flowering (day 40-54) enough rain was available, but during the phases in between the rains had failed almost completely.
The complete, best seasonal calculation results of scenario A and B and the related rainfall patterns are documented in annex 4-15.

4.3.2.3 Relative Yield in relation to planting date

Closely related to the temporal rainfall distribution is the choice of the planting date. The right choice depends a lot on the experience of the farmers and finally, it seems that a portion of luck is needed, too. This fact becomes clear by looking at the modelling results of the 1973/74 and the 1978/79 season: In the first case the simulation with the planting date laid on 6th of February 1974 resulted in optimum yield throughout all soil units and scenarios. Starting the simulation only four days later, all results showed a total crop failure.
In the second example the situation is similar. Starting the simulation with the planting date 12th of January 1979, the modelling results in optimum yield throughout all soil units and scenarios (except soil unit IV, scenario B). Starting the simulation only two days later all results were only average yield.
As a consequence, statements on the best time for planting Tepary beans are very difficult and characterise the real situation only very basic.
Looking at all simulation results of the modelling period in relation to the planting dates, the dates that proved to show the best result per season, vary a lot from season to season. For example, in the season of 1966/67 the best result was achieved with the planting date 7th of March 1967, while in the 1974/75 season 4th of January 1975 showed the best seasonal result.

Table 4-2: Temporal distribution (%) of planting dates with best seasonal modelling results (1960/61 – 1988/89)

Month	*Jan*			*Feb*			*Mar*		
Decade	***1***	***2***	***3***	***1***	***2***	***3***	***1***	***2***	***3***
Percentage of planting dates with best seasonal modelling result	9,68	19,35	22,58	12,90	9,68	6,45	19,35	0,00	0,00

In general, the best seasonal simulation results throughout the simulation period from 1960/61 – 1988/89 were always achieved within a time frame comprising the period from the first decade of January to the first decade of March. Table 4-2 shows the temporal distribution of planting dates with best seasonal modelling results during the rainy seasons from 1960/61 – 1988/89. According to this table, the chances to choose a favourable planting date for Tepary beans are highest during the second and third decade of January and during the first decade of March. For the documentation of all planting dates that were applied for the modelling see annex 2-5.

4.3.2.4 Yield and climatic phenomena

Climatic phenomena are worldwide in focus, especially if agricultural yields are concerned. Especially *El Niño* is often held responsible for dry climatic conditions that result in total crop failures in southern Africa. As far as the calculated Tepary yields at the AOI are concerned, no definite statement is possible. During four of the eight *El Niño* events within the modelling period optimum to sub-optimum yields were calculated, while during the other four events the results were total crop failures. The results during the three *La Niña* events were, depending on the soil unit, optimum during one season, average to marginal during another season and marginal to a total crop failure during the last season.

In fact, these inhomogeneous results are not very surprising, because as shown in chapter 3.2.2.3.5, there is no clear relation between *El Niño, La Niña* and rainfall amounts and number of rainy days at the AOI (see annex 3-1). An exception may be seasons with *La Niñal Benguela El Niño* or *Benguela El Niño* events. During all three seasons with such events, the results of each scenario and soil unit were optimum yield.

5 DISCUSSION

The thesis at hand had two major goals: The first was to introduce a model based method to evaluate crop cultivation potentials into the Namibian context. The intention was to explain the method to any interested persons, e.g. students, agricultural experts or decision makers. They should easily understand the method and maybe decide to apply it themselves. Therefore it was tried to describe the method as detailed and graphic as necessary, but also as short and simple as possible. Whether this goal was accomplished or not, remains the decision of the interested reader.

The second goal was to apply the method to an example area and to produce reliable results for that given area. As far as this goal is concerned, several aspects have to be mentioned, regarding the accuracy and meaningfulness of the whole procedure and the results:

The process to reduce a real system to a model by using a selection of some important factors that characterise the system will always afford a certain grade of simplification and generalisation regarding the input data. Therefore, the more precise the pool of the input data is, the less negative influence have such generalisations and the more accurate are the model and the results of a simulation.

The input data that were required to run the MARCROP model were specific plant, soil and climatic parameters. The plant data were obtained through long-term experiments, that have been conducted at the Department of Cultural and Regional Geography at the University of Trier/ Germany. These data can be considered as precise.

The necessary soil data were raised on-site in Namibia and, as far as necessary, processed at the soils laboratory of the University of Trier. It was an attempt to describe as many soil profiles as possible at the AOI in the time that was available for this study. Most important was the determination of certain characteristic soil areas of the AOI, as well as the analysis of the water holding capacity (represented by field capacity Fc) and the plant available water (represented by available field capacity nFc) of the characteristic soils at the AOI. To define the soil areas, already existing information of MENDELSOHN et al. (2000) could be used. These information was completed by personal observations on site. The results of the soil survey and soil sample analysis proved, that the method to work on the background vegetation types was quite right.

For the assessment of Fc and aFc values, as well as other factors, e.g. salinity and nutrient levels, internationally approved methods were used. As the MARCROP-calculation was done with only one defined Fc and one aFc value per soil unit, only the most representative value per soil units could enter the simulation. This means that the modelling results will not match exactly with the real local soil situation at every site within AOI.

Regarding climate data, the only available rainfall and evaporation data were those collected by the Namibian Weather Office and its associated partners. Unfortunately, these data were quite limited, so the simulation could only be done for a period from 1960/61–1988/89. Another problem was that only the climate station of Ongandjera/ Okahao was located within the AOI. In addition, this station was also located only at the fringe of the AOI and did not record evaporation. In consequence it was decided to use the rainfall data of this station in combination with data from other stations, namely Otjovasandu and Ermo, to describe the rainfall situation throughout the AOI in a more detailed manner. To describe evaporation, the data of Mahenene and Okaukejo

had to be used. To do the more detailed spatial analysis of the rainfall amounts and evaporation rates throughout the AOI only a simple interpolation (see chapter 2.3.2.2 and 2.3.2.3) could be used. Other helpful geo-mathematical methods, like e.g. *Kriging*, *Cubic Splining* or *Thiessen Polygones*, that may produce more sophisticated results under certain circumstances could unfortunately not be applied. These methods would have needed a more dense network of climate stations to provide reasonable results. However, a comparison of the interpolation results with rainfall maps in MENDELSOHN et al. (2000) and an evaporation map of Namibia (MAWRD, 1985) proved that the interpolation results match quite well with the data of those two sources.[1] The interpolation results of course never reflect the absolute situation at the AOI and therefore are a factor of inaccuracy in the model, too. On the other hand the results do reflect the general situation an therefore their application seems justifiable.

Another factor regarding the accuracy of the modelling results is the number of scenarios that are used to describe the climatic situation throughout the AOI. The more scenarios applied, the more precise and detailed are the findings and statements. The decision to use two scenarios in the context of this thesis was made not at least on the background of the limited time frame of this study. The amount of data that additional scenarios would have produced would not have been manageable in the available time. Anyway, now that all necessary input-data for the model are available, more scenarios can be calculated by any interested person, institution or organisation. It is questionable though, if calculations with new scenarios for the AOI would make any sense: All scenarios will only differ in the rainfall amounts that are used for the calculations. The results of scenario A and B of this study show quite clearly though, that in the case of central and western Omusati it is predominately the temporal distribution of the rainfalls and not so much their total amount that decides on the yields. Yet, as far as data of the temporal rainfall distribution at the AOI exist, they have already been applied: in scenario A and B of this study.

As far as the MARCROP software and the calculation parameters are concerned, the following should be considered: MARCROP was especially programmed for crop simulations in dry arid and semi-arid areas and the development of the software was supported by field experiments in Kenya, where the model was also calibrated and validated. Nevertheless, is MARCROP designed in a way that it can generally be applied in any region dry arid and semi-arid area. During several studies in eastern Africa MARCROP has proved its potential for regional transfer. As far as this study is concerned, it can be mentioned that the environmental circumstances in the area where MARCROP was calibrated and validated are similar to those of the study area of this thesis: MARCROP was validated in a natural environment with sandy to sandy-clayey, reddish brown soils of 10-20mm field capacity and mean a rainfall amount of 500-600mm during a rainy season of 2-3months.

[1] It has to be mentioned, that the interpolation technique was only applicable, due to the extremely flat and uniform landscape of Owambo. In a more varied, mountainous area the method would have been inadequate.

Nonetheless, for any serious future application in Namibia or in case the findings of this study make their way in any planning or decision process, it would be desirable and is recommendable, to crosscheck MARCROP simulation results with a series of local planting trials.

Assuming that the modelling results and findings of this study are meaningful, several conclusions can be drawn:
It was already known that Tepary beans are, compared to other crops, extremely drought resistant. It was also known, that the success of rain-fed agriculture in arid and semi-arid regions depends a lot on the temporal rainfall distribution and the capacity of soils to store and provide the water to the plants. All these facts are clearly reflected in the results of this study:
It is quite impressive that under the natural circumstances at the AOI Tepary beans can produce optimum yield with only 155,9mm and respectively with only eight days of rainfall, provided that the rainfall amount and the days with precipitation are evenly distributed. It is also remarkable that under certain conditions even a dry spell of 20 days allows the production of an optimum yield (see chapter 4.3.2.2).
Apart from rainfall distribution the soils are an important factor for such cultivation results. The results of the study clearly show that the best conditions for successful crop cultivation at the AOI are provided by the soils that are found in the area of the *Mopane-Combretum savanna on sandy soils,* the *Western sand plains,* the *Mixed savanna on loamy to sandy soils*[1] and in the area of the *Mopane shrubs & low trees on loamy sands*. The soil conditions in the area of the *Western mopane-pan mosaic* and the *Cuvelai palms & fruit-trees on loamy sands* are less favourable.
As far as rainfall at the AOI is concerned, the statistical analysis (see chapter 4.3.1) has shown that rainfall conditions would have permitted favourable Tepary yields in 61,2% / 61,2% (north-eastern part of the AOI = scenario A / central to south-western part of the AOI = scenario B) of the seasons within the simulation period. During 12,1% / 9,48% of the seasons only marginal yield was possible and in 26,7% / 29,3% of the seasons the climatic conditions resulted in a total crop failure.[2] In other words: The climatic conditions at the AOI make a marginal yield or total crop failure of Tepary beans statistically probable in app. four out of ten years.
How to deal with this fact?
Several options are conceivable and it is not the task of the study at hand to provide a solution. Nonetheless, three possible options should briefly be summarised:

<u>1st option:</u> The risk to have crop failures and marginal yields with Tepary beans is appraised as too high and agriculture at the AOI should concentrate on the cultivation of other drought resistant crops. This would be a legitimate decision. Still, it will be hard to find any other crop that is as drought tolerant as Tepary beans are. The drought tolerant Bambarra groundnuts for example are already widely cultivated throughout Owamboland. A simulation of Bambarra groundnut cultivation potentials in the soil units I and IV at the AOI with MARCROP has

[1] It has to be mentioned that successful crop cultivation in the area of the *Mixed savanna on loamy to sandy soils* most probably will be impaired by the high salinity of the soils in that area.

[2] The figures represent the rounded mean of the four soil units/ per scenario.

shown, that Tepary beans have out-performed (regarding relative yield) Bambarra groundnuts in each of the simulated seasons (an overview on the results of this simulation is documented in annex 5-1).
Interesting in the context of alternative crops would be the performance of very drought tolerant millet varieties, such as the *Okashana* breeds, because millet is the main staple food in Owambo. Unfortunately, the eco-physiological data, especially concerning hydrature, of Okashana are not yet available in the format that is required to do a simulation with MARCROP. A simulation of Okashana varieties with MARCROP would be an interesting and useful task in the future.

2nd option: The risk of marginal yields and crop failures of Tepary beans is confirmed, but Tepary is cultivated nevertheless, because the risk of crop failures with other crops would be even higher. It is quite unlikely, that Tepary beans will ever become the most important crop for small scale farmers at the AOI, because millet is still the most favoured staple food in the area and plays an important role in the culture of the Owambo people. Nevertheless, Tepary beans could be cultivated alongside the traditional crops. They generally have a positive effect on soil fertility and might play an important role in additional food supply, during season where other crops perform badly or fail. Extremely bad seasons, where all crops fail, would have to be compensated by government aid of course and/ or by the traditional Owambo strategy of diversified income sources.

3rd option: The risk of marginal yields and crop failures of Tepary bean cultivation at the AOI is appraised as too high and the modelling results are rated as signal that rain-fed agriculture is generally too risky at the AOI.[1] Logically, this would mean, that agricultural activities should not further expand into the AOI and the area should remain what is was for hundreds of years - a savanna that traditionally provides pasture and wood. Of course, this option would have far-reaching consequences, because the present trend is to start more and more agricultural activities within the AOI and this trend will have to be stopped by local and/ or government authorities. Such action again cannot be taken without providing alternatives to the affected people.

[1] According to B. HORNETZ Tepary beans may be indeed a useful indicator concerning the spatial limitations of rain-fed agriculture in semi-arid and arid regions (conversation 12th of November 2002).

6 SUMMARY

In Namibia an ever growing population is looking for jobs to earn a living, but the potentials to create formal employment opportunities are relatively limited, because of the "*smallness and weakness of the Namibian economy"* (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995, p.74). In urban areas, unemployment is already high and the advancing rural-urban migration *"is merely to increase the incidence of poverty in the low-income suburbs and peri-urban informal settlements"* (SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995, p.26). The rural-urban migration is often accelerated by droughts like in 1992/93, when drought-prone farmers searched for jobs and steady income in towns.

Of course, development of the secondary and tertiary sector in Namibia is necessary to support the growing population. But several publications (e.g. SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA, 1995; NATIONAL PLANNING COMISSION, 2000; SPRINGER, 2002) also emphasise justifiably, that agriculture should and will retain its importance within the Namibian economy, because other development options are limited. Many experts involved in development and economic politics of Namibia agree that, apart from the meat exporting commercial farming sector, Namibia will never get in the position to be a large-scale producer of farming products or to export significant amounts of agricultural, especially food, products. Indeed, modern Namibia is highly dependent on food imports, mainly coming from South Africa and other countries in the region. Most probably Namibia will never reach the level of self-supply concerning food, due to it's environmental limitations. Nevertheless it is a fact, that small scale farming still is an important source of livelihoods at present, especially in north-central Namibia. The observation that agricultural activities today are advancing into areas with decreasing rainfall (see chapter 4.1) also show the prolonged importance of agriculture in sustaining the livelihoods of many Namibians.

Yet, the start of agricultural activities in previously uncultivated regions of developing countries, is often a difficult venture, especially in areas that are characterised by aridity and drought. It is not unusual for such developments to fail. The reasons for such failures can be e.g. bad soil quality resulting in nutrient exhaustion, or soil salinisation, in case badly managed irrigation methods are applied. Very often can also climatic conditions be the reason, in case they do not support the successful cultivation of certain crops or crops in general on the long-term scale. The outcome of such development mistakes are large, open fallow areas with unproductive, exhausted or salinised soils. The natural vegetation is destroyed and the areas get severely affected by erosion. What also remains is an impoverished population without perspectives and income alternatives.

Agro-ecological crop simulation models are a tool to reduce the risk of such mistakes. They can help to better understand and assess the climatic and soil conditions that are characteristic for a specific area. They can also contribute to find crop varieties that can successfully be cultivated under the special conditions at a certain area.

This thesis has introduced one such model and shown that the application of the technique in the Namibian context is possible with relatively little effort and relatively high accuracy, as far as the available input-data and the practical execution of the method are concerned.

The findings and results that were made during the whole procedure, can provide valuable information regarding the future of agriculture in central and western Omusati: The soils in the region have a generally low nutrient content. This fact is not very positive, but typical for most semi-arid and arid regions. However, GANNSEN (1963) mentions that results of nutrient analyses concerning Namibian soils should not be compared with results and fertiliser recommendations concerning e.g. soils from central Europe. Namibian soils, even those with very low nutrient levels, are able to produce satisfying yields. The nutrient deficit is usually balanced by the loose structure and favourable aeration of Namibian soils, so roots can reach deep into the ground, where they can tap additional sources of nutrients. Precondition for successful crop cultivation are of course sufficient rainfall and non-saline soils with neutral to slightly alkaline reaction (GANNSEN, 1963, p.100).

As far as crop cultivation in central and western Omusati is concerned, the of the modelling results show clearly that it is not so much the rainfall amounts, but the temporal rainfall distribution that determines the cultivation success. In addition, it is the drainage and water-holding characteristics of the soils that can reduce the risk of bad harvests during some seasons with erratic rainfall. As it is impossible to influence the temporal rainfall distribution, any future agricultural activities should therefore concentrate on the soils of the *Mopane-Combretum savanna on sandy soils*, the *Western sand plains*, the *Mixed savanna on loamy to sandy soils* and the *Mopane shrubs & low trees on loamy sands* area. These soils have better soil-water qualities and are, except for the soils in the area of the *Mixed savanna on loamy to sandy soils*, generally less saline than those in the area of the *Western mopane-pan mosaic* and the *Cuvelai palms & fruit-trees on loamy sands* vegetation unit. An additional reason to choose the area of the *Western sand plains* for agricultural activities would be the apparently higher K_2O-concentrations of the soils there.

Beyond the concentration of farming activities to areas with favourable soil qualities, special farming techniques, e.g. the *Matuta*[1]-system, *Agroforestry* and wind-breaking hedges to reduce evaporation can additionally promote the soil-water situation.

Yet, it seems debatable to the author, if any further development of rain-fed agriculture would make sense in central and western Omusati. A decision on this point depends on how the risk of a marginal harvest or total crop failures in statistically four out of ten years is appraised by official planners/ decision makers and by the affected local population.

It is true that the calculated risks of bad harvests only apply for Tepary bean cultivation, but as Tepary is known as an extremely resistant and drought tolerant crop, it is questionable whether the risk is less, if other crop varieties are cultivated.

[1] The *Matuta*-system is a cultivation technique, which is widely applied in western and also in eastern Africa. The method is to plant the crops on top of little dams of soil that have a positive effect on soil-moisture.

In any case, farmers who intend to start agricultural activities in the previously non-cultivated areas of central and western Omusati should get information about the special characteristics of the area and about ways to reduce the risk of crop failures.

7 REFERENCES

7.1 LITERATURE

ABTEILUNG BODENKUNDE DER UNIVERSITAET TRIER (1992): Script zur Bodenphysik, ueberarbeitete Version Fruehjahr 1992. Trier (unpublished)

ABTEILUNG BODENKUNDE DER UNIVERSITAET TRIER (1998): Laboranleitungen zur chemischen Bodenanalyse. Trier (unpublished)

AG BODEN (1994): Bodenkundliche Kartieranleitung. 4th Edition. Hannover

AROWOLO, O. (1994): Namibia population data for development planning. National planning commission. Windhoek

BAIER, W. (1977): Crop-weather models and their use in yield assessments. World Meteorological Organization, Technical Note, No. 151. Geneva

BERNARD, F. E., CAMPBELL, D.J. & THOM, D.J. (1989): Carrying capacity of the eastern ecological gradient of Kenya. – National Geographic Research 5, No. 4, pp. 399-421

BRADEN, H. (1982): Simulationsmodell fuer den Wasser-, Energie- und Stoffhaushalt in Pflanzenbestaenden. Bonner Meteorologische Abhandlungen, Vol. 31. Bonn

BRAUN, G. (1985): Nord-Sued-Konflikt und Entwicklungspolitik. Opladen

BROWN, C. J. (1993): Land as a factor in poverty alleviation in Namibia: environmental considerations (pp. 72-100) – In: ANON. (Ed.): Land as a factor in poverty alleviation. Ministry of Lands, Resettlement and Rehabilitation. Windhoek

CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1994): Provisional population projections 1991-2011 Namibia. Windhoek

CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1994): 1991 Population and Housing Census. Basic Analysis with Highlights. Windhoek

CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1999): 1998 / 1999 Annual Agricultural Survey. Basic Analysis of Communal Agriculture. Windhoek

CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (2001): 1999 / 2000 Annual Agricultural Survey. Basic Analysis of Communal Agriculture. Windhoek

CHRISTIAN, I., WOHLLEBER, B. (1996): Changing times for “Subsistence Agriculture”. GTZ paper. Windhoek

De WIT, C. T., GOUDRIAAN, J. (1978) : Simulation of ecological processes. Simulation Monographs. Wageningen

DIELS, L., MILDBRAED, J. & SCHULZE-MENZ, G. K. (1963): Vegetationskarte von Afrika. Willdenowia, Mitteilungen aus dem Botanischen Garten und Museum Berlin-Dahlem, Beiheft 1. Berlin

DIEPEN, C. A. et al. (1988) : Wofost – CWFS crop growth simulation model. Wageningen

DIETZ, K. R. (1981): Grundlagen und Methoden geographischer Luftbildinterpretation. Muenchner Geographische Abhandlungen, Vol. 25. Muenchen

DOORENBOS, J., KASSAM, A. H. (1979): Yield response to water. FAO irrigation and drainage paper, No. 33. Rome

DOORENBOS, J., PRUITT, W. O. (1977): Guidelines for predicting crop water requirements. Revised Edition. FAO irrigation and drainage paper, No. 24. Rome

DUKE, J. A. (1981): Handbook of legumes of world economic importance. New York

FACHREDAKTION DES BIBLIOGRAPHISCHEN INSTITUTS (1962): Meyers Handbuch ueber Afrika. Mannheim

FAO (1998): World reference base for soil resources. Rome

FAO (1990): Guidelines for Soil Profile Description. 3rd Edition. Rome

FAO (1988): Soil Map of the World. Revised Legend. World Soil Resources Report, No. 60. Rome

FAO & UNESCO (1977): Soil Map of the World, 1:5 000 000. Vol. VI, Africa. Paris

FAO (1977): Guidelines for Soil Profile Description. 2nd Edition. Rome

FORBES IRVING, T. (1996): Managing water points and grazing areas in Namibia. The Cuvelei – Ohangwena, Omusati, Oshana and Oshikoto regions. Windhoek

FRANKE, W. (1989): Nutzpflanzenkunde. Nutzbare Gewaechse der gemaeßigten Breiten, Subtropen und Tropen. 2nd Edition. Stuttgart

FRANKENBERG, P. (1985): Zum Problem der Trockengrenze. - Geographische Rundschau, No. 37, pp. 350-358

FRENKEN, G. (1991): Raumzeitliche Dynamik von Agropotentialen im Trockengrenzbereich SE-Kenyas anhand eines Niederschlags-Simulationsmodells fuer ENSO- und Anti-Enso-Perioden. Diploma-thesis at the Faculty of Geography and Geographical Sciences, University of Trier, Germany. Trier

FRIEDRICH-EBERT-STIFTUNG (1997): Namibia regional resources manual compiled by International Development Consultancy. 2nd Edition. Windhoek

GAMMELSROED, T. et al. (1995) : Intrusion of warm surface layers along the SW African coast in February-March 1995: The Benguela Niño 1995. Bergen

GANSSEN, R. (1963): Suedwest-Afrika- Boeden und Bodenkultur. Versuch einer Klimapedologie warmer Trockengebiete. Berlin

GANSSEN, R. (1968): Trockengebiete- Boeden, Bodennutzung, Bodenkultivierung, Bodengefaehrdung. Mannheim

GESELLSCHAFT FUER TECHNISCHE ZUSAMMENARBEIT(GTZ) (1994): Geographische Informationssysteme. Einsatz in Projekten der Technischen Zusammenarbeit. Eschborn

HAINES-YOUNG, R., GREEN, D. R. & COUSINS, H. (1993): Landscape ecology and geographic information systems. London

HAREGREAVES, G. H., SAMANI, Z. A. & ZUNGIA, E. (1989): Modelling yields from rainfall and supplemental irrigation. – Journal of Irrigation and Draining Engineering, No.115, pp. 239-247

HENDL, M. & LIEDTKE, H. (Eds.)(1997): Lehrbuch der Allgemeinen Physischen Geographie. 3rd Edition. Gotha

HILGEMANN, W., KETTERMAN, G. & HERGT, M. (1984): Afrika. 2nd Edition. dtv-Perthes-Weltatlas, Großraeume in Vergangenheit und Gegenwart, Vol. 7. Darmstadt

HORNETZ B., SHISANYA C. A. & GITONGA, N. M. (2001): Crop water relationships and thermal adaption of kathika beans (Phaseolus vulgaris) and green grams (Vigna radiata) with special regard to temporal patterns of potential growth in the drylands of SE-Kenya. – Journal of Arid Environments, No. 48/4, pp. 591-601

HORNETZ, B. (1997): Ressourcenschutz und Ernaehrungssicherung in den semiariden Gebieten Kenyas. Ein holistischer methodischer Ansatz unter Verwendung von agraroekologischen Experimenten, Computersimulationsmodellen und Geographischen Informationssystemen (GIS). Berlin

HORNETZ, B. (1994): Agro(silvi)pastorale Systeme in den semiariden Tropen – Moeglichkeiten zur ressourcenschonenden Stabilisierung der Nahrungsmittelproduktion an der agronomischen Trockengrenze (mit Beispielen aus N- uns SE-Kenya). – Geomethodica, Vol. 19. Basel

HORNETZ, B. et al. (1992): Beziehungen zwischen Klima, Weideverhaeltnissen und Anbaumoeglichkeiten in marginalen semiariden und ariden Tropen mit Beispielen aus Nord- und Ost-Kenya. Materialien zur Ostafrika-Forschung, Vol. 9. Trier

HORNETZ, B. (1991): Optimierung der Landnutzung im Trockengrenzbereich des Anbaus. Hydraturbezogene Reaktionsmuster von Tepary-Bohnen und Bambarra-Erderbsen unter Trockenstressbedingungen sowie Moeglichkeiten zur Bestimmung von Ertragsschwellenwerten in potentiellen Anbaugebieten mit Hilfe eines agrooekologischen Simulationsmodelles (mit einem Anwendungsbeispiel aus Suedostkenya). Trierer Geographische Schriften, Vol. 8. Trier

HORNETZ, B. (1988): Ecophysiological Experiments for Improving Landuse Patterns in the Drylands of South-East Kenya by Means of Drought Resistant Leguminous Crops (Tepary Beans, Bambarra

Groundnuts). – Plant Research and Development, No. 31 (separate print)

IBRAHIM, F. (1992): Gruende des Scheiterns der bisherigen Strategien zur Bekaempfung der Desertifikation in der Sahelzone. – Geomethodica, Vol. 17. Basel

JAETZOLD, R. (1980): Entwicklungsmoeglichkeiten im Grenzgebiet des Regenfeldbaus in Kenya. – Entwicklung und laendlicher Raum, No. 6, pp.3-8

JAETZOLD, R. (1979a): Die Bestimmung der unteren Anbaugrenze des Hochlandes von Kenya. Ein Beitrag zur Trockengrenzdiskussion. – Geomethodica, Vol. 4. Basel

JAETZOLD, R. (1979b): Agro-climatic conditions for land use in the settlement areas east of Thika. Materialien zur Ostafrika-Forschung, Vol. 1. Trier

KEYLER, S. K. (1996): Economy Of The Namibian Millet Subsector. Michigan

KLINK, H.-J. (1996): Vegetationsgeographie. 2nd Edition. Das Geographische Seminar. Braunschweig

KNAPP, R. (1973): Die Vegetation von Afrika unter Beruecksichtigung von Umwelt, Entwicklung, Wirtschaft, Agrar- und Forstgeographie. Vegetationsmonographien der einzelnen Großraeume, Vol.3. Stuttgart

KOITZSCH, R. (1977): Schaetzungen der Bodenfeuchte aus meteorologischen Daten, Boden- und Pflanzenparametern mit einem Mehrschichtenmodell. – Zeitschrift fuer Meteorologie, No. 27, pp.302-306

KOMP, K.-U. (1991): Fernerkundung: Instrument fuer die Entwicklungszusammenarbeit – Remote sensing: Tools for Development. Schriftenreihe der GTZ, Vol. 221. Rossdorf

KRAMER, H., KRESS, A. & VOIGT, M. (Eds.)(1989): Haack Kartenbuch Afrika. Gotha

KREEB, K. H. (1977): Methoden der Pflanzenoekologie. Stuttgart

KREEB, K. H. (1974): Oekophysiologie der Pflanzen. Eine Einfuehrung. Jena

KREEB, K. H. (1958): Die Bedeutung der Hydratur fuer die Kontrolle der Wasserversorgung bei Kulturpflanzen. Hohenheim

KUNTZE, H., ROESCHMANN, G. & SCHWERDTFEGER, G. (1994): Bodenkunde. 5th Edition. Stuttgart

KUTSCH, H., SCHUH, H. J. (1983): Simplified computer-based modelling of water balance in defined crop stands (pp. 239.253) – In: REINER, L., GEIDEL, H. (Ed.): Informationsverarbeitung Agrarwissenschaft. Muenchen

LESER, H. et al. (1995a) : Diercke – Woerterbuch der Allgemeinen Geographie, Vol. 1. 5th Edition. Muenchen, Braunschweig

LESER, H. et al. (1995b) : Diercke – Woerterbuch der Allgemeinen Geographie, Vol. 2. 5th Edition. Muenchen, Braunschweig

LILLESAND, T. M., KIEFER, R. W. (1994): Remote sensing and image interpretation. New York

LITSCHKO, T. (1990): PASTURE – ein Wasserbilanzmodell als Instrument der landnutzungsorientierten, klimaoekologischen Zonierung der Trockengebiete Nord-Kenyas. Diploma-thesis at the Faculty of Geography and Geographical Sciences, University of Trier, Germany. Trier

MAINGUET, M. (1999): Aridity. Droughts and Human Development. Berlin

MAINGUET, M. (1991): Desertification - Natural Background and Human Mismanagement. Berlin

MALAN, J. S. (1998): Die Voelker Namibias. Goettingen/ Windhoek

MARSH, A., SEELY, M. (1992): Oshanas, Sustaining People, Environment and Development in Central Owambo, Namibia. Windhoek

MARTIN, J. H. & LEONARD, W. H. (1967): Principles of Field Crop Production. London

McDONAGH, J. F., HILLYER, A. E. M. (1999): Soils and nitrogen fixation in northern Namibia. – Abstracts of Agricultural Research, year 1999, pp.162-166.

MENDELSOHN, J., El OBEID, S. & ROBERTS, C. (2000): A profile of north-central Namibia. Windhoek

MILDBRAED, J. (1966): Grundzuege der Vegetation des tropischen Kontinental-Afrika. Willdenowia, Mitteilungen aus dem Botanischen Garten und Museum Berlin-Dahlem, Beiheft 2. Berlin

MOELLER, L. (1997): Soils of the regions Omusati, Ohangwena, Oshana and Oshikoto. Report to Forest Awareness and Treeplanting Project. Ongwediva

NATIONAL ACADEMY OF SCIENCE (1979): Tropical legumes: Resources for the future. Washington D. C.

NATIONAL PLANNING COMISSION (2000) Second National Development Plan (NDP2), First Draft. Windhoek (unpublished)

NGHITILA, T. M. K. (1997): An Overview Of The Environmental Situation In Four Northern Regions. Ohangwena, Omusati, Oshana and Oshikoto. DRFN, Occasional paper 6. Windhoek

OYAMA, M. (1970): Revised Standard Soil Color Charts. 2nd Edition. Tokyo

PALGRAVE, K. C. (1983-93): Trees of Southern Africa. 2nd Edition. Cape Town

PENNING de VRIES, F. W. T., VAN LAAR, H. H. (1982) : Simulation of plant growth and crop production. Simulation Monographs. Wageningen

PLACE, R. E., BROWN, D. M. (1987): Modelling corn yields from soil moisture estimates: description, sensivity analysis and validation. – Agricultural and Forest Meteorology, No. 41, pp.31-56

RASMUSSON, V. P., HANKS, R. J. (1978): Spring wheat yield model for limited moisture conditions. – Agronomy Journal, No. 70, pp.940-944

SCHALLER, K. (1993): Praktikum zur Bodenkunde und Pflanzenernaehrung. 7th Edition. Geisenheimer Berichte Vol.2. Geisenheim

SCHEFFER, F. & SCHACHTSCHABEL, P. (1992): Lehrbuch der Bodenkunde. 13th Edition. Stuttgart

SCHLICHTING, E., BLUME, H.-P. & STAHR, K. (1995): Bodenkundliches Praktikum. 2nd Edition. Pareys Studientexte, Vol. 81. Berlin

SCHNEIDER, S. (1974): Luftbild und Luftbildinterpretation. Lehrbuch der Allgemeinen Geographie, Vol. 11. Berlin

SCHROEDER, D. (1984): Soils – Facts and Concepts. Bern

SCHULTZ, A., MIRSCHEL, W. (1994): Modelle auf dem Pruefstand – Wie genau sind agraroekologische Simulationsmodelle? – Zeitschrift fuer Agrarinformatik, No. 2/2, pp.22-29.

SEELY, M. (1999): Climate Variability – Implications for sustainable natural resource management. DRFN key paper for the International Conference on Integrated Drought Management, 20-22 September 1999, Pretoria, South Africa.

SHISANYA, C. A. (1996): Chances and risks of maize and bean growing in the semi-arid areas of south-east Kenya during expected deficient, normal and above normal rainfall of the short rainy seasons. Materialien zur Ostafrika-Forschung, Vol. 14. Trier

SHIVUTE, O. (1998): Conservancy plan sparks tribal row. - The Namibian, 16th of July 1998. Newspaper report. Windhoek

SLABBERS, P. J., SORBELLO-HERRENDORF, V. & STAPPER, M. (1979): Evaluation of simplified water-crop yield models. – Agricultural water management, No. 2, pp.95-129

SOCIAL SCIENCES DIVISION & MULTI-DISCIPLINARY RESEARCH CENTRE UNIVERSITY OF NAMIBIA (1995): Namibia Poverty Profile. A Report for SIDA. Final draft. Windhoek

SPRENT, J. I. (1975): Adherence of Sand Particles to Soybean Roots under Water Stress. - The New Phytologist, No. 74, pp.480-489

SPRINGER, M. (2002): Kooperation noetig. - Allgemeine Zeitung, 20th of September 2002. Newspaper report. Windhoek

TARR, P. (Ed.) (1995): Namibia Environment, Vol. 1. Windhoek

UNITED NATIONS (1999): Common Country-assessment of Namibia. New York

VAN DER MERWE, J. H. (Ed.)(1983):National Atlas of South West Africa/ Namibia. Cape Town

VAN WYK, B., VAN WYK, P. (1997): Field guide to Trees of southern Africa. Cape Town

VERSTEEG, M. N., VAN KEULEN, H. (1986): Potential crop production prediction by some simple calculation methods, as compared with computer simulations. – Agricultural systems, No. 19, pp. 249-272

VOGT, N., WIESENHUETTER, J. (2001): Land use and socio-economic structure of Taita Taveta District (Kenya) – Potentials and constraints. Materialien zur Ostafrika-Forschung, Vol. 25. Trier

WARREN, A., SUD, Y. C. & ROZANOV, B. (1996): The future of deserts. – Journal of Arid Environments No. 32.

WARREN, G. P., ATWAL, S. S. & IRUNGU, J. W. (1997): Soil nitrate variations under grass, sorghum and bare fallow in semi-arid Kenya. Experimental Agriculture, No. 33, pp. 312-333

WIGHT, J. R., HANKS, R. J. (1981): A water-balance, climate model for range herbage production. – Journal of range management, No. 34, pp.307-311

7.2 INTERVIEWS

AMAMBOO, O.: Local facilitator for the northern regions, Desert Research Foundation of Namibia; 29th of November 2001 and 2nd of February 2002

DAVIES, D.: Geographer, Northern Namibian Environmental Project; 1st of February 2002

PISANI du, L.: Agro-meteorologist, Ministry of Agriculture, Water Affairs and Rural Development; 3rd of December 2001

FITTER, J.: Head of Namibian office, Gesellschaft fuer Technische Zusammenarbeit; 29th of November 2001

FLEISSNER, K.: Senior researcher, Legumes Research Programme, Ministry of Agriculture, Water Affairs and Rural Development; 12th of February 2002

KALUNDUKA, M.: Project manager, Rural Development Center, Ongwediva; 31st of January 2002

KROLL, T.: Project manager of Gesellschaft fuer Technische Zusammenarbeit; 4th of December 2001

MENDELSOHN, J.: Researcher, Atlas GIS project, Department of Environmental Affairs; 21st of November 2001

NEGUMBO, A.: Head of Agricultural Extension Office, Ongwediva, Ministry of Agriculture, Water Affairs and Rural Development; 31st of January 2002

OLSZEWSKI, J.: Former officer at the Namibian Weather Office, now associated with the Desert Research Foundation of Namibia; 26th of November 2001

ROTHKEGEL, B.: Director of Agricultural Planning Commission, Ministry of Agriculture, Water Affairs and Rural Development; 4th of December 2001

SEELY, M.: Head of the Desert Research Foundation of Namibia; 14th of February 2002

STRUBACH, B.: Head of National Botanical Research Institute; 29th of November 2001

In addition several spontaneous interviews were held with farmers of the Omusati and the Oshana region during December 2001 – February 2002.

7.3 MAPS

FAO & UNESCO (1972): Soil Map of the world, 1:5 000 000. Paris

MINISTRY OF AGRICULTURE, WATER AFFAIRS & RURAL DEVELOPMENT (1985): Evaporation Map of Namibia. Windhoek

MINISTRY OF MINES AND ENERGY, GEOLOGICAL SURVEY OF NAMIBIA (2000): Etosha West, Sheet 1814, Mineral Resources of Namibia. Economic Geology 1:250 000 Map Series. Summary of mineral deposits and occurrences. Windhoek

MINISTRY OF MINES AND ENERGY, GEOLOGICAL SURVEY OF NAMIBIA (2000): Oshakati, Sheet 1714, Mineral Resources of Namibia. Economic Geology 1:250 000 Map Series. Summary of mineral deposits and occurrences. Windhoek

SURVEYOR GENERAL (1981): Namibia 1:250 000, Sheet 1814 Etosha (Wes). 2nd Edition. Windhoek

SURVEYOR GENERAL (1975): Namibia 1:250 000, Sheet 1714 Oshakati. 2nd Edition. Windhoek

7.4 AERIAL PHOTOGRAPHS

SURVEYOR GENERAL (1996): Aerial photographs of 1996 survey flights, 1: 78 500

SURVEYOR GENERAL (1970): Aerial photographs of 1970 survey flights, 1: 50 000

7.5 DATA SETS

CENTRAL BUREAU OF STATISTICS / NATIONAL PLANNING COMISSION (1991): 1991 Census data. Windhoek

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (2002): Atlas GIS-data. Windhoek

HYDROLOGICAL SERVICE at MAWRD/ NAMIBIAN WEATHER OFFICE (2002): Ongandjera rainfall. Windhoek

HYDROLOGICAL SERVICE at MAWRD/ NAMIBIAN WEATHER OFFICE (2002): Otjovasandu rainfall. Windhoek

HYDROLOGICAL SERVICE at MAWRD/ NAMIBIAN WEATHER OFFICE (2002): Ermo rainfall. Windhoek

HYDROLOGICAL SERVICE at MAWRD/ NAMIBIAN WEATHER OFFICE (2002): Mahenene evaporation. Windhoek

HYDROLOGICAL SERVICE at MAWRD/ NAMIBIAN WEATHER OFFICE (2002): Okaukuejo evaporation. Windhoek

MINISTRY OF AGRICULTURE, WATER AFFAIRS & RURAL DEVELOPMENT (2002): Naris data, Vol. A, B, C by Agro-ecological Zoning Unit. Windhoek

NORTHERN NAMIBIAN ENVIRONMENTAL PROJECT (2002): Enviromapper/ NNEP-Data. Oshakati

7.6 WORLD WIDE WEB SITES

ALKAEMPER, J. (2000): Tepary Bohne. - http://bibd.uni-giessen.de/gdoc/2000/uni/p000003/teparybo.htm

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (2002): - http://www.dea.met.gov.na/nnep/ maps.htm

DEPARTMENT OF ENVIRONMENTAL AFFAIRS (2002): - http://www.dea.met.gov.na/data/Atlas/ Atlas_web.htm

FAO (2002): - http://www.fao.org/

GOUVERNMENT OF NAMIBIA (2002): Region Faces El Nino Threat. - http://www.grnnet.gov.na/News/Archive/2002/May/Week4/region.htm

HARRISON, P., PEARCE, F. (2000): AAAS Atlas of Population and Environment. - http://www.ourplanet.com/aaas/pdfs/71-74.pdf

INTERNATIONAL RESEARCH INSTITUTE FOR CLIMATE PREDICTION (1999): El Niño/La Niña Update. - http://www.wmo.ch/nino/updat.html

OLSZEWSKI, J. (2001a): Benguela El Nino: The new boy on the block. - http://www.economist.com.na/2001/120401/story14.htm

OLSZEWSKI, J. (2001b): The unpacific Pacific and rainfall prospects. - http://www.economist.com.na/2001/170801/story9.htm

SOUTHERN AFRICA REGION CLIMATE OUTLOOK FORUM (1997): Summary. - http://www.sadcfanr.org.zw/rrsu/monitor/windhoek.htm

Annex 1-1: Selected data on population growth and population engaged in agricultural activities (acc. to FAO, 2002)

Total population (x1000)

	1970	1980	1990	2000
Developing Countries	2.611.628	3.258.633	3.998.886	4.742.170
Africa	356.338	466.871	619.480	793.626
Namibia	786	989	1.375	1.757

Mean annual population growth (%)

	1970-80	1980-90	1990-00
Developing Countries	2,5	2,3	1,9
Africa	3,1	3,2	2,8
Namibia	2,6	3,9	2,8

Total number of persons depending on agricultural activities (x1000)

	1970	1980	1990	2000
Developing Countries	1.799.468	2.056.671	2.304.441	2.467.222
Africa	264.801	311.901	376.577	441.254
Namibia	556	634	784	861

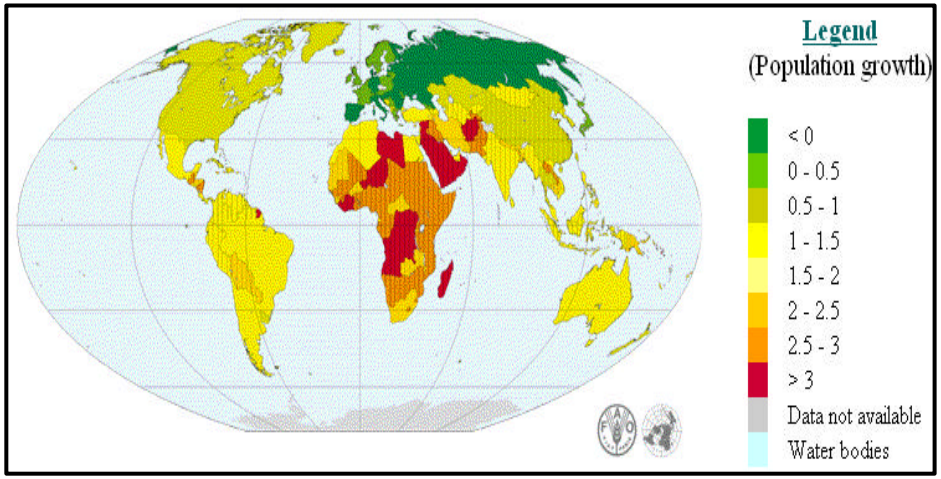
Mean annual increase of total numbers of persons depending on agricultural activities (%)

	1970-80	1980-90	1990-00
Developing Countries	1,4	1,2	0,7
Africa	1,8	2,1	1,7
Namibia	1,4	2,4	1,0

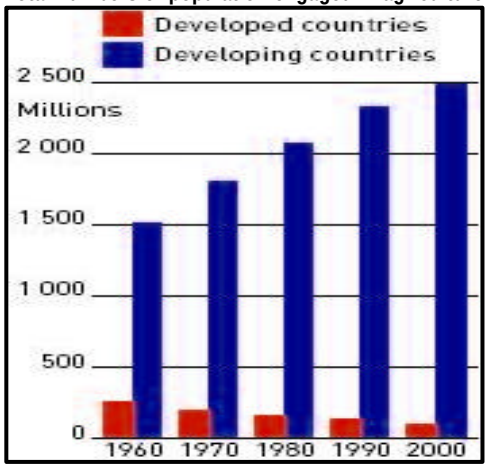
Proportion of total population depending on agricultural activities (%)

	1970	1980	1990	2000
Developing Countries	68,9	63,1	57,6	52,0
Africa	74,3	66,8	60,8	55,6
Namibia	70,7	64,1	57,0	49,0

Annual population growth 1998 (%) according to FAO (2002)

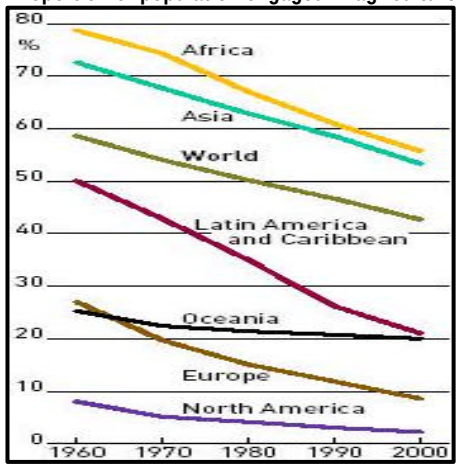


Total numbers of population engaged in agriculture



Source: HARRISON & PEARCE (2000)

Proportion of population engaged in agriculture



Source: HARRISON & PEARCE (2000)

Annex 2-1a: Copy of the data collection sheet used for the soil survey

Profile number:	samples: yes / no	Date:	Altitude: m.a.s.l.
Latitude:	Longitude:	map ref.:	

Means of survey: soil-auger ("PUERKHAUER"-Bohrer) profile-pit

Soil classification:

World reference base (FAO, 1998):

Landform and Topography

Topography: <0.5% 0.5-2% 2-5% 5-10%

Landform: major landform: PL plain BA Basin

second level: AP alluvial Plain LP Lacustrine Plain PN Peneplain

Land element: PA Pan VA Valley CH Channel LE Levee FP Floodplain

Position: Flat or almost flat → HI higher part IN intermediate part

LO lower part BO bottom

Vegetation and land use:

Land use: *communal grazing and agriculture* Crop:

Vegetation: No veget. Grassland Forest Woodland Shrubland Savanna

Human influence: None Not known Vegetation slightly disturbed moderately disturbed

strongly disturbed disturbed (unspec.) ploughing manure/fertilizers

burning pollution clearing artificial drainage irrigation

borrow pit others/remarks:

Parent material:

Parent material: AU Aeolian deposits AS Aeolian sands LI Littoral deposits

FL Fluvial deposits AL Alluvial deposits UU Unconsoidated (unspec.)

CO Colluvial deposits

Effective soil depth: cm

Surface characteristics:

Surface coarse fragments

Abundance (%): Greatest dimensions: cm Nature:

Erosion

Category: Type: Area affected: Degree:

Surface sealing

Thickness: cm Consistency:

Surface cracks

Width: cm Average distance: cm

Salinity

Salinity: Nature:

Other surface characteristics:

Soil-water-relationships:

Drainage-class: Groundwater depth:

Quality: Moisture conditions:

Weather conditions:

Annex 2-1b: Copy of the data collection sheet used for the soil survey (continued)

Genetic horizon					
Depth in cm					
Horizon boundary					
Texture					
Bulk density					
Structure:					
Grade					
Size					
Consistence:					
Dry					
Moist					
Stickiness (wet)					
Plasticity (wet)					
Mineral nodules:					
Abundance %					
Contrast					
Nature					
Rock fragments:					
Abundance %					
Size					
Shape					
Nature					
Mottles:					
Abundance %					
Size					
Contrast					
Colour					
Soil colour (moist)					
Cutans:					
Abundance %					
Contrast					
Nature					
Location					
Cementation:					
Nature					
Degree					
Continuity					
Roots					
Biological features:					
Abundance/ m^2					
Kind					
pH (quick-test)					
HCl-reaction					
Diagnostic horizon					

Sample references:

Remarks:

Annex 2-2: Table displaying available field capacity and field capacity in relation to soil texture and bulk density (Source: AG BODEN, 1994)

1(+)				2(+)			3(+)		
Bodenart*	Luftkapazität Poren >50 µm (pF < 1,8)			nutzbare Feldkapazität Poren 0,2–50 µm (pF 4,2 bis 1,8)			Feldkapazität Poren < 50 µm (pF ≥ 1,8)		
Kurzzeichen	Ld1–2	Ld3	Ld4–5	Ld1–2	Ld3	Ld4–5	Ld1–2	Ld3	Ld4–5
Ss	22,5	19,5	–	12	10,5	–	18,5	16,5	–
Sl2	16,5	12,5	9	19	17,5	16	26	24	20,5
Sl3	12,5	11	7	21,5	18	15,5	30.5	26	23,5
Sl4	12	10	5,5	20,5	17	14,5	33	28,5	25,5
Slu	8,5	6,5	5,5	27,5	21	17	37,5	31,5	28,5
St2	18,5	15,5	11	18,5	14	13,5	26	23	21,5
St3	–	9	7	–	15,5	12	–	29,5	26
Su2	17	13,5	11	17,5	16	13	24	21,5	18,5
Su3	11,5	9	5,5	23	20,5	18	32	28	25,5
Su4	9,5	7,5	4,5	26,5	22	20	35	29	27
Ls2	9,5	7	6	21	15,5	13,5	40,5	33,5	30
Ls3	9	6,5	4,5	20	15	13	42	33,5	29
Ls4	10,5	8	4,5	21	16	12,5	40	31,5	28
Lt2	8	5	3,5	17,5	15	11	47,5	39	33,5
Lt3	7	3,5	2,5	17,5	14	10	50,5	43,5	37,5
Lts	5	4,5	3,5	17,5	13,5	10,5	48,5	42	32
Lu	7,5	6	4	21	17	14,5	43,5	36,5	33,5
Uu	6,5	3	–	28,5	26	–	39,5	36,5	–
Uls	8,5	6,5	3,5	26	22	19,5	39,5	33	30,5
Us	8	5	–	27	25,5	–	39	33	–
Ut2	9	4	2	27	25	21	39	36	32
Ut3	9,5	4,5	2	25,5	23,5	21,5	38	36	33
Ut4	9	5,5	2,5	22	20,5	18	39	36	33,5
Tt	–	2,5	1,5	–	16	11	–	56	47,5
Tl	5	3,5	2	18,5	14,5	11	56,5	50,5	43,5
Tu2	4	3	2	21,5	14,5	11	58	49	42,5
Tu3	6	4,5	3,5	21	15,5	11,5	52	41,5	36
Tu4	7	5,5	4	19,5	16	12	45,5	37	32,5
Sande									
gSfs	24	18,5	–	17	15,5	–	20	17,5	–
mS	28	25	–	9	7,5	–	13,5	11	–
mSgs	26	23,5	–	11	8	–	15	11	–
mSfs	23	19,5	–	14,5	12,5	–	19	16	–
fS	17,5	10	–	21,5	20	–	25,5	24	–
fSms	22	16	–	17,5	16,5	–	21	19,5	–

+ column 1 displays soil texture

+ column 2 and 3 display available field capacity, respectively field capacity in relation to soil texture and bulk density (represented by 'Ld' in the table)

Annex 2-3: References concerning the WATBAL and MARCROP crop simulation models

Basic literature:

DOORENBOS, J., KASSAM, A.H. (1979): Yield response to water. FAO irrigation and drainage paper, No.33. Rome

DOORENBOS, J., PRUITT, W.O. (1977): Guidelines for predicting crop water requirements. Revised Edition. FAO irrigation and drainage paper, No.24. Rome

HORNETZ, B. (1991): Optimierung der Landnutzung im Trockengrenzbereich des Anbaus. Hydraturbezogene Reaktionsmuster von Tepary-Bohnen und Bambarra-Erderbsen unter Trockenstressbedingungen sowie Moeglichkeiten zur Bestimmung von Ertragsschwellenwerten in potentiellen Anbaugebieten mit Hilfe eines agrooekologischen Simulationsmodells (mit einem Anwendungsbeispiel aus Suedostkenya). Trierer Geographische Schriften, Volume 8. Trier

HORNETZ, B. (1988): Ecophysiological Experiments for Improving Landuse Patterns in the Drylands of South-East Kenya by Means of Drought Resistant Leguminous Crops (Tepary Beans, Bambarra Groundnuts). – Plant Research and Development, No. 31 (separate print)

KOITZSCH, R. (1977): Schaetzungen der Bodenfeuchte aus meteorologischen Daten, Boden- und Pflanzenparametern mit einem Mehrschichtenmodell. – Zeitschrift fuer Meteorologie, No.27, pp.302-306

KREEB, K.H. (1958): Die Bedeutung der Hydratur fuer die Kontrolle der Wasserversorgung bei Kulturpflanzen. Hohenheim

KREEB, K.H. (1974): Oekophysiologie der Pflanzen. Eine Einfuehrung. Jena

KREEB, K.H. (1977): Methoden der Pflanzenoekologie. Stuttgart

KUTSCH, H., SCHUH, H.J. (1983): Simplified computer-based modelling of water balance in defined crop stands (pp. 239.253) – In: REINER, L., GEIDEL, H. (Ed.): Informationsverarbeitung Agrarwissenschaft. Muenchen

Secondary literature:

De WIT, C.T., GOUDRIAAN, J. (1978): Simulation of ecological processes. Simulation Monographs. Wageningen

FRENKEN, G. (1991): Raumzeitliche Dynamik von Agropotentialen im Trockengrenzbereich SE-Kenyas anhand eines Niederschlags-Simulationsmodells fuer ENSO- und Anti-Enso-Perioden. Diploma-thesis at the Faculty of Geography and Geographical Sciences, University of Trier, Germany. Trier

HORNETZ B., SHISANYA C.A. & GITONGA, N.M. (2001): Crop water relationships and thermal adaption of Kathika beans (Phaseolus vulgaris) and green grams (Vigna radiata) with special regard to temporal patterns of potential growth in the drylands of SE-Kenya. – Journal of Arid Environments, No. 48/4, pp. 591-601

PENNING de VRIES, F.W.T., VAN LAAR, H.H. (1982): Simulation of plant growth and crop production. Simulation Monographs. Wageningen

SHISANYA, C.A. (1996): Chances and risks of maize and bean growing in the semi-arid areas of south-east Kenya during expected deficient, normal and above normal rainfall of the short rainy seasons. Materialien zur Ostafrika-Forschung, Volume 14. Trier

VERSTEEG, M.N., VAN KEULEN, H. (1986): Potential crop production prediction by some simple calculation methods, as compared with computer simulations. – Agricultural systems, No.19, pp. 249-272

WIGHT, J.R., HANKS, R.J. (1981): A water-balance, climate model for range herbage production. – Journal of range management, No.34, pp.307-311

Annex 2-4: Pan coefficients (Kp) to convert Class-A-Pan evaporation values into reference crop evapotranspiration (Et_o) values (acc. to DOORENBOS & PRUITT, 1977)

	Case A: Pan placed in short green cropped area				Case B*: Pan placed in dry fallow area			
Wind km/ day	**Windward side distance of green crop (m)**	**RH mean (%): low <40**	**RH mean (%): medium 40-70**	**RH mean (%) high >70**	**Windward side distance of dry fallow (m)**	**RH mean (%): low <40**	**RH mean (%): medium 40-70**	**RH mean (%) high >70**
light < 175	1	0,55	0,65	0,75	1	0,7	0,8	0,85
	10	0,65	0,75	0,85	10	0,6	0,7	0,8
	100	0,7	0,8	0,85	100	0,55	0,65	0,75
	1000	0,75	0,85	0,85	1000	0,5	0,6	0,7
moderate 175-425	1	0,5	0,6	0,65	1	0,65	0,75	0,8
	10	0,6	0,7	0,75	10	0,55	0,65	0,7
	100	0,65	0,75	0,8	100	0,5	0,6	0,65
	1000	0,7	0,8	0,8	1000	0,45	0,55	0,6
strong 425-700	1	0,45	0,5	0,6	1	0,6	0,65	0,7
	10	0,55	0,6	0,65	10	0,5	0,55	0,65
	100	0,6	0,65	0,7	100	0,45	0,5	0,6
	1000	0,65	0,7	0,75	1000	0,4	0,45	0,55
very strong >700	1	0,4	0,45	0,5	1	0,5	0,6	0,65
	10	0,45	0,55	0,6	10	0,45	0,5	0,55
	100	0,5	0,6	0,65	100	0,4	0,45	0,5
	1000	0,55	0,6	0,65	1000	0,35	0,4	0,45

***** For extensive areas of bare-fallow soils and no agricultural development, reduce Kp by 20% under hot, windy conditions; by 5-10% for moderate wind, temperature and humidity conditions

Annex 2-5:Table with planting dates applied in the modelling
(dates which produced the best calculation results per season are marked grey)*

Season		1960-1961	1961-1962	1962-1963	1963-1964	1964-1965	1965-1966	1966-1967	1967-1968	1968-1969
Planting dates used for the modelling		07.02.1961	08.01.1962	01.01.1963	04.01.1964	28.01.1965	11.01.1966	16.01.1967	06.02.1968	26.11.1968
		03.03.1961	07.02.1962	15.01.1963	22.02.1964	02.02.1965	15.01.1966	06.02.1967	01.03.1968	23.01.1969
		07.03.1961	09.02.1962	28.02.1963	09.03.1964	17.02.1965	20.01.1966	13.02.1967	08.03.1968	30.01.1969
								28.02.1967		01.02.1969
								07.03.1967		

Season	1969-1970	1970-1971	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	1976-1977	1977-1978	1978-1979
Planting dates used for the modelling	19.01.1970	10.01.1971	03.01.1972	02.01.1973	03.01.1974	04.01.1975	17.01.1976	10.01.1977	13.01.1978	12.01.1979
	25.01.1970	27.01.1971	02.03.1972	12.02.1973	16.01.1974	14.01.1975	25.01.1976	21.01.1977	17.01.1978	14.01.1979
	04.02.1970	31.01.1971	07.03.1972	02.03.1973	30.01.1974	04.02.1975	30.01.1976	16.02.1977	29.01.1978	21.01.1979
	24.02.1970	14.02.1971			06.02.1974		28.02.1976			
					10.02.1974					

Season	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989
Planting dates used for the modelling	04.02.1980	05.01.1981	29.01.1982	01.01.1983	03.01.1984	26.01.1985	18.01.1986	07.02.1987	10.01.1988	10.11.1988
	19.02.1980	05.03.1981	01.02.1982	31.01.1983	05.02.1984	29.01.1985	20.01.1986	15.02.1987	27.02.1988	10.12.1988
	05.03.1980		12.02.1982	10.02.1983	05.03.1984	08.03.1985	07.02.1986	26.02.1987		04.01.1989
			19.02.1982				19.02.1986			16.01.1989
										28.01.1989
										05.02.1989

* In seasons with unmarked planting dates each calculation resulted in a total crop failure.

Annex 3-1: Seasons (1960/61- 1988/89) classified by risk of crop drought, rainfall and number of rainy days at Ongandjera/ Okahao (acc. to chapter 3.2.2.3.5)

Season	Climatic phenomenon	Risk of crop drought*	seasonal (Nov-Apr) rainfall amount (mm)	Class of total seasonal rainfall amount	rainfall amount (mm) during cropping	rainfall amount during cropping period	r of days with rainfall (Nov-	Class of number of days with rainfall (Nov-Apr)	r of days with rainfall (Jan-	Class of number of days with rainfall (Jan-Apr)	of days with productive rainfall (Nov-Apr)	number of days with productive rainfall (Nov-Apr)	of days with productive rainfall (Jan-Apr)	number of days with productive rainfall (Jan Apr)
1960-61	none	low risk	259,5	below-normal	227,4	normal	24	below norma	19	normal	7	below normal	5	below norma
1961-62	none	high risk	200,1	below-normal	140,3	below-normal	37	normal	28	normal	7	below normal	5	below norma
1962-63	Benguela El Niño	low risk	494,0	above-normal	474,9	above-normal	59	above norma	45	above norma	16	above normal	15	above norma
1963-64	El Niño	high risk	318,5	normal	173,3	below-normal	33	normal	18	below norma	13	above normal	7	below norma
1964-65	La Niña	low risk	247,9	below-normal	190,3	below-normal	35	normal	28	normal	11	normal	8	normal
1965-66	El Niño	depending	333,3	normal	216,9	below-normal	31	normal	20	normal	12	normal	8	normal
1966-67	none	no risk	481,1	above-normal	415,9	above-normal	53	above norma	43	above norma	12	normal	11	above norma
1967-68	none	low risk	674,5	above-normal	339,8	normal	54	above norma	26	normal	20	above normal	10	normal
1968-69	none	low risk	564,0	above-normal	381,8	above-normal	49	above norma	34	above norma	19	above normal	13	above norma
1969-70	El Niño	no risk	314,5	below-normal	285,8	normal	39	normal	29	above norma	11	normal	10	normal
1970-71	La Niña	no risk	508,2	above-normal	413,3	above-normal	49	above norma	40	above norma	16	above normal	13	above norma
1971-72	none	depending	397,6	normal	372,5	above-normal	49	above norma	39	above norma	13	normal	13	above norma
1972-73	El Niño	depending	426,4	normal	309,9	normal	42	above norma	29	above norma	14	above normal	10	normal
1973-74	La Niña/ Benguela El Niño	no risk	793,1	above-normal	775,5	above-normal	60	above norma	52	above norma	26	above normal	25	above norma
1974-75	none	low risk	375,0	normal	237,5	normal	44	above norma	29	above norma	12	normal	9	normal
1975-76	La Niña/ Benguela El Niño	no risk	558,5	above-normal	465,7	above-normal	59	above norma	43	above norma	21	above normal	20	above norma
1976-77	El Niño	low risk	342,3	normal	307	normal	39	normal	33	above norma	14	above normal	12	above norma
1977-78	El Niño	low risk	435,0	above-normal	375,5	above-normal	33	normal	25	normal	13	normal	11	above norma
1978-79	none	no risk	615,4	above-normal	502,8	above-normal	32	normal	26	normal	17	above normal	15	above norma
1979-80	none	very high risk	258,3	below-normal	155,2	below-normal	28	below norma	16	below norma	8	below normal	4	below norma
1980-81	none	very high risk	150,7	below-normal	119,9	below-normal	13	below norma	9	below norma	6	below normal	5	below norma
1981-82	none	low risk	217,5	below-normal	199	below-normal	16	below norma	14	below norma	10	below normal	9	normal
1982-83	El Niño	depending	285,6	below-normal	187,1	below-normal	30	normal	17	below norma	10	below normal	6	below norma
1984-85	none	very high risk	206,9	below-normal	143,9	below-normal	17	below norma	13	below norma	9	below normal	8	normal
1985-86	none	low risk	322,8	normal	276,8	normal	21	below norma	17	below norma	11	below normal	9	normal
1986-87	El Niño	very high risk	155,6	below-normal	94,1	below-normal	15	below norma	9	below norma	6	below normal	4	below norma
1987-88	none	very high risk	539,5	above-normal	525	above-normal	16	below norma	13	below norma	9	below normal	8	normal
1988-89	La Niña	very high risk	393,5	normal	223,8	normal	18	below norma	10	below norma	12	normal	6	below norma

No risk: Season with very favourable temporal rainfall distribution for crop cultivation. Only few, short periods without rain.
Low risk: Season with good (regarding crop cultivation) temporal rainfall distribution. Only few, relatively short dry spells.
Depending: Season is significantly divided in one wet and one dry period. Risk of crop-failure is depending on time of planting.
Increased risk: Season with frequent and/ or long dry spells and only few periods with favourable rainfall for crop c
High risk: Season with frequent dry spells and very few/ short periods with favourable rainfall for crop culti
Very high risk: Season with very erratic and/ or low rainfall. Water supply for crop cultivation is unvafourable for quasi the whole rainy sea

Annex 4-1a: Explanations concerning the soil profile data in annex 4-2 to 4-7

Profile:

Horizons:

A,B,C acc. to *1)

L (= layer of organic litter) acc. to *2)

Suffixes acc. to *1), except "i" acc. to *6)

k: accumulation of calcium carbonate
z: accumulation of salts
x: occurence of a fragipan
p: disturbed by ploughing / tillage
h: accumulation of organic material
s: accumulation of sesquioxides
t: illuvial accumulation of clay
m: indicating cementation, consolidation, induration; combined with another suffix, to explain nature of cementation
w: alteration in situ as reflected e.g. by clay content, colour, structure...
c: indicating accumulations in form of concretions; combined with another suffix, to explain the nature of concretionary material
i: only initially developed

Profile-class: acc. to *6)

1: C-profiles
2: A/C-profiles
3: A/B/C-profiles
P: profile with cementations; grade of cementation acc. to *1)
Suffixes: see above

Texture: acc. to *2)

Class:	***Name***	***Clay (%)***	***Silt (%)***	***Sand (%)***
Su2:	slightly silty sand	0-5	0-10	85-100
Su3:	medium silty sand	0-8	25-40	52-75
Su4:	heavy silty sand	0-8	40-50	42-60
Lu:	silty loam	17-30	50-65	5-33
Ls2:	slightly sandy loam	17-25	40-50	25-43
Ls4:	heavy sandy loam	17-25	15-30	45-68
Us:	sandy silt	0-8	50-80	12-50
Lts	sandy-clayey loam	25-45	15-30	25-60
Uu:	pure silt	0-8	80-100	0-20
Ss:	sandy/ pure sand	0-5	0-10	85-100

Sub-classes of sand:	***Name***	***Fine sand (%)***	***Middle sand (%)***	***Coarse sand (%)***
gSfs:	fine sandy coarse sand	25-50	0-40	10-75
mSgs:	coarse sandy middle sand	0-25	40-65	10-60
mSfs:	fine-sandy middle sand	25-50	40-75	0-35
fSms:	middle sandy fine sand	50-75	15-50	0-35

Grain-sizes in mm (fractions < 2mm)

coarse sand:	2,0-0,63
middle sand:	0,63-0,2
fine sand:	0,2-0,063
silt:	0,063-0,002
clay:	< 0,002

Annex 4-1b: Explanations concerning the soil profile data in annex 4-2 to 4-7 (continued)

Bulk density:	acc. to *2)	***Class:***	***Quality***
		1	very low
		2	low
		3	medium
		4	high
		5	very high
Fc (mm):	acc. to *2)	field capacity (= soil water) at pF >1,8	
aFc (mm):	acc. to *2)	available field capacity (= plant available soil water) at pF>1,8 and <4,2	
pH-level:	determined in demineralised H_2O suspension		
Conductivity (mS/ cm²):	specific electric conductivity under dry soil conditions		
Conductivity-class:	acc. to *3)	***Class***	***mS/ cm²***
		EC 0 (very low)	< 0,75
		EC 1 (low)	0,75 - 2
		EC 2 (moderate)	>2 - 4
		EC 3 (medium)	>4 - 8
		EC 4 (high)	>8 - 15
		EC 5 (very high)	>15
Class of K2O content:	acc. to *4)	***Class (soils with <10% clay):***	***Content (mg/ 100g soil)***
		E (extremly high)	> 25
		D (very high)	21-25
		C (high)	15-20
		B (medium)	7-14
		A (low)	< 7
Class of P2O5 content:	acc. to *4)	***Class (soils with <10% clay):***	***Content (mg/ 100g soil)***
		E (extremly high)	> 40
		D (very high)	26-39
		C (high)	15-25
		B (medium)	7-14
		A (low)	< 7
Colour codes:	acc. to *5)		

***1):** FAO (1990)
***2):** AG BODEN (1996)
***3):** SCHLICHTING, E., BLUME, H.-P. & STAHR, K. (1995)
***4):** SCHALLER, K. (1993)
***5):** OYAMA, M. (1970)
***6):** own classification in context of this study

Annex 4-2: Findings of the soil survey in the area of the *Cuvelai palms and fruit-trees on loamy sands* - vegetation unit

Profile-no.	12	13	14	15	51
Profile-class	1	2p	3z	P2x	2z
Profile	L / C	Ap / C	iAh / iCBs / Cz	iAh / Cx (weakly cemented)	iA / C1 / Cz2
Thickness of horizons (cm)	0-50+	0-20 / 20-72+	0-7 / 7-30 / 30-72+	0-2 / 2-50+	0-0,5 / 0,5-30 / 30-72+
Texture	mSfs	mSfs / mSfs	Su2 / Su2 / Su2	mSfs / mSfs	mSgs / mSfs / mSfs
Bulk density	- / 2	1 / 2 (20cm+)	2 / 2 / 2	1 / 1 (35-38cm: 3, fragipan)	1 / 1 / 3 (30cm+)
Avail. space f. rooting (cm)	50+	72+	72+	50+	72+
Fc (mm) at pf >1,8	19	19	24	19	19
aFc (mm) at pf >1,8 & <4,2	14,5	14,5	17,5	14,5	11 / 14,5 / 12,5
pH-level	6,4	6,95	6,85 (A / B), 7,85 (C)	6,2	7,25 (Ai / C1), 7,4 (Cz2)
Conductivity (mS /cm²)	0,46	1,04	10,4 (A/B), 83,12 (C)	n.a.	0,66 (Ai/C1), 16,66 (C2z)
Conductivity-class	0	1	4 / 5	n.a.	0 / 5
K2O (mg/ 100g dry soil)	9,76	7,59			
Class of K_2O content	B	B			
P2O5 (mg/ 100g dry soil)	0,40	1,29			
Class of P_2O_5 content	A	A			
C%	0,187	0,137			
$N_{(total)}$%	0,021	0,015			
C / N-ratio	8,90	9,13			
Colour-code	10YR 5-2	10YR 4-2	5YR 4-2 / 5YR 5-1 / 10YR 6-1	2.5Y 4-2	10YR 6-1 / 2.5Y 5-2 / 2.5Y 5-2
Groundcover (%)	<5	<5	<5	<5	<5
Latitude (decimal degree)	18,0004670°S	18,0024000°S	17,9533000°S	17,9257670°S	17,9733330°S
Longitude (decimal degree)	15,090350°E	15,089950°E	15,097983°E	15,063717°E	15,026333°E
m.s.l.(m)	1132	1127	1120	1128	1134
Remark			close to a small pan		alluvial plain

Annex 4-3: Findings of the soil survey in the area of the *Mopane shrub and low trees on oshanas* - vegetation unit

Profile-no.	4	5	9	11	1	6
Profile-class	2	3	P1xk	2	3	1
Profile	iA / C	iAh / iBts / C	L / C1 / Cxck2 (strongly cemented)	iA / C	Ah / CBs	L / C
Thickness of horizons (cm)	0-0,5 / 0,5-72+	0-3 / 3-29 / 29-72+	0-19 / 19-34+	0-3 / 3-72+	0-3 / 3-62+	0-72+
Texture	Su2 / Su2	Su2 / Su2 / mSfs	Su2 / Su2	Su2 / Su2	Su2 / Su2	Su2
Bulk density	2 / 2	2 / 2 / 2	- / 2 / 2-3 (19cm+), 4 (34cm+)	1 / 2 (3cm+)	2 / 2	- / 2
Avail. space f. rooting (cm)	72+	72+	34	72+	62+	72+
Fc (mm) at pf >1,8	24	24 / 24 / 19	24	24	24	24
aFc (mm) at pf >1,8 & <4,2	17,5	17,5 / 17,5 / 14,5	- / 17,5 / 17 (+60cm),13 (34cm+)	17,5	17,5	17,5
pH-level	6,45	6,6	6,3	6,1	6,5	7,15
Conductivity (mS /cm²)	1,22	1,25	1,06	n.a.	0,81	1,04
Conductivity-class	1	1	1	n.a.	1	1
K2O (mg/ 100g dry soil)	35,78	9,76				12,65
Class of K_2O content	E	A				B
P2O5 (mg/ 100g dry soil)	0,93	0,04				0,44
Class of P_2O_5 content	A	A				A
C%	0,299	0,134				0,172
$N_{(total)}$%	0,028	0,013				0,021
C / N-ratio	10,68	10,31				8,19
Colour-code	5Y 4-1	7.5R 3-3 / 5YR 3-6 / 2.5YR 4-3	n.a.	10YR 3-1 / 10YR 5-2	10YR 3-4 / 5YR 4-4	7.5YR 5-8
Groundcover (%)	20	10	40	35	25	25
Latitude (decimal degree)	18,4874670°S	18,4874670°S	18,2992000°S	18,0973769°S	18,1333207°S	18,3636775°S
Longitude (decimal degree)	15,144817°E	15,144817°E	15,170767°E	15,149364°E	15,092216°E	15,140066°E
m.s.l.(m)	1118	1125	1126	1126	1123	1136
Remark			CaCO3 outcrops all around			

Annex 4-4a: Findings of the soil survey in the area of the *Mopane-Combretum savanna on sandy soils* - vegetation unit

Profile-no.	3	7	8	10	19	26
Profile-class	2	2	2	2	2	2k
Profile	iA / C	iA / C	iA / C	iAh / C	iAh / C	iAh / Ck
Thickness of horizons (cm)	0-0,5 / 0,5-72+	0-3 / 3-72+	0-4 / 4-72+	0-5 / 5-72+	0-20 / 20-72+	0-10 / 10-72+
Texture	mSfs / mSfs	Su2 / Su2	mSfs / mSfs	fSms / fSms	Su2 / Su2	fSms / Su2
Bulk density	1 / 2 (30cm+)	1 / 2 (3cm+)	1 / 2 (4cm+)	1 / 1	1 / 2 (30cm+)	1 / 2 (10cm+)
Avail. space f. rooting (cm)	72+	72+	72+	72+	72+	72+
Fc (mm) at pf >1,8	19	24	19	21	24	21 / 24
aFc (mm) at pf >1,8 & <4,2	14,5	17,5	14,5	17,5	17,5	17,5 / 17,5
pH-level	7,45	6,4	6,55	6,5	6,3	7,2
Conductivity (mS /cm²)	1,12	0,79	0,68	0,71	0,51	2,40
Conductivity-class	1	1	0	0	0	2
K2O (mg/ 100g dry soil)	11,44				7,47	
Class of K_2O content	B				B	
P2O5 (mg/ 100g dry soil)	0,58				0,71	
Class of P_2O_5 content	A				A	
C%	0,206				0,245	
$N_{(total)}$%	0,025				0,023	
C / N-ratio	8,24				10,65	
Colour-code	5YR 4-3	10YR 4-3 / 7.5YR 4-6	7.5YR 3-4 / 7.5YR 4-6	7.5YR 4-3 / 7.5YR 5-6	7.5YR 3-4 / 7.5YR 4-6	7.5YR 2-3 / 5YR 4-3
Groundcover (%)	15	40	40	25	40	20
Latitude (decimal degree)	18,4908830°S	18,3164512°S	18,3564968°S	18,1988215°S	18,0301330°S	18,3421670°S
Longitude (decimal degree)	15,050150°E	15,050428°E	15,050716°E	15,150380°E	14,956900°E	14,604550°E
m.s.l.(m)	1124	1127	1127	1136	1138	1186
Remark				trans. to mop.shru.-low tr.o.lm.sands		

Annex 4-4b: Findings of the soil survey in the area of the *Mopane-Combretum savanna on sandy soils* - vegetation unit (continued)

Profile-no.	30	42	45	46	49	50
Profile-class	3	2	2	2	2	2
Profile	iAh / iBts / C	iAh / C	iAh / C	iAh / C	iAh / C	iAh / C
Thickness of horizons (cm)	0-5 / 5-30 / 30-72+	0-5 / 5-72+	0-15 / 15-72+	0-15 / 15-72+	0-19 / 19-72+	0-15 / 15-72+
Texture	gSfs / Su2 / Su2	Su2 / fSms	fSms / fSms	mSfs / fSms	fSms / fSms	fSms / fSms
Bulk density	2 / 2 / 2	1 / 2 (28cm+)	1 / 2 (40cm+)	1 / 2 (30cm+)	1 / 2 (25cm+)	1 / 2 (30cm+)
Avail. space f. rooting (cm)	72+	72+	72+	72+	72+	72+
Fc (mm) at pf >1,8	20 / 24 / 24	24 / 21	21	19 / 21	21	21
aFc (mm) at pf >1,8 & <4,2	17 / 17,5 / 17,5	17,5 / 17,5	17,5	14,5 / 17,5	17,5	17,5
pH-level	6,35	6,9	7,65	7,15	7,65	7,35
Conductivity (mS /cm²)	0,67	3,37	2,20	1,19	2,97	1,15
Conductivity-class	0	2	2	1	2	1
K2O (mg/ 100g dry soil)	9,52			6,87		8,67
Class of K_2O content	B			A		B
P2O5 (mg/ 100g dry soil)	0,00			0,04		0,53
Class of P_2O_5 content	A			A		A
C%	0,223			0,207		0,254
$N_{(total)}$%	0,023			0,021		0,025
C / N-ratio	9,70			9,86		10,16
Colour-code	7.5YR 3-3 / 5YR 3-3 / 5YR 4-6	5YR 4-6 / 2.5YR 5-6	7.5YR 3-3 / 7.5YR 4-6	10YR 3-3 / 5YR 5-8	10YR 2-2 / 7.5YR 4-4	10YR 5-3 / 7.5YR 5-8
Groundcover (%)	15	30	25	25	15	20
Latitude (decimal degree)	18,1784330°S	18,2132170°S	18,0890830°S	18,070000°S	18,0741477°S	18,0692170°S
Longitude (decimal degree)	14,981467°E	14,554850°E	14,806117°E	14,660000°E	14,662134°E	14,851917°E
m.s.l.(m)	1136	1173	1142	1154	1134	n.a.
Remark						

Annex 4-4c: Findings of the soil survey in the area of the *Mopane-Combretum savanna on sandy soils* - vegetation unit (continued)

Profile-no.	53	57	25	31
Profile-class	2	2	2	2
Profile	iAh / C	iA / C	iAh / C	iAh / C
Thickness of horizons (cm)	0-10 / 10-72+	0-10 / 10-72+	0-17 / 17-72+	0-7 / 7-72+
Texture	Su2 / fSms	fSms / fSms	mSfs / mSfs	mSfs / fSms
Bulk density	1 / 2 (45cm+)	1 / 2 (40cm+)	1 / 2 (17cm+)	1 / 2 (7cm+)
Avail. space f. rooting (cm)	72+	72+	72+	72+
Fc (mm) at pf >1,8	24 / 21	21	19	19 / 21
aFc (mm) at pf >1,8 & <4,2	17,5 / 17,5	17,5	14,5	14,5 / 17,5
pH-level	7,6	7,35	6,45	6,45
Conductivity (mS /cm²)	1,70	2,57	3,58	1,49
Conductivity-class	1	2	2	1
K2O (mg/ 100g dry soil)		30,6		
Class of K_2O content		E		
P2O5 (mg/ 100g dry soil)		1,11		
Class of P_2O_5 content		A		
C%		0,253		
$N_{(total)}$%		0,031		
C / N-ratio		8,16		
Colour-code	7.5YR 3-4 / 5YR 4-6	5YR 4-4 / 5YR 4-8	5YR 3-3 / 2.5YR 4-6	7.5YR 3-4 / 5YR 4-8
Groundcover (%)	15	20	25	20
Latitude (decimal degree)	18,1921934°S	18,3891606°S	18,2887830°S	18,2493602°S
Longitude (decimal degree)	14,312865°E	14,540941°E	14,545517°E	15,012632°E
m.s.l.(m)	1229	1288	1197	n.a.
Remark			transition to w. sand plains	transition to w. sand plains

Annex 4-5a: Findings of the soil survey in the area of the *Western sand plains* - vegetation unit

Profile-no.	2	23	24	27	28	29
Profile-class	2	2	2	2	2	2
Profile	L / iA / C	iA / C	iAh / C	iAh / C	iAh / C	iAh / C
Thickness of horizons (cm)	0-0,5 / 0,5-72+	0-2 / 2-72+	0-5 / 5-72+	0-2 / 2-72+	0-10 / 10-72+	0-10 / 10-72+
Texture	gSfs / fSms	gSfs / fSms	mSfs / fSms	fSms / fSms	mSfs / fSms	gSfs / Su2
Bulk density	- / 2 / 2	1 / 2 (30cm+)	1 / 2 (30cm+)	1 / 2 (26cm+)	1 / 2 (25cm+)	1 / 2 (25cm+)
Avail. space f. rooting (cm)	72+	72+	72+	72+	72+	72+
Fc (mm) at pf >1,8	20 / 21	20 / 21	19 / 21	21	19 / 21	20 / 24
aFc (mm) at pf >1,8 & <4,2	17 / 17,5	17 / 17,5	14,5 / 17,5	17,5	14,5 / 17,5	17 / 17,5
pH-level	6,2	6,65	6,4	6,85	6,95	6,05
Conductivity (mS /cm²)	1,02	0,99	0,80	1,42	0,77	1,12
Conductivity-class	1	1	1	1	1	1
K2O (mg/ 100g dry soil)	7,47			7,95		
Class of K_2O content	B			B		
P2O5 (mg/ 100g dry soil)	0,53			0,53		
Class of P_2O_5 content	A			A		
C%	0,158			0,172		
$N_{(total)}$%	0,017			0,02		
C / N-ratio	9,29			8,60		
Colour-code	5YR 4-6	5YR 4-6	10YR 4-2 / 7.5YR 4-6	5YR 3-3 / 5YR 4-4	7.5YR 4-3 / 5YR 4-6	5YR 3-4 / 5YR 4-6
Groundcover (%)	35	20	20	15	20	15
Latitude (decimal degree)	18,3947330°S	18,2589215°S	18,2167330°S	18,3816167°S	18,3488330°S	18,2357000°S
Longitude (decimal degree)	14,914550°E	14,624369°E	14,703117°E	14,687550°E	14,854483°E	14,885183°E
m.s.l.(m)	1134	1133	1161	1166	1137	1144
Remark						

Annex 4-5b: Findings of the soil survey in the area of the *Western sand plains* - vegetation unit (continued)

Profile-no.	32	33	34	35	36
Profile-class	2	2	2	P3k	P2k
Profile	iAh / C	iA / C	iA / C	Ah / BC / C1 / Cmk2 (strongly cemented)	iAh / C1 / Cmk2 (weakly cemented)
Thickness of horizons (cm)	0-0,5 / 0,5-72+	0-0,5 / 0,5-72+	0-1 / 1-72+	0-13 / 13-40 / 40-70 / crust	0-2 / 2-60+
Texture	mSfs / mSfs	mSfs / mSfs	fSms / fSms	Su2 / Su2 / Su2 / crust	mSfs / mSfs
Bulk density	1 / 1-2 (20cm+)	1 / 2 (15cm+)	1 / 2 (20cm+)	1 / 2 (13cm+) / 2 / 4+	1 / 2 (35cm+)
Avail. space f. rooting (cm)	72+	72+	72+	70	60+
Fc (mm) at pf >1,8	19	19	21	24	19
aFc (mm) at pf >1,8 & <4,2	14,5	14,5	17,5 / 17,5	17,5 / crust	14,5
pH-level	6,25	7,95	6,45	7,15 (A / C1), 8,5 (C2)	6,9
Conductivity (mS /cm²)	0,71	1,37	1,21	1,79 (A/C1), 1,30 (C2)	1,26
Conductivity-class	0	1	1	1 / 1	1
K2O (mg/ 100g dry soil)		2,89			10,96
Class of K_2O content		A			B
P2O5 (mg/ 100g dry soil)		0,62			0,53
Class of P_2O_5 content		A			A
C%		0,343			0,171
$N_{(total)}$%		0,036			0,02
C / N-ratio		9,53			8,55
Colour-code	2.5YR 4-6 / 2.5YR 4-8	7.5YR 3-4 / 7.5YR 5-8	5YR 4-6 / 2.5YR 4-8	10YR 4-3 / 7.5YR 4-4 / 7.5YR 4-3 / 7.5Y 8-1	7.5YR 4-4 / 5YR 5-8 / n.a.
Groundcover (%)	20	15	15	15	15
Latitude (decimal degree)	18,4947000°S	18,4966830°S	18,4861330°S	18,4994330°S	18,4996330°S
Longitude (decimal degree)	14,945533°E	14,865883°E	14,827767°E	14,609083°E	14,475867°E
m.s.l.(m)	1146	1162	1151	1176	1213
Remark					

Annex 4-5c: Findings of the soil survey in the area of the *Western sand plains* - vegetation unit (continued)

Profile-no.	47	52	56	58	62
Profile-class	2	P2k	2	2k	2
Profile	iAh / C	iA / C1 / Cmk2 (weakly cemented)	iAh / C	iA / Ck	iAh / C
Thickness of horizons (cm)	0-6 / 6-72+	0-0,5 / 0,5-72+	0-12 / 12-72+	0-5 / 5-72+	0-4 / 4-72+
Texture	fSms / fSms	fSms / fSms	mSfs / mSfs	Su4 / Su2	fSms / fSms
Bulk density	1 / 2 (31cm+)	1 / 2 (45cm+)	1 / 2 (45cm+)	1 / 2 (45cm+)	1 / 1
Avail. space f. rooting (cm)	72+	72+	72+	72+	72+
Fc (mm) at pf >1,8	21	21	19	35 / 24	21
aFc (mm) at pf >1,8 & <4,2	17,5 / 17,5	17,5 / 17,5	14,5	26,5 / 17,5	17,5 / 17,5
pH-level	6,75	7,95	7,55	7,75	7
Conductivity (mS /cm²)	1,02	1,92	0,76	1,58	0,77
Conductivity-class	1	1	1	1	1
K2O (mg/ 100g dry soil)	8,31		4,46		8,91
Class of K_2O content	B		A		B
P2O5 (mg/ 100g dry soil)	0,53		0,49		0,53
Class of P_2O_5 content	A		A		A
C%	0,17		0,174		0,163
$N_{(total)}$%	0,018		0,056		0,019
C / N-ratio	9,44		3,11		8,58
Colour-code	7.5YR 3-4 / 5YR 4-8	7.5YR 4-4 / 5YR 5-8 / n.a.	5YR 3-4 / 5YR 4-6	10YR 5-2 / 10YR 6-4	7.5YR 4-4 / 5YR 5-8
Groundcover (%)	15	15	25	20	25
Latitude (decimal degree)	18,0483500°S	18,1718228°S	18,5032872°S	18,5052595°S	18,4336453°S
Longitude (decimal degree)	14,729267°E	14,581832°E	14,323055°E	14,388502°E	14,745520°E
m.s.l.(m)	1146	1229	1260	1294	1233
Remark					

Annex 4-5d: Findings of the soil survey in the area of the *Western sand plains* - vegetation unit (continued)

Profile-no.	43	44
Profile-class	2	2
Profile	iAh / C	iAh / C
Thickness of horizons (cm)	0-10 / 10-72+	0-20 / 20-72+
Texture	gSfs / gSfs	fSms / fSms
Bulk density	1 / 2 (15cm+)	1 / 2 (37cm+)
Avail. space f. rooting (cm)	72+	72+
Fc (mm) at pf >1,8	20	21
aFc (mm) at pf >1,8 & <4,2	17	17,5 / 17,5
pH-level	7,1	6,7
Conductivity (mS /cm²)	0,93	1,05
Conductivity-class	1	1
K2O (mg/ 100g dry soil)		
Class of K_2O content		
P2O5 (mg/ 100g dry soil)		
Class of P_2O_5 content		
C%		
$N_{(total)}$%		
C / N-ratio		
Colour-code	7.5YR 4-3 / 5YR 4-6	10YR 4-6 / 7.5YR 5-8
Groundcover (%)	20	15
Latitude (decimal degree)	18,1654000°S	18,1375170°S
Longitude (decimal degree)	14,653583°E	14,710800°E
m.s.l.(m)	1155	1147
Remark		

Annex 4-6a: Findings of the soil survey in the area of the *Western mopane-pan mosaic* - vegetation unit

Profile-no.	20	21	22	39	40
Profile-class	2kz	2kz	P2xk	P2zk	P2zk
Profile	Ah / Czk	Ah / C1 / Cwzk2	iAh / Ck1 / Cx(k)2 (strongly cemented, HCl reac.extr.wea	iAhz / Cmzk (weakly cemented	iAhzk / Cmzk (weakly cemented)
Thickness of horizons (cm)	0-24 / 24-60+	0-1 / 1-43 / 43-60+	0-1 / 1-20 / 20-72+	0-1 / 1-30+	0-10 / 10-40+
Texture	Su4 / Us	Su2 / Su2 / Us	Su2 / Su2 / Su2	Us / Uu	Us / Uu
Bulk density	1 / 2 (24cm+)	1 / 2 (1cm+) / 2	2 / 2 / 3 (20cm+)	1 / 2 (1cm+)	1 / 2 (10cm+)
Avail. space f. rooting (cm)	60+	60+	72+	30+ (but saltcrust)	40+
Fc (mm) at pf >1,8	35 / 39	24 / 24 / 39	24	39 / 39,5	39 / 39,5
aFc (mm) at pf >1,8 & <4,2	26,5 / 27	17,5 / 17,5 / 27	17,5	27 / 28,5	27 / 28,5
pH-level	7,2	7,15 (A / C1), 6,8 (C2)	6,8	7,2 (A), 7,7 (C)	7,4
Conductivity (mS /cm²)	2,72 (A), 27,80 (C)	2,29 (A/C1), 23,57 (C2)	1,26	25,93 (A), 22,03 (C)	20,15
Conductivity-class	2 / 5	2 / 5	1	5 / 5	5
K2O (mg/ 100g dry soil)		8,31	9,4		
Class of K_2O content		B	B		
P2O5 (mg/ 100g dry soil)		0,58	0,40		
Class of P_2O_5 content		A	A		
C%		0,229	0,219		
$N_{(total)}$%		0,021	0,018		
C / N-ratio		10,90	12,17		
Colour-code	5Y 3-1 / 2.5Y 8-1	5Y 3-1 / 10YR 4-1 / 2.5Y 8-1	5Y 3-1 / 2.5Y 5-1 / 2.5Y 5-1	2.5YR 3-1 / 2.5YR 7-2	7.5YR 3-1 / 10YR 6-2
Groundcover (%)	20	20	50	15	15
Latitude (decimal degree)	18,0748699°S	18,1050484°S	18,1263484°S	18,2362000°S	18,2749000°S
Longitude (decimal degree)	14,931977°E	14,905598°E	14,879625°E	14,400417°E	14,429033°E
m.s.l.(m)	1130	1130	1131	1227	1216
Remark					

Annex 4-6b: Findings of the soil survey in the area of the *Western mopane-pan mosaic* - vegetation unit (continued)

Profile-no.	41	48
Profile-class	P2zk	P2zk
Profile	iAh / Cmzk (strongly cemented)	iAk(z) / Cmzk (strongly cemented)
Thickness of horizons (cm)	0-4 / 4-30+	0-9 / 9-72+
Texture	Us / Uu	Su2 / Lts
Bulk density	1 / 3 (4cm+)	1 / 1, 3-4 (60cm+)
Avail. space f. rooting (cm)	30+ (but saltcrust)	72+ (but saltcrust)
Fc (mm) at pf >1,8	39 / 39,5	24 / 48,5, 37 (60cm+)
aFc (mm) at pf >1,8 & <4,2	27 / 26	17,5 / 17,5 , 12 (60cm+)
pH-level	7,15 (A), 7,45 (C)	6,65 (<60cm), 8,2 (>60cm)
Conductivity (mS /cm²)	3,38 (A), 24,43 (C)	4,12 (<60cm), 26,65 (>60cm)
Conductivity-class	2 / 5	3 / 5
K2O (mg/ 100g dry soil)		31,2
Class of K_2O content		E
P2O5 (mg/ 100g dry soil)		0,93
Class of P_2O_5 content		A
C%		0,452
$N_{(total)}$%		0,046
C / N-ratio		9,83
Colour-code	2.5YR 3-1 / 2.5YR 7-2	5YR 3-1 / 5YR 4-1
Groundcover (%)	15	5
Latitude (decimal degree)	18,2486170°S	18,0997082°S
Longitude (decimal degree)	14,482133°E	14,376611°E
m.s.l.(m)	1208	1149
Remark		

Annex 4-7a: Findings of the soil survey in the area of the *Mixed savanna on loamy to sandy soils* - vegetation unit

Profile-no.	37	38	54	55	66
Profile-class	2kz	P2zk	1k	2	P2x
Profile	iA / C1 / Ckz2	iAhk(z) / Ck1 / Cmk(z)2 (very strongly cemented, rock-lik	Ck	iAh / C	iAh / C1 / Cx2 (weakly cemented)
Thickness of horizons (cm)	0-0,5 / 0,5-28 / 28-72+	0-0,5 / 0,5-25 / crust	0-72+	0-16 / 16-72+	0-18 / 18-50 / 50-72+
Texture	Su3 / Su3 / fSms	Su3	Ls2	fSms / fSms	fsms / fSms / fSms
Bulk density	1 / 1 / 2 (28cm+)	2 / 2 / rock (25cm+)	1 / 2 (5cm+)	1 / 2 (40cm+)	2 / 2 / 3 (50cm+)
Avail. space f. rooting (cm)	72+	25	72+	72+	72+
Fc (mm) at pf >1,8	32 / 32 / 21	32	40,5	21	21 / 21 / 19,5
aFc (mm) at pf >1,8 & <4,2	23 / 23 / 17,5	23	21	17,5	17,5 / 17,5 / 16,5 (50cm+)
pH-level	6,7 (A / C1), 8,5 (C2)	7,7 (A / C1), 9,04 (C2)	7,7	7,7	7 (A / C1), 6,7 (C2)
Conductivity (mS /cm²)	3,01 (A/C1), 11,36 (C2)	4,46 (A/C1), 2,13 (C2)	1,69	0,84	1,89 (A/C1), 0,40 (C2)
Conductivity-class	2 / 4	3 / 2	1	1	1 / 0
K2O (mg/ 100g dry soil)				3,25	8,79
Class of K_2O content				A	B
P2O5 (mg/ 100g dry soil)				0,27	0,67
Class of P_2O_5 content				A	A
C%				0,12	0,367
$N_{(total)}$%				0,011	0,033
C / N-ratio				10,91	11,12
Colour-code	n.a. / 10YR 3-4 / 10YR 4-3	10YR 3-2 / 10YR 3-3 / 10YR 8-1	N 3-3	7.5YR4-4 / 5YR4-6	10YR 3-2 / 7.5YR 4-4 / 7.5YR 4-4
Groundcover (%)	15	15	15	25	10
Latitude (decimal degree)	18,3785403°S	18,3476442°S	18,3094500°S	18,4341856°S	18,1115016°S
Longitude (decimal degree)	14,489591°E	14,437646°E	14,314322°E	14,322572°E	14,298964°E
m.s.l.(m)	1206	1222	1227	1247	1237
Remark					

Annex 4-7b: Findings of the soil survey in the area of the *Mixed savanna on loamy to sandy soils* - vegetation unit (continued)

Profile-no.	67	68
Profile-class	P3k(x)	P3k(x)
Profile	iAh / iCBst / Cckm(x) (strongly cemented)	iAh / CBckm(x) (strongly cemented)
Thickness of horizons (cm)	0-2 / 2-18 / 18+	0-7 / 7-50+
Texture	Lu / Ls4 / Ls4	Ls4 / Ls4
Bulk density	1 / 3 (2cm+) / 4 (18cm+)	1 / 3 (7cm+)
Avail. space f. rooting (cm)	18	50+(but saltcrust)
Fc (mm) at pf >1,8	43,5 / 31,5 / 28	40 / 31,5
aFc (mm) at pf >1,8 & <4,2	21 / 16 (2cm+) /12,5 (18cm+)	21 / 16 (7cm+)
pH-level	7,1 (A / C1), 7,15 (C2)	7,15 (A), 7,1 (C)
Conductivity (mS /cm²)	1,39(A/C1), 0,17 (C2)	1,89 (A), 2,09 (C)
Conductivity-class	1 / 0	1 / 2
K2O (mg/ 100g dry soil)		21,2
Class of K_2O content		D
P2O5 (mg/ 100g dry soil)		0,67
Class of P_2O_5 content		A
C%		missing
$N_{(total)}$%		missing
C / N-ratio		missing
Colour-code	2.5Y 3-2 / 10YR 3-3 / 10YR 3-3	10YR 2-1 / 10YR 3-1
Groundcover (%)	10	10
Latitude (decimal degree)	18,0739421°S	18,0244909°S
Longitude (decimal degree)	14,294091°E	14,290607°E
m.s.l.(m)	1230	1218
Remark		

Annex 4-8: Explanations regarding annex 4-9 to 4-15

Yield classes, respectively agro-ecological types as calculated by MARCROP:

	Name	Relative yield (%)
Class 1:	optimum	80-100
Class 2:	sub-optimum	60-80
Class 3:	average	40-60
Class 4:	marginal	20-40
Class 5:	marginal	20-40
Class 6a:	minimal	10-20
Class 6b-d:	total crop failure	<10

In the diagrams of annex 4-9 to 4-15 the classes 4 & 5 were assembled into one class !!!

Soil units as used in annex 4-9 to 4-15:

Soil unit I: Soils of the *Mopane-Combretum savanna on sandy soils-*, the *Western sand plains-* and the *Mixed savanna on loamy to sandy soils-* vegetation units
Soil unit II: Soils of the *Mopane shrubs & low trees on loamy sands-* vegetation unit
Soil unit III: Soils of the *Western mopane-pan mosaic-* vegetation unit
Soil unit IV: Soils of the *Cuvelai palms & fruit-trees on loamy sands-* vegetation unit

Annex 4-9a: Total MARCROP-calculation results (1960/61 – 1968/69)

Soil unit:	Unit I		Unit II		Unit III		Unit IV	
Scenario:	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Planting dates/ season								
1960-1961								
07.02.61	4a	4a	4a	4a	4a	4a	4a	4a
03.03.61	1	1	1	1	3a	3a	3a	3a
07.03.61	4a	4a	4a	4a	4a	4a	4a	4a
1961-1962								
08.01.62	6b	6c	6c	6c	6c	6c	6c	6c
07.02.62	4a	4b	4a	4b	6b	6b	6b	6b
09.02.62	5c	6a	6b	6b	6b	6b	6b	6b
1962-1963								
01.01.63	6a	6a	6a	6a	6a	6a	6b	6b
15.01.63	6b	6b	6b	6b	6b	6b	6b	6b
28.02.63	1	1	1	1	1	1	1	1
1963-1964								
04.01.64	6b	6b	6b	6b	6b	6b	6b	6b
22.02.64	6b	6b	6b	6b	6b	6b	6b	6b
09.03.64	6b	6b	6b	6b	6b	6b	6b	6b
1964-1965								
28.01.65	4a	4a	6a	6a	6a	6a	6a	6b
02.02.65	6b	6b	6b	6b	6b	6b	6b	6b
17.02.65	6b	6b	6b	6b	6b	6b	6b	6b
1965-1966								
11.01.66	6b	6b	6b	6b	6b	6b	6b	6b
15.01.66	6b	6b	6b	6b	6b	6b	6b	6b
20.01.66	6b	6b	6b	6b	6b	6b	6b	6b
1966-1967								
16.01.67	1	3a	1	3a	3a	3a	3a	3a
06.02.67	1	1	1	1	1	1	1	1
13.02.67	3a	3a	3a	3a	3a	3a	3a	3a
28.02.67	1	1	3a	3a	3a	3a	3a	3a
07.03.67	1	1	1	1	1	1	1	1
1967-1968								
06.02.68	6b	6b	6b	6b	6b	6b	6b	6c
01.03.68	1	2	1	2	1	2	3a	3a
08.03.68	3a	3a	3a	3a	3a	3a	4a	4a
1968-1969								
26.11.68	6b	6b	6b	6b	6b	6b	6b	6b
23.01.69	1	1	1	1	2	2	1	1
30.01.69	1	2	1	2	3a	3b	3a	3a
01.02.69	2	3a	3a	3a	4a	4a	3a	3a

Annex 4-9b: Total MARCROP-calculation results (1969/70 – 1978/79)

Soil unit:	Unit I		Unit II		Unit III		Unit IV	
Scenario:	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Planting dates/ season								
1969-1970								
19.01.70	1	1	1	3a	3a	3a	1	1
25.01.70	3a	3a	3a	3a	3a	3a	3a	3a
04.02.70	1	1	3a	3a	3a	3a	1	3a
24.02.70	6a	6a	6b	6b	6b	6b	6a	6a
1970-1971								
10.01.71	3a	3a	3a	4a	4a	4a	3a	3a
27.01.71	1	1	1	1	1	1	1	1
31.01.71	1	1	1	1	3a	3a	1	1
14.02.71	1	1	1	1	1	1	1	1
1971-1972								
03.01.72	6b	6b	6b	6b	6b	6b	6b	6b
02.03.72	1	1	1	1	2	2	2	2
07.03.72	3a	3a	3a	3a	4a	4a	3a	3a
1972-1973								
02.01.73	6b	6b	6b	6b	6b	6b	6c	6c
12.02.73	4a	4a	4a	4a	4a	4a	6c	6c
02.03.73	1	1	1	1	1	1	1	1
1973-1974								
03.01.74	1	1	1	1	1	1	1	1
16.01.74	1	1	1	1	1	1	1	1
30.01.74	1	1	1	1	1	1	1	1
06.02.74	1	1	1	1	1	1	1	1
10.02.74	6d	6d	6d	6d	6d	6d	6d	6d
1974-1975								
04.01.75	4a	4a	4a	4a	4a	6b	6b	6b
14.01.75	6a	6b	6a	6b	6b	6b	6b	6b
04.02.75	6b	6b	6b	6b	6b	6b	6b	6b
1975-1976								
17.01.76	1	1	1	1	1	1	3a	3a
25.01.76	1	1	1	1	1	1	1	1
30.01.76	1	1	1	1	1	1	1	1
28.02.76	2	2	3a	3a	4a	4a	3a	3a
1976-1977								
10.01.77	4a	6b	6b	6b	6b	6b	6b	6b
21.01.77	6b	6b	6b	6b	6b	6b	6b	6b
16.02.77	1	1	2	2	3a	3a	2	2
1977-1978								
13.01.78	1	1	1	1	1	1	1	1
17.01.78	1	1	1	1	1	1	1	1
29.01.78	1	1	1	1	1	1	1	1
1978-1979								
12.01.79	1	1	1	1	1	1	3a	3a
14.01.79	3a	3a	3a	3a	3a	3a	3a	3a
21.01.79	1	1	1	1	1	1	1	1

Annex 4-9c: Total MARCROP-calculation results (1979/80 – 1988/89)

Soil unit:	Unit I		Unit II		Unit III		Unit IV	
Scenario:	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Planting dates/ season								
1979-1980								
04.02.80	6d	6d	6d	6d	6d	6d	6d	6d
19.02.80	6a	6b	6b	6b	6b	6b	6b	6b
05.03.80	6b	6b	6b	6b	6b	6b	6b	6b
1980-1981								
05.01.81	6c	6c	6c	6c	6c	6c	6c	6c
05.03.81	4a	4a	4a	4a	4a	4a	6c	6c
1981-1982								
29.01.82	3a	3a	3a	3a	3a	3a	3a	3a
01.02.82	3a	3a	3a	3a	3a	3a	3a	3a
12.02.82	2	2	2	2	2	2	3a	3a
19.02.82	6d	6d	6d	6d	6d	6d	6d	6d
1982-1983								
01.01.83	6b	6b	6b	6b	6b	6b	6b	6b
31.01.83	6b	6b	6b	6b	6b	6b	6b	6b
10.02.83	6b	6b	6b	6b	6b	6b	6b	6b
1983-1984								
03.01.84	6b	6b	6b	6b	6b	6b	6b	6b
05.02.84	4a	4a	4a	4a	4a	4a	4a	4a
05.03.84	1	1	2	2	2	2	1	1
1984-1985								
26.01.85	6b	6b	6b	6b	6b	6b	6b	6b
29.01.85	6b	6b	6b	6b	6b	6b	6b	6b
08.03.85	6c	6c	6c	6c	6c	6c	6c	6c
1985-1986								
18.01.86	1	1	1	3a	3a	3a	3a	3a
20.01.86	3a	3a	3a	3a	3a	3a	3a	3a
07.02.86	3a	3a	3a	3a	3a	3a	3a	3a
19.02.86	3a	3b	3b	3b	3b	3b	5b	5b
1986-1987								
07.02.87	6b	6b	6b	6b	6b	6b	6b	6b
15.02.87	6b	6b	6b	6b	6b	6b	6b	6b
26.02.87	6b	6b	6b	6b	6b	6b	6b	6b
1987-1988								
10.01.88	6b	6b	6b	6b	6b	6b	6b	6b
27.02.88	6b	6c	6c	6c	6c	6c	6c	6c
1988-1989								
10.11.88	3a	3a	5b	5b	5c	5c	5c	5c
10.12.88	6b	6b	6b	6b	6b	6b	6b	6b
04.01.89	3a	3a	3a	3a	3a	3a	4a	4a
16.01.89	4a	4a	4a	4a	4a	4a	6a	6a
28.01.89	6b	6b	6b	6b	6b	6b	6b	6b
05.02.89	6b	6b	6b	6b	6b	6b	6b	6b

Annex 4-9d: Best calculation results per season, scenario and soil unit (differences in results of scenario A and B are marked grey)

Soil units		1960-1961		1961-1962		1962-1963		1963-1964		1964-1965		1965-1966		1966-1967		1967-1968		1968-1969	
		Scen. A	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Unit I		1	1	4	4	1	1	6b	6b	4	4	6b	6b	1	1	1	2	1	1
Unit II		1	1	4	4	1	1	6b	6b	6a	6a	6b	6b	1	1	1	2	1	1
Unit III		3	3	6b	6b	1	1	6b	6b	6a	6a	6b	6b	1	1	1	2	2	2
Unit IV		3	3	6b	6b	1	1	6b	6b	6a	6b	6b	6b	1	1	3	3	1	1

Soil units	1969-1970		1970-1971		1971-1972		1972-1973		1973-1974		1974-1975		1975-1976		1976-1977		1977-1978		1978-1979	
	Scen. A	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Unit I	1	1	1	1	1	1	1	1	1	1	4	4	1	1	1	1	1	1	1	1
Unit II	1	3	1	1	1	1	1	1	1	1	4	4	1	1	2	2	1	1	1	1
Unit III	3	3	1	1	2	2	1	1	1	1	4	6b	1	1	3	3	1	1	1	1
Unit IV	1	1	1	1	2	2	1	1	1	1	6b	6b	1	1	2	2	1	1	1	1

Soil units	1979-1980		1980-1981		1981-1982		1982-1983		1983-1984		1984-1985		1985-1986		1986-1987		1987-1988		1988-1989	
	Scen. A	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*	*Scen. A*	*Scen. B*
Unit I	6a	6b	4	4	2	2	6b	6b	1	1	6b	6b	1	1	6b	6b	6b	6b	3	3
Unit II	6b	6b	4	4	2	2	6b	6b	2	2	6b	6b	1	3	6b	6b	6b	6b	3	3
Unit III	6b	6b	4	4	2	2	6b	6b	2	2	6b	6b	3	3	6b	6b	6b	6b	3	3
Unit IV	6b	6b	6c	6c	3	3	6b	6b	1	1	6b	6b	3	3	6b	6b	6b	6b	4	4

Annex 4-10: Correspondence of calculation results from scenario A and B by soil unit

Comparison of total seasonal calculation results from scenario A and B by soil unit:

	Soil unit I	Soil unit II	Soil unit III	Soil unit IV
Total number of calculations/ soil unit	98	98	98	98
Factor of correspondence (rounded)	0,95	0,94	0,98	0,99
Total number of calculations resulting in different yield classes between Scenario A & B	5	6	2	1
quality of difference:				
difference 1 class	3	3	1	0
difference 2 classes	2	3	1	1

Comparison of best seasonal calculation results from scenario A and B by soil unit:

	Soil unit I	Soil unit II	Soil unit III	Soil unit IV
Total number of calculations/ soil unit	29	29	29	29
Factor of correspondence (rounded)	0,93	0,90	0,93	0,97
Total number of calculations resulting in different yield classes between Scenario A & B	2	3	2	1
quality of difference:				
difference 1 class	2	1	1	1
difference 2 classes	0	2	1	0

Annex 4-11: Total number and percentage of reclassified, best seasonal calculation results by scenario, class, soil unit and decade

Soil unit		favourable yield*		marginal/ minimal yield*		total crop failure*	
Unit I		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total seasons (29)	*total number*	18	18	5	4	6	7
	%	62,07	62,07	17,24	13,79	20,69	24,14
sixties (9 seasons)	*total number*	5	5	2	2	2	2
	%	55,56	55,56	22,22	22,22	22,22	22,22
seventies (10 seasons)	*total number*	9	9	1	1	0	0
	%	90,00	90,00	10,00	10,00	0,00	0,00
eighties (10 seasons)	*total number*	4	4	2	1	4	5
	%	40,00	40,00	20,00	10,00	40,00	50,00

Unit II		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total seasons (29)	*total number*	18	18	4	4	7	7
	%	62,07	62,07	13,79	13,79	24,14	24,14
sixties (9 seasons)	*total number*	5	5	2	2	2	2
	%	55,56	55,56	22,22	22,22	22,22	22,22
seventies (10 seasons)	*total number*	9	9	1	1	0	0
	%	90,00	90,00	10,00	10,00	0,00	0,00
eighties (10 seasons)	*total number*	4	4	1	1	5	5
	%	40,00	40,00	10,00	10,00	50,00	50,00

Unit III		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total seasons (29)	*total number*	18	18	3	2	8	9
	%	62,07	62,07	10,34	6,90	27,59	31,03
sixties (9 seasons)	*total number*	5	5	1	1	3	3
	%	55,56	55,56	11,11	11,11	33,33	33,33
seventies (10 seasons)	*total number*	9	9	1	0	0	1
	%	90,00	90,00	10,00	0,00	0,00	10,00
eighties (10 seasons)	*total number*	4	4	1	1	5	5
	%	40,00	40,00	10,00	10,00	50,00	50,00

Unit IV		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total seasons (29)	*total number*	17	17	2	1	10	11
	%	58,62	58,62	6,90	3,45	34,48	37,93
sixties (9 seasons)	*total number*	5	5	1	0	3	4
	%	55,56	55,56	11,11	0,00	33,33	44,44
seventies (10 seasons)	*total number*	9	9	0	0	1	1
	%	90,00	90,00	0,00	0,00	10,00	10,00
eighties (10 seasons)	*total number*	3	3	1	1	6	6
	%	30,00	30,00	10,00	10,00	60,00	60,00

*) **favourable yield:** MARCROP classes 1 (optimum, 80-100% yield), 2 (sub-optimum, 60-80% yield) and 3 (average, 40-60% yield)
marginal/ minimal yield: MARCROP classes 4 (marginal, 20-40% yield), 5 (marginal, 20-40% yield) and 6a (minimal, 10-20% yield)
total crop failure: MARCROP classes 6b-d (total crop failure, <10% yield)

Annex 4-12: Total number and percentage of best seasonal calculation results by scenario, class, soil unit and decade

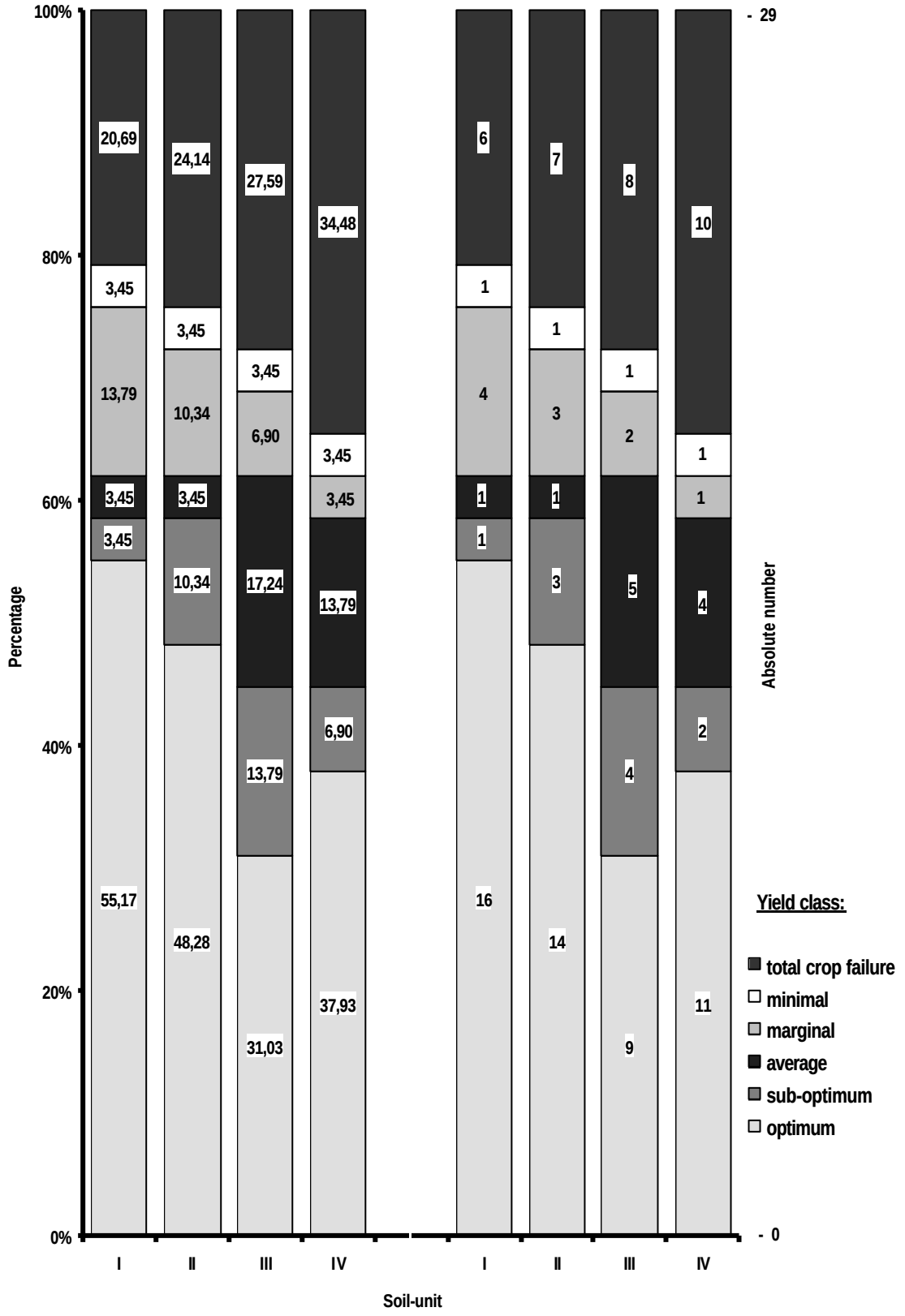
Soil unit		1 (optimum)		2 (sub-optimum)		3 (average)		4 & 5 (marginal)		6a (minimal)		6b-d (tot.c.fail.)	
Unit I		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total (29 seasons)	*total number*	16	15	1	2	1	1	4	4	1	0	6	7
	%	55,17	51,72	3,45	6,90	3,45	3,45	13,79	13,79	3,45	0,00	20,69	24,14
Sixties (9 seasons)	*total number*	5	4	0	1	0	0	2	2	0	0	2	2
	%	55,56	44,44	0,00	11,11	0,00	0,00	22,22	22,22	0,00	0,00	22,22	22,22
seventies (10 seasons)	*total number*	9	9	0	0	0	0	1	1	0	0	0	0
	%	90,00	90,00	0,00	0,00	0,00	0,00	10,00	10,00	0,00	0,00	0,00	0,00
eighties (10 seasons)	*total number*	2	2	1	1	1	1	1	1	1	0	4	5
	%	20,00	20,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	0,00	40,00	50,00

Unit II		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total (29 seasons)	*total number*	14	11	3	4	1	3	3	3	1	1	7	7
	%	48,28	37,93	10,34	13,79	3,45	10,34	10,34	10,34	3,45	3,45	24,14	24,14
Sixties (9 seasons)	*total number*	5	4	0	1	0	0	1	1	1	1	2	2
	%	55,56	44,44	0,00	11,11	0,00	0,00	11,11	11,11	11,11	11,11	22,22	22,22
seventies (10 seasons)	*total number*	8	7	1	1	0	1	1	1	0	0	0	0
	%	80,00	70,00	10,00	10,00	0,00	10,00	10,00	10,00	0,00	0,00	0,00	0,00
eighties (10 seasons)	*total number*	1	0	2	2	1	2	1	1	0	0	5	5
	%	10,00	0,00	20,00	20,00	10,00	20,00	10,00	10,00	0,00	0,00	50,00	50,00

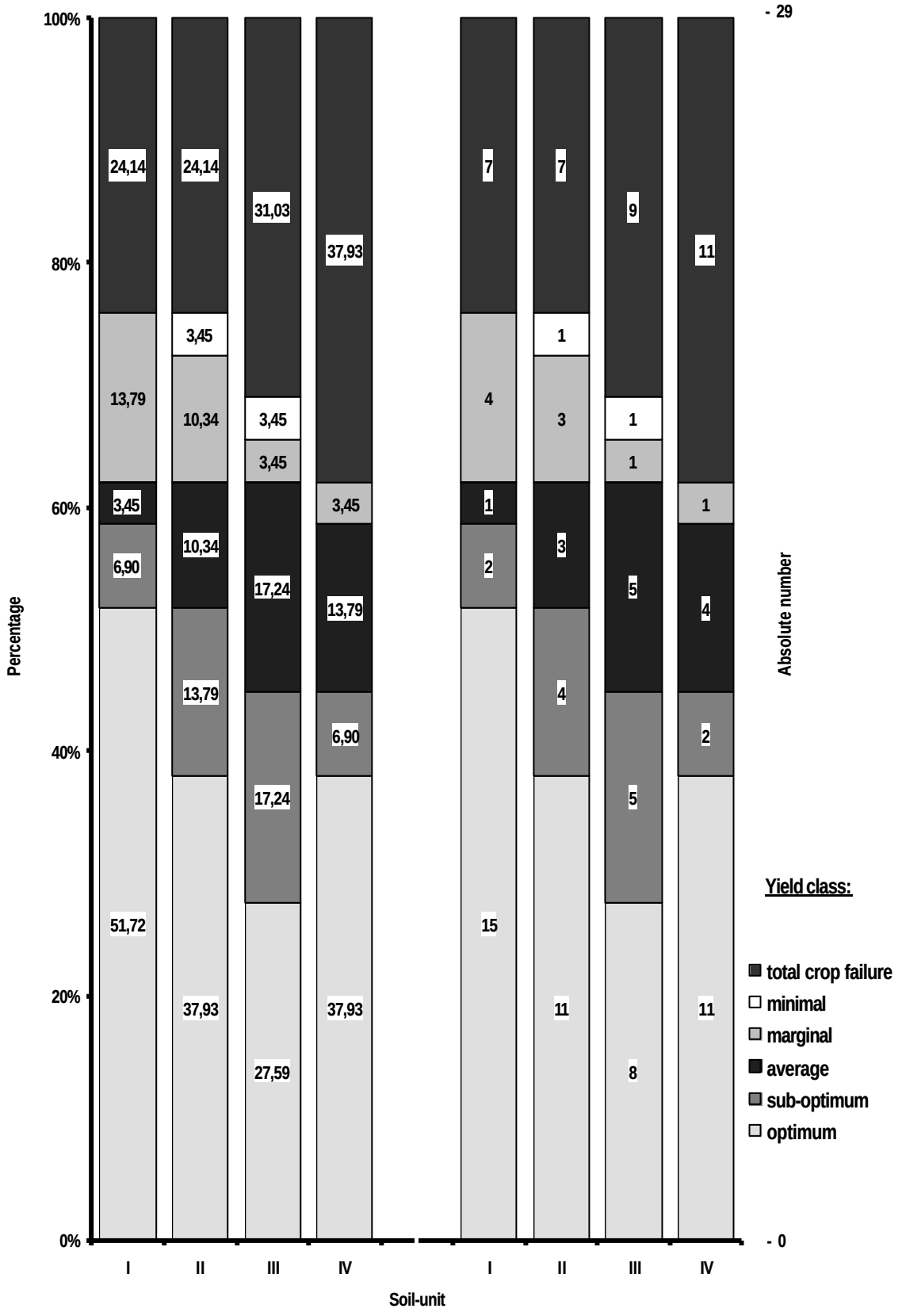
Unit III		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total (29 seasons)	*total number*	9	8	4	5	5	5	2	1	1	1	8	9
	%	31,03	27,59	13,79	17,24	17,24	17,24	6,90	3,45	3,45	3,45	27,59	31,03
Sixties (9 seasons)	*total number*	3	2	1	2	1	1	0	0	1	1	3	3
	%	33,33	22,22	11,11	22,22	11,11	11,11	0,00	0,00	11,11	11,11	33,33	33,33
seventies (10 seasons)	*total number*	6	6	1	1	2	2	1	0	0	0	0	1
	%	60,00	60,00	10,00	10,00	20,00	20,00	10,00	0,00	0,00	0,00	0,00	10,00
eighties (10 seasons)	*total number*	0	0	2	2	2	2	1	1	0	0	5	5
	%	0,00	0,00	20,00	20,00	20,00	20,00	10,00	10,00	0,00	0,00	50,00	50,00

Unit IV		*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*	*scen. A*	*scen. B*
total (29 seasons)	*total number*	11	11	2	2	4	4	1	1	1	0	10	11
	%	37,93	37,93	6,90	6,90	13,79	13,79	3,45	3,45	3,45	0,00	34,48	37,93
Sixties (9 seasons)	*total number*	3	3	0	0	2	2	0	0	1	0	3	4
	%	33,33	33,33	0,00	0,00	22,22	22,22	0,00	0,00	11,11	0,00	33,33	44,44
seventies (10 seasons)	*total number*	7	7	2	2	0	0	0	0	0	0	1	1
	%	70,00	70,00	20,00	20,00	0,00	0,00	0,00	0,00	0,00	0,00	10,00	10,00
eighties (10 seasons)	*total number*	1	1	0	0	2	2	1	1	0	0	6	6
	%	10,00	10,00	0,00	0,00	20,00	20,00	10,00	10,00	0,00	0,00	60,00	60,00

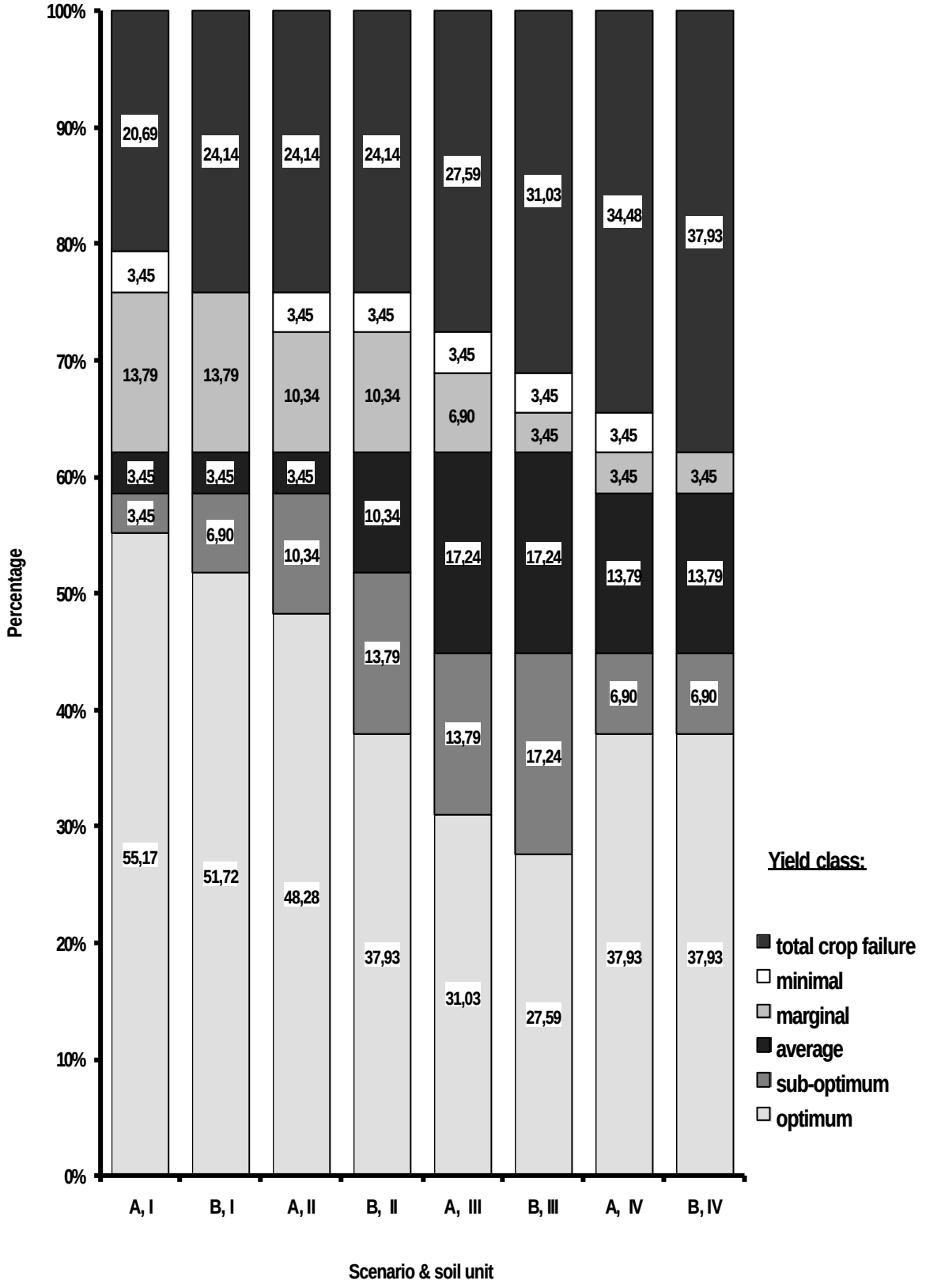
Annex 4-13a: Scenario A- percentage (left) and absolute numbers (right) of calculation results by soil unit (29 seasons, best result/ season)



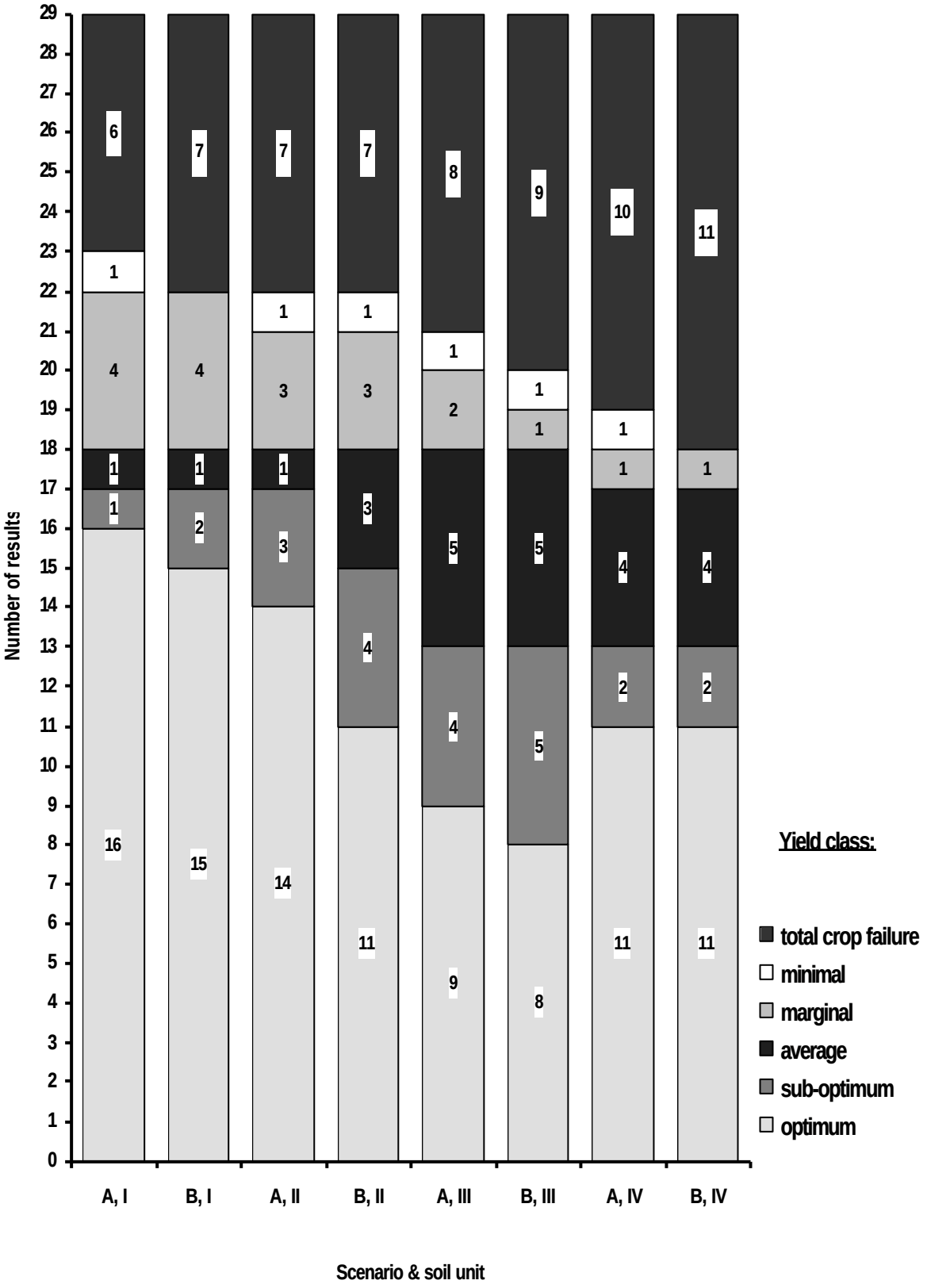
Annex 4-13b: Scenario B - percentage (left) and absolute numbers (right) of calculation results by soil unit (29 seasons, best result/ season)



Annex 4-14a: Comparison scenario A/B - percentage of calculation results in relation to the soil units (29 seasons, best result/ season)



Annex 4-14b: Comparison scenario A/B - absolute numbers of calculation results in relation to the soil units (29 seasons, best result/ season)



Annex 4-15a: Scenario A - best seasonal calculation results (1960/61-1968/69) in relation to rainfall distribution

Season	Starting date of simulation with best results per season	Calculated yield (scen. A) per soil unit (I/II/III/IV)	Total number of days with rainfall during veget. cycle of Tepary	Total number of days during growth phase I	Total number of days during growth phase II	Total number of days during growth phase III	Total number of days during growth phase IV	Rainfall amount (mm, scen. A) during veget. cycle of Tepary	Rainfall amount (mm, scen. A) during growth phase I	Rainfall amount (mm, scen. A) during growth phase II	Rainfall amount (mm, scen. A) during growth phase III	Rainfall amount (mm, scen. A) during growth phase IV	Days during the vegetation cycle with rainfall
1960-61	03. Mrz	1/1/3/3	8	3	2	3	0	184,5	73,5	10,9	100,1	0,0	1, 3-4, 7,11,16, 29, 31,35
1961-62	07. Feb	4a/4a/6b/6b	15	5	1	5	4	82,0	74,5	0,1	7,1	0,4	1-4, 6, 8, 20, 22, 36-38, 47-48, 52, 54
1962-63	28. Feb	1/1/1/1	27	5	8	7	7	320,0	86,3	146,4	58,0	29,2	1-4,7,9-14,16-17,21,23, 27-29,37, 39-40, 42, 45-48, 55
1963-64	04. Jan	6b/6b/6b/6b	11	4	2	1	4	131,7	75,4	14,7	0,2	41,5	1-4, 17-18, 20, 40, 50, 54-55
1963-64	22. Feb	6b/6b/6b/6b	9	3	3	3	0	51,7	22,0	16,9	12,9	0,0	1,5-6, 11, 17, 20-21, 36, 39
1963-64	09. Mrz	6b/6b/6b/6b	5	3	0	2	0	26,8	22,8	0,0	4,0	0,0	1, 4-5, 20, 23
1964-65	28. Jan	4a/6a/6a/6a	18	4	4	4	6	130,3	55,2	25,7	47,6	1,8	1-2, 4, 6, 8-9, 16-17, 21-24, 40, 46, 51-54
1965-66	11. Jan	6b/6b/6b/6b	12	3	6	3	0	141,6	43,8	69,2	28,6	0,0	1, 6-7, 9-10, 14-16, 19-22
1965-66	15. Jan	6b/6b/6b/6b	12	4	7	0	1	119,4	40,5	74,7	0,0	4,2	1, 3, 5-6, 10-12, 15-18, 52
1965-66	20. Jan	6b/6b/6b/6b	11	4	4	0	3	121,2	29,2	62,0	0,0	30,0	1, 5-7, 10-13, 47, 54-55
1966-67	06. Feb	1/1/1/1	25	5	5	12	3	300,8	131,3	27,0	112,0	30,5	1-2, 5-12, 22-26, 29-30, 33-34, 37-39, 52-54
1966-67	28. Feb	1/3a/3a/3a	21	5	6	8	2	156,8	28,4	77,3	43,4	7,7	1-4, 7-8, 11-12, 15-17, 30-32, 35-39, 54-55
1967-68	01. Mrz	1/1/1/3a	16	5	7	4	0	287,2	44,7	217,9	24,6	0,0	1-4, 7-8, 10, 12-14, 18-20, 27-28, 37
1968-69	23. Jan	1/1/2/1	18	2	7	6	3	224,5	19,8	116,2	84,9	3,7	1-2, 8-11, 13-15, 24, 26-27, 34, 36, 38, 41-43

Annex 4-15b: Scenario B - best seasonal calculation results (1960/61-1968/69) in relation to rainfall distribution

Season	Starting date of simulation with best results per season	Calculated yield (scen. B) per soil unit (I/II/III/IV)	Total number of days with rainfall during veget. cycle of Tepary	Total number of days during growth phase I	Total number of days during growth phase II	Total number of days during growth phase III	Total number of days during growth phase IV	Rainfall amount (mm, scen. B) during veget. cycle of Tepary	Rainfall amount (mm, scen. B) during growth phase I	Rainfall amount (mm, scen. B) during growth phase II	Rainfall amount (mm, scen. B) during growth phase III	Rainfall amount (mm, scen. B) during growth phase IV	Days during the vegetation cycle with rainfall
1960-61	03. Mrz	1/1/3/3	8	3	2	3	0	184,7	70,7	10,8	103,1	0,0	1, 3-4, 7,11,16, 29, 31,35
1961-62	07. Feb	4b/4b/6b/6b	15	5	1	5	4	79,2	71,8	0,1	6,8	0,4	1-4, 6, 8, 20, 22, 36-38, 47-48, 52, 54
1962-63	28. Feb	1/1/1/1	27	5	8	7	7	318,5	84,8	144,9	58,4	30,3	1-4,7,9-14,16-17,21,23, 27-29,37, 39-40, 42, 45-48, 55
1963-64	04. Jan	6b/6b/6b/6b	11	4	2	1	4	122,4	68,8	13,4	0,2	40,0	1-4, 17-18, 20, 40, 50, 54-55
1963-64	22. Feb	6b/6b/6b/6b	9	3	3	3	0	50,7	21,2	17,7	11,8	0,0	1,5-6, 11, 17, 20-21, 36, 39
1963-64	09. Mrz	6b/6b/6b/6b	5	3	0	2	0	26,5	22,6	0,0	3,9	0,0	1, 4-5, 20, 23
1964-65	28. Jan	4a/6a/6a/6b	18	4	4	4	6	123,7	51,2	24,8	45,9	1,8	1-2, 4, 6, 8-9, 16-17, 21-24, 40, 46, 51-54
1965-66	11. Jan	6b/6b/6b/6b	12	3	6	3	0	129,8	40,0	63,2	26,6	0,0	1, 6-7, 9-10, 14-16, 19-22
1965-66	15. Jan	6b/6b/6b/6b	12	4	7	0	1	109,8	37,0	68,7	0,0	4,1	1, 3, 5-6, 10-12, 15-18, 52
1965-66	20. Jan	6b/6b/6b/6b	11	4	4	0	3	113,4	26,7	57,1	0,0	29,7	1, 5-7, 10-13, 47, 54-55
1966-67	06. Feb	1/1/1/1	25	5	5	12	3	293,3	126,6	26,1	110,4	30,2	1-2, 5-12, 22-26, 29-30, 33-34, 37-39, 52-54
1966-67	28. Feb	1/3a/3a/3a	21	5	6	8	2	155,9	27,7	76,5	43,6	8,0	1-4, 7-8, 11-12, 15-17, 30-32, 35-39, 54-55
1967-68	01. Mrz	2/2/2/3a	16	5	7	4	0	284,4	44,2	215,6	24,6	0,0	1-4, 7-8, 10, 12-14, 18-20, 27-28, 37
1968-69	23. Jan	1/1/2/1	18	2	7	6	3	213,6	18,1	110,0	81,9	3,6	1-2, 8-11, 13-15, 24, 26-27, 34, 36, 38, 41-43

Annex 4-15c: Scenario A - best seasonal calculation results (1970/71-1978/79) in relation to rainfall distribution

Season	Starting date of simulation with best results per season	Calculated yield (scen. A) per soil unit (I/II/III/IV)	Total number of days with rainfall during veget. cycle of Tepary	Total number of days during growth phase I	Total number of days during growth phase II	Total number of days during growth phase III	Total number of days during growth phase IV	Rainfall amount (mm, scen. A) during veget. cycle of Tepary beans	Rainfall amount (mm, scen. A) during growth phase I	Rainfall amount (mm, scen. A) during growth phase II	Rainfall amount (mm, scen. A) during growth phase III	Rainfall amount (mm, scen. A) during growth phase IV	Days during the vegetation cycle with rainfall
1969-70	19. Jan	1/1/3a/1	27	5	7	7	8	270,2	98,1	26,1	107,7	38,3	1-2, 4-5, 7, 11-14, 16-18, 20, 24-25, 31, 36-38, 40, 46, 48-51, 53-54
1969-70	04. Feb	1/3a/3a/1	17	3	3	11	0	160,3	17,1	35,1	108,1	0,0	1-2, 4, 8-9, 15, 20-22, 24, 30, 32-35, 37-38
1970-71	27. Jan	1/1/1/1	27	6	7	11	3	267,9	60,8	59,3	117,6	30,1	1-6, 8-10, 16-20, 23, 25-30, 32-34, 40, 47-48
1970-71	31. Jan	1/1/3a/1	26	5	6	10	5	113,3	7,7	30,1	53,4	22,1	1-2, 8, 15-16, 24, 26-27, 29, 35, 54-55
1970-71	14. Feb	1/1/1/1	20	4	8	4	4	102,6	27,1	49,6	3,8	22,1	1-2, 10, 12-13, 15, 21, 40-41
1971-72	02. Mrz	1/1/2/2	22	7	4	7	4	233,5	86,0	51,3	72,3	23,8	1-9, 11-12, 23, 25-28, 36, 38, 49, 51-53
1972-73	02. Mrz	1/1/1/1	18	4	6	8	0	250,7	60,6	64,2	125,9	0,0	1-2, 5, 7, 12-13, 16-20, 23-24, 26, 29, 31-32, 35
1973-74	03. Jan	1/1/1/1	30	6	6	8	10	552,1	141,3	171,8	88,1	150,9	1, 3-7, 14-20, 24, 28-29, 35-36, 38-40, 42-49, 53
1973-74	16. Jan	1/1/1/1	30	7	3	13	7	457,0	171,9	35,6	203,0	46,5	1-7, 11, 15-16, 22-23, 25-27, 29-36, 40, 45, 49-51, 53-54
1973-74	30. Jan	1/1/1/1	29	2	10	9	8	378,8	34,2	191,6	57,4	95,7	1-2, 8-9, 11-13, 15-22, 26, 31, 35-37, 39-40, 43, 45-47, 52-54
1973-74	06. Feb	1/1/1/1	28	5	9	9	5	345,0	55,9	147,3	86,3	55,6	1-2, 4-6, 8-15, 19, 24, 28-30, 32-33, 36, 38-40, 45-47, 54
1974-75	04. Jan	4a/4a/4a/6b	13	1	7	5	0	136,5	25,4	57,0	54,1	0,0	1-2, 10-15, 18, 24, 32-34, 38
1975-76	25. Jan	1/1/1/1	26	7	4	9	6	353,3	149,6	76,3	59,4	67,9	1-9, 14-15, 25-26, 31-33, 35, 37, 39-42, 45, 47, 49, 53
1975-76	30. Jan	1/1/1/1	21	4	2	12	3	217,8	75,6	14,8	111,6	15,7	1-4, 9-10, 20-21, 26-28, 30, 32, 34-37, 40, 42, 44, 48
1976-77	16. Feb	1/2/3a/2	19	6	4	7	2	199,3	99,3	27,1	49,1	23,6	1-6, 9-10, 12, 14, 21, 23-25, 28, 36, 39, 54-55
1977-78	13. Jan	1/1/1/1	21	5	6	8	2	341,3	55,8	58,9	146,7	79,9	1-3, 5, 7-10, 17-19, 21-23, 25-27, 35-36, 43, 50
1977-78	17. Jan	1/1/1/1	20	5	6	6	3	345,1	51,3	147,1	75,9	70,7	1, 3-6, 13-15, 17-19, 21-23, 31-32, 39, 46, 54-55
1977-78	29. Jan	1/1/1/1	16	6	4	3	3	296,7	147,1	23,7	103,8	22,0	1-3, 5-7, 9-11, 19-20, 27, 34, 42-43, 48
1978-79	12. Jan	1/1/1/3a	23	3	5	9	6	457,9	26,7	257,7	56,3	117,3	1, 3, 5, 10-12, 18-20, 24, 26-27, 31-35, 43-47, 49
1978-79	21. Jan	1/1/1/1	21	3	6	10	2	453,6	207,3	59,0	156,0	31,3	1-3, 9-11, 15, 17-18, 22-26, 34-38, 40, 49

Annex 4-15d: Scenario B - best seasonal calculation results (1970/71-1978/79) in relation to rainfall distribution

Season	Starting date of simulation with best results per season	Calculated yield (scen. B) per soil unit (I/II/III/IV)	Total number of days with rainfall during veget. cycle of Tepary	Total number of days during growth phase I	Total number of days during growth phase II	Total number of days during growth phase III	Total number of days during growth phase IV	Rainfall amount (mm, scen. B) during veget. cycle of Tepary beans	Rainfall amount (mm, scen. B) during growth phase I	Rainfall amount (mm, scen. B) during growth phase II	Rainfall amount (mm, scen. B) during growth phase III	Rainfall amount (mm, scen. B) during growth phase IV	Days during the vegetation cycle with rainfall
1969-70	19. Jan	1/3a/3a/1	27	5	7	7	8	256,2	89,5	24,8	103,9	37,9	1-2, 4-5, 7, 11-14, 16-18, 20, 24-25, 31, 36-38, 40, 46, 48-51, 53-54
1969-70	04. Feb	1/3a/3a/3a	17	3	3	11	0	155,6	16,5	33,9	105,2	0,0	1-2, 4, 8-9, 15, 20-22, 24, 30, 32-35, 37-38
1970-71	27. Jan	1/1/1/1	27	6	7	11	3	256,1	55,6	57,2	113,5	29,8	1-6, 8-10, 16-20, 23, 25-30, 32-34, 40, 47-48
1970-71	31. Jan	1/1/3a/1	26	5	6	10	5	257,4	39,0	35,9	111,0	71,5	1-2, 8, 15-16, 24, 26-27, 29, 35, 54-55
1970-71	14. Feb	1/1/1/1	20	4	8	4	4	220,3	50,7	86,8	45,0	37,8	1-2, 10, 12-13, 15, 21, 40-41
1971-72	02. Mrz	1/1/2/2	22	7	4	7	4	232,4	85,1	50,8	71,8	24,8	1-9, 11-12, 23, 25-28, 36, 38, 49, 51-53
1972-73	02. Mrz	1/1/1/1	18	4	6	8	0	249,2	59,9	63,6	125,7	0,0	1-2, 5, 7, 12-13, 16-20, 23-24, 26, 29, 31-32, 35
1973-74	03. Jan	1/1/1/1	30	6	6	8	10	514,5	129,0	156,8	83,1	145,6	1, 3-7, 14-20, 24, 28-29, 35-36, 38-40, 42-49, 53
1973-74	16. Jan	1/1/1/1	30	7	3	13	7	431,2	156,9	32,5	195,8	46,0	1-7, 11, 15-16, 22-23, 25-27, 29-36, 40, 45, 49-51, 53-54
1973-74	30. Jan	1/1/1/1	29	2	10	9	8	367,2	31,2	184,8	56,5	94,7	1-2, 8-9, 11-13, 15-22, 26, 31, 35-37, 39-40, 43, 45-47, 52-54
1973-74	06. Feb	1/1/1/1	28	5	9	9	5	336,4	53,9	142,1	85,4	55,0	1-2, 4-6, 8-15, 19, 24, 28-30, 32-33, 36, 38-40, 45-47, 54
1974-75	04. Jan	4a/4a/6b/6b	13	1	7	5	0	107,5	3,4	52,0	52,1	0,0	1-2, 10-15, 18, 24, 32-34, 38
1975-76	25. Jan	1/1/1/1	26	7	4	9	6	335,4	136,6	73,6	69,3	55,9	1-9, 14-15, 25-26, 31-33, 35, 37, 39-42, 45, 47, 49, 53
1975-76	30. Jan	1/1/1/1	21	4	2	12	3	211,8	72,2	14,3	117,1	8,2	1-4, 9-10, 20-21, 26-28, 30, 32, 34-37, 40, 42, 44, 48
1976-77	16. Feb	1/2/3a/2	19	6	4	7	2	195,2	95,8	26,2	48,6	24,6	1-6, 9-10, 12, 14, 21, 23-25, 28, 36, 39, 54-55
1977-78	13. Jan	1/1/1/1	21	5	6	8	2	324,5	50,9	53,7	141,5	78,4	1-3, 5, 7-10, 17-19, 21-23, 25-27, 35-36, 43, 50
1977-78	17. Jan	1/1/1/1	20	5	6	6	3	329,5	46,9	139,4	73,3	69,9	1, 3-6, 13-15, 17-19, 21-23, 31-32, 39, 46, 54-55
1977-78	29. Jan	1/1/1/1	16	6	4	3	3	285,6	139,4	22,9	101,5	21,8	1-3, 5-7, 9-11, 19-20, 27, 34, 42-43, 48
1978-79	12. Jan	1/1/1/3a	23	3	5	9	6	427,2	24,3	235,2	54,3	113,3	1, 3, 5, 10-12, 18-20, 24, 26-27, 31-35, 43-47, 49
1978-79	21. Jan	1/1/1/1	21	3	6	10	2	424,9	189,2	54,3	150,5	30,9	1-3, 9-11, 15, 17-18, 22-26, 34-38, 40, 49

Annex 4-15e: Scenario A - best seasonal calculation results (1980/81-1988/89) in relation to rainfall distribution

Season	Starting date of simulation with best results per season	Calculated yield (scen. A) per soil unit (I/II/III/IV)	Total number of days with rainfall during veget. cycle of	Total number of days during growth phase I	Total number of days during growth phase II	Total number of days during growth phase III	Total number of days during growth phase IV	Rainfall amount (mm, scen. A) during veget. cycle of Tepary	Rainfall amount (mm, scen. A) during growth phase I	Rainfall amount (mm, scen. A) during growth phase II	Rainfall amount (mm, scen. A) during growth phase III	Rainfall amount (mm, scen. A) during growth phase IV	Days during the vegetation cycle with rainfall
1979-80	04. Feb	6d/6d/6d/6d	10	1	5	4	0	139,8	18,5	46,4	75,0	0,0	1, 9, 13, 15-17, 31, 33-35
1979-80	19. Feb	6a/6b/6b/6b	6	2	4	0	0	105,2	30,3	70,0	5,0	0,0	1-2, 16, 18-20
1979-80	05. Mrz	6b/6b/6b/6b	4	4	0	0	0	75,0	75,0	0,0	0,0	0,0	1, 3-5
1980-81	05. Mrz	4a/4a/4a/6c	6	1	2	3	0	100,0	18,3	37,7	44,1	0,0	1, 17-18, 23-24, 36
1981-82	12. Feb	2/2/2/3a	9	1	3	5	0	139,7	19,0	44,7	75,9	0,0	1, 8, 11, 19-20, 25, 28, 30, 37
1982-83	01. Jan	6b/6b/6b/6b	11	3	4	2	2	110,9	29,2	25,9	23,6	32,2	1-3, 8-10, 16, 21, 31, 41, 47
1982-83	31. Jan	6b/6b/6b/6b	7	1	2	2	2	92,8	19,3	32,2	1,1	40,2	1, 11, 17, 31, 36, 42, 43
1982-83	10. Feb	6b/6b/6b/6b	4	2	0	2	0	75,0	32,2	0,0	41,3	1,5	1, 7, 21, 26, 32-33, 51
1983-84	05. Mrz	1/2/2/1	12	3	5	4	0	177,3	50,1	63,0	64,1	0,0	1, 3, 6, 9, 11, 14-15, 18, 24-25, 33-34
1984-85	26. Jan	6b/6b/6b/6b	9	4	4	0	1	106,2	57,4	38,5	0,0	10,4	1, 4, 6-10, 12, 42
1984-85	29. Jan	6b/6b/6b/6b	8	6	1	1	0	95,9	82,0	3,4	10,4	0,0	1, 3-7, 9, 39
1984-85	08. Mrz	6c/6c/6c/6c	4	1	1	2	0	36,1	10,4	3,5	22,2	0,0	1, 19-20, 28
1986-87	07. Feb	6b/6b/6b/6b	9	2	4	3	0	92,0	22,0	20,3	49,7	0,0	1-2, 9-10, 13-14, 20-21, 24
1986-87	15. Feb	6b/6b/6b/6b	7	4	3	0	0	70,0	20,3	49,7	0,0	0,0	1-2, 5-6, 12-13, 16
1986-87	26. Feb	6b/6b/6b/6b	3	3	0	0	0	49,7	49,7	0,0	0,0	0,0	1-2, 5
1987-88	10. Jan	6b/6b/6b/6b	9	6	0	2	1	422,1	399,8	0,0	12,0	10,2	1-3, 5-7, 32, 34, 49
1987-88	27. Feb	6b/6c/6c/6c	4	1	0	1	2	82,3	10,2	0,0	5,8	66,3	1, 24, 41, 50
1988-89	04. Jan	3a/3a/3a/4a	10	2	1	7	0	213,4	31,4	33,4	148,6	0,0	1, 7, 13, 24-26, 29-30, 33, 35

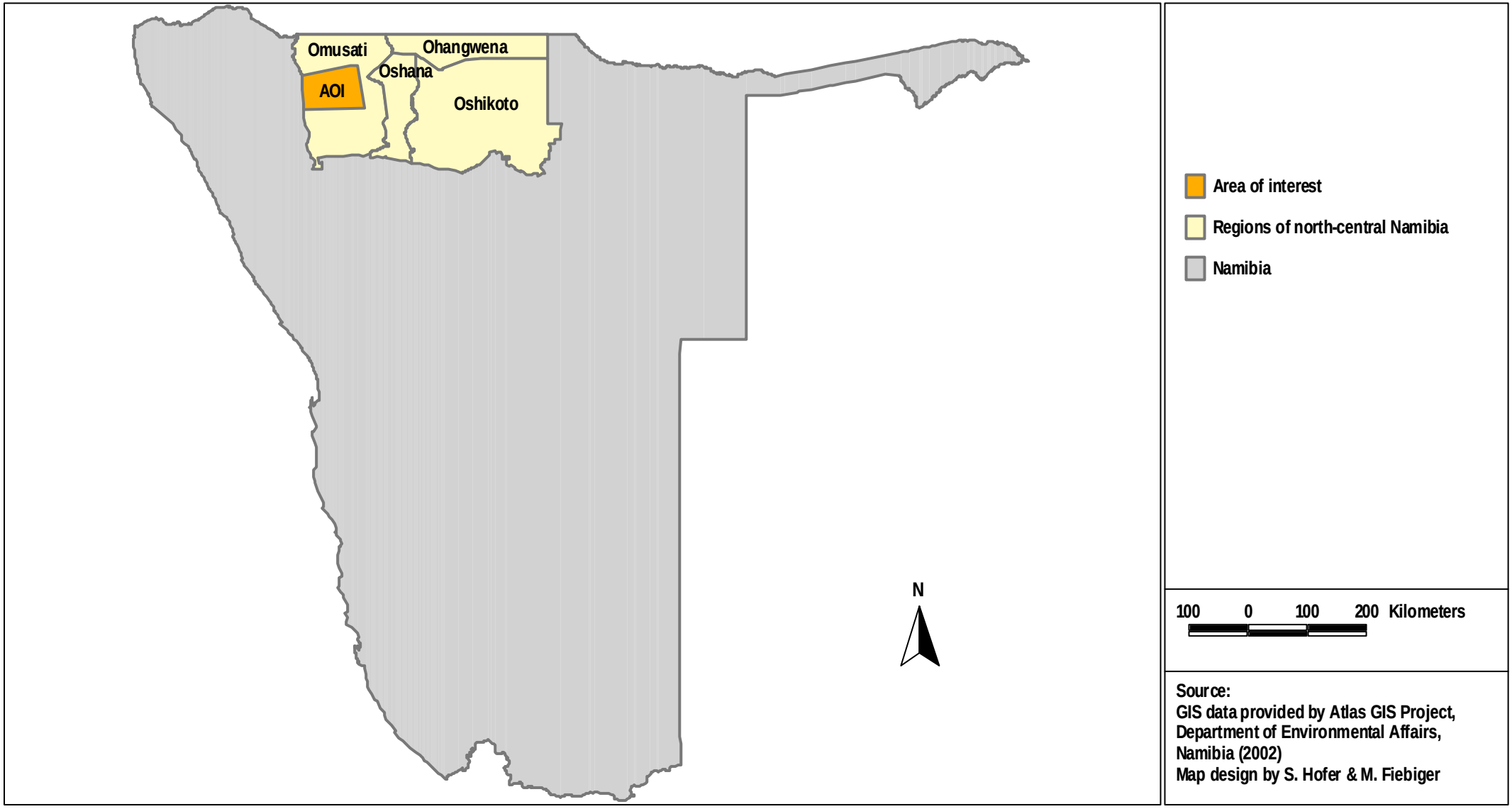
Annex 4-15f: Scenario B - best seasonal calculation results (1979/80-1988/89) in relation to rainfall distribution

Season	Starting date of simulation with best results per	Calculated yield (scen. B) per soil unit	Total number of days with rainfall during veget. cycle of Tepary beans	Total number of days during growth	Total number of days during growth	Total number of days during growth	Total number of days during growth	Rainfall amount (mm, scen. B) during veget. cycle of	Rainfall amount (mm, scen. B) during growth	Rainfall amount (mm, scen. B) during growth	Rainfall amount (mm, scen. B) during growth	Rainfall amount (mm, scen. B) during growth phase	Days during the vegetation cycle with rainfall
1979-80	04. Feb	6d/6d/6d/6d	10	1	5	4	0	136,8	17,9	44,7	74,2	0,0	1, 9, 13, 15-17, 31, 33-35
1979-80	19. Feb	6b/6b/6b/6b	6	2	4	0	0	103,4	29,2	74,2	0,0	0,0	1-2, 16, 18-20
1979-80	05. Mrz	6b/6b/6b/6b	4	4	0	0	0	74,2	74,2	0,0	0,0	0,0	1, 3-5
1980-81	05. Mrz	4a/4a/4a/6c	6	1	2	3	0	99,5	18,1	37,3	44,1	0,0	1, 17-18, 23-24, 36
1981-82	12. Feb	2/2/2/3a	9	1	3	5	0	137,1	18,4	43,6	75,1	0,0	1, 8, 11, 19-20, 25, 28, 30, 37
1982-83	01. Jan	6b/6b/6b/6b	11	3	4	2	2	102,9	26,7	23,6	21,5	31,1	1-3, 8-10, 16, 21, 31, 41, 47
1982-83	31. Jan	6b/6b/6b/6b	7	1	2	2	2	89,6	17,6	31,1	1,1	39,8	1, 11, 17, 31, 36, 42, 43
1982-83	10. Feb	6b/6b/6b/6b	4	2	0	2	0	70,8	39,8	0,0	31,0	0,0	1, 7, 21, 26, 32-33, 51
1983-84	05. Mrz	1/2/2/1	12	3	5	4	0	176,7	49,6	62,4	64,8	0,0	1, 3, 6, 9, 11, 14-15, 18, 24-25, 33-34
1984-85	26. Jan	6b/6b/6b/6b	9	4	4	0	1	101,0	53,6	37,1	0,0	10,3	1, 4, 6-10, 12, 42
1984-85	29. Jan	6b/6b/6b/6b	8	6	1	1	0	91,6	78,0	3,3	10,3	0,0	1, 3-7, 9, 39
1984-85	08. Mrz	6c/6c/6c/6c	4	1	1	2	0	36,2	10,3	3,4	22,5	0,0	1, 19-20, 28
1986-87	07. Feb	6b/6b/6b/6b	9	2	4	3	0	88,9	21,2	19,6	48,2	0,0	1-2, 9-10, 13-14, 20-21, 24
1986-87	15. Feb	6b/6b/6b/6b	7	4	3	0	0	67,7	19,6	48,2	0,0	0,0	1-2, 5-6, 12-13, 16
1986-87	26. Feb	6b/6b/6b/6b	3	3	0	0	0	48,2	48,2	0,0	0,0	0,0	1-2, 5
1987-88	10. Jan	6b/6b/6b/6b	9	6	0	2	1	422,1	399,8	0,0	12,0	10,2	1-3, 5-7, 32, 34, 49
1987-88	27. Feb	6c/6c/6c/6c	4	1	0	1	2	82,3	10,2	0,0	5,8	66,3	1, 24, 41, 50
1988-89	04. Jan	3a/3a/3a/4a	10	2	1	7	0	198,6	28,6	30,5	139,4	0,0	1, 7, 13, 24-26, 29-30, 33, 35

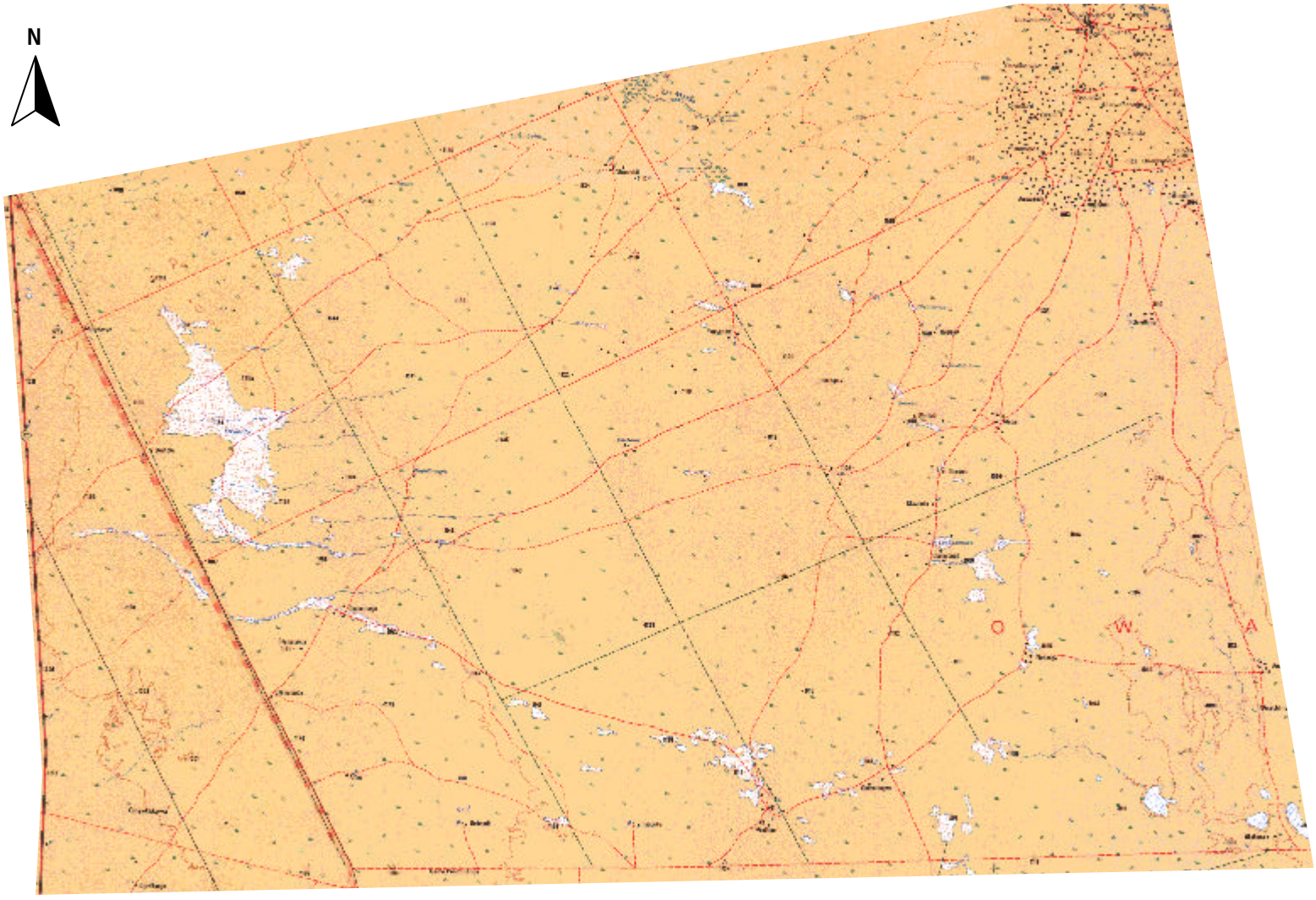
Annex 5-1: Comparison of best seasonal calculation results (scenario B, best result per season, soil units I & IV) of Tepary beans and Bambarra groundnut

	Class:	1 (optimum)		2 (sub-optimum)		3 (average)		4 (marginal)		5 (marginal)		6a (minimal)		6b-d (total crop failure)	
Scenario B, Soil-unit I		*Tepary*	*Bambarra*	*Tepary*	*Bambarra*	*Tepary*	*Bambarra*	*Tepary*	*Bambarra*	*Tepary*	*Bambarra*	*Tepary*	*Bambarra*	*Tepary*	*Bambarra*
1960 / 61 - 1988 / 89	***Total number***	15	0	2	13	1	5	4	6	0	0	0	0	7	5
	%	51,72	0,00	6,90	44,83	3,45	17,24	13,79	20,69	0,00	0,00	0,00	0,00	24,14	17,24
Sixties	***Total number***	4	0	1	3	0	2	2	3	0	0	0	0	2	1
	%	44,44	0,00	11,11	33,33	0,00	22,22	22,22	33,33	0,00	0,00	0,00	0,00	22,22	11,11
Seventies	***Total number***	9	0	0	8	0	1	1	1	0	0	0	0	0	0
	%	90,00	0,00	0,00	80,00	0,00	10,00	10,00	10,00	0,00	0,00	0,00	0,00	0,00	0,00
Eighties	***Total number***	2	0	1	2	1	2	1	2	0	0	0	0	5	4
	%	20,00	0,00	10,00	20,00	10,00	20,00	10,00	20,00	0,00	0,00	0,00	0,00	50,00	40,00
Scenario B, Soil-unit IV															
1960 / 61 - 1988 / 89	***Total number***	11	0	2	11	4	6	1	3	0	0	0	0	11	9
	%	37,93	0,00	6,90	37,93	13,79	20,69	3,45	10,34	0,00	0,00	0,00	0,00	37,93	31,03
Sixties	***Total number***	3	0	0	2	2	3	0	1	0	0	0	0	4	3
	%	33,33	0,00	0,00	22,22	22,22	33,33	0,00	11,11	0,00	0,00	0,00	0,00	44,44	33,33
Seventies	***Total number***	7	0	2	7	0	2	0	0	0	0	0	0	1	1
	%	70,00	0,00	20,00	70,00	0,00	20,00	0,00	0,00	0,00	0,00	0,00	0,00	10,00	10,00
Eighties	***Total number***	1	0	0	2	2	1	1	2	0	0	0	0	6	5
	%	10,00	0,00	0,00	20,00	20,00	10,00	10,00	20,00	0,00	0,00	0,00	0,00	60,00	50,00

Map 1: Location of the area of interest (AOI) and the four regions of north-central Namibia



Map 2: Topographical map of the central and western Omusati region

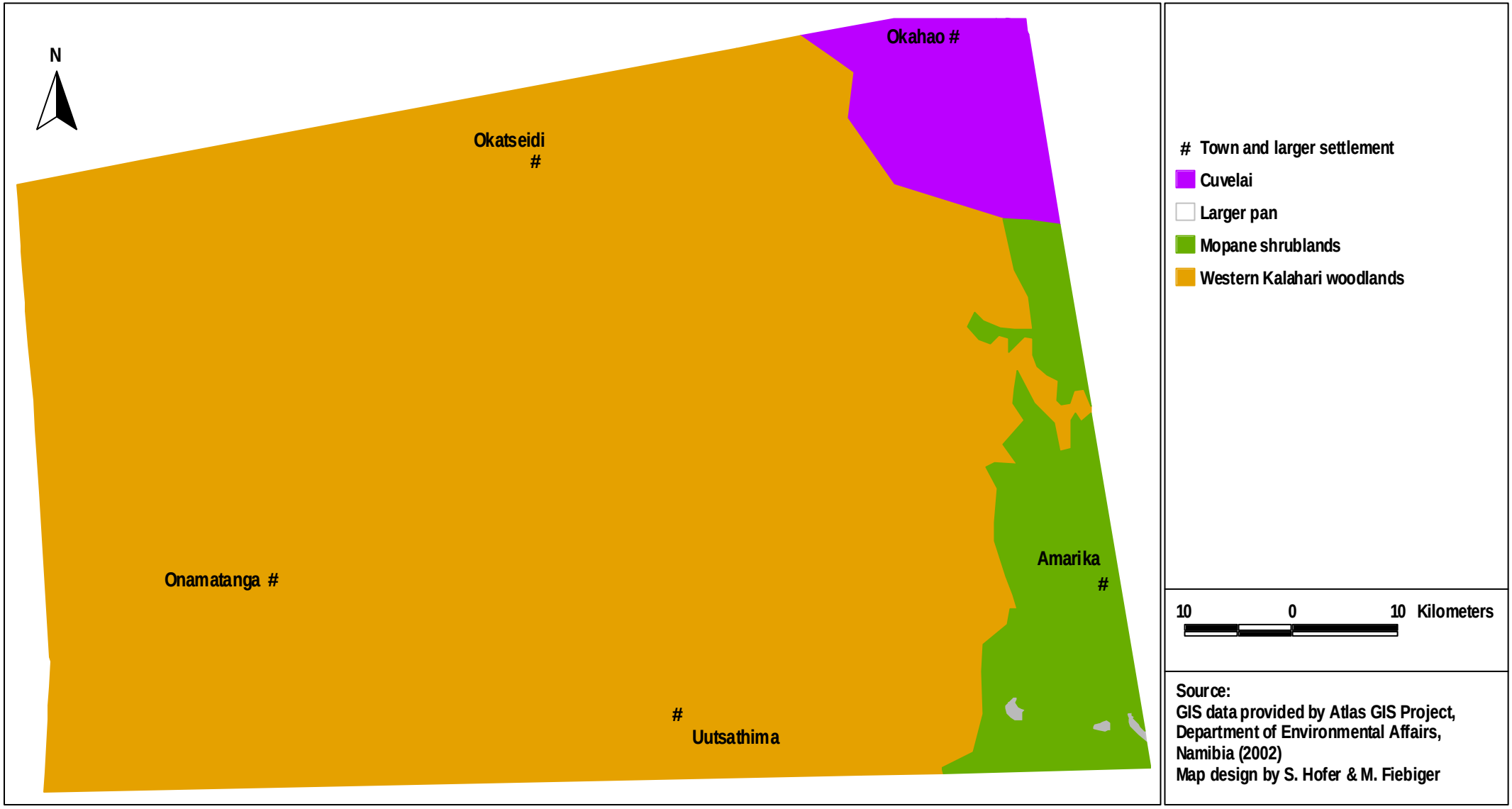


This map was composed by merging the topographical maps "sheet 1814 Etosha (Wes)" and "sheet 1714 Oshakati", scale 1:250 000.

10 0 10 Kilometers

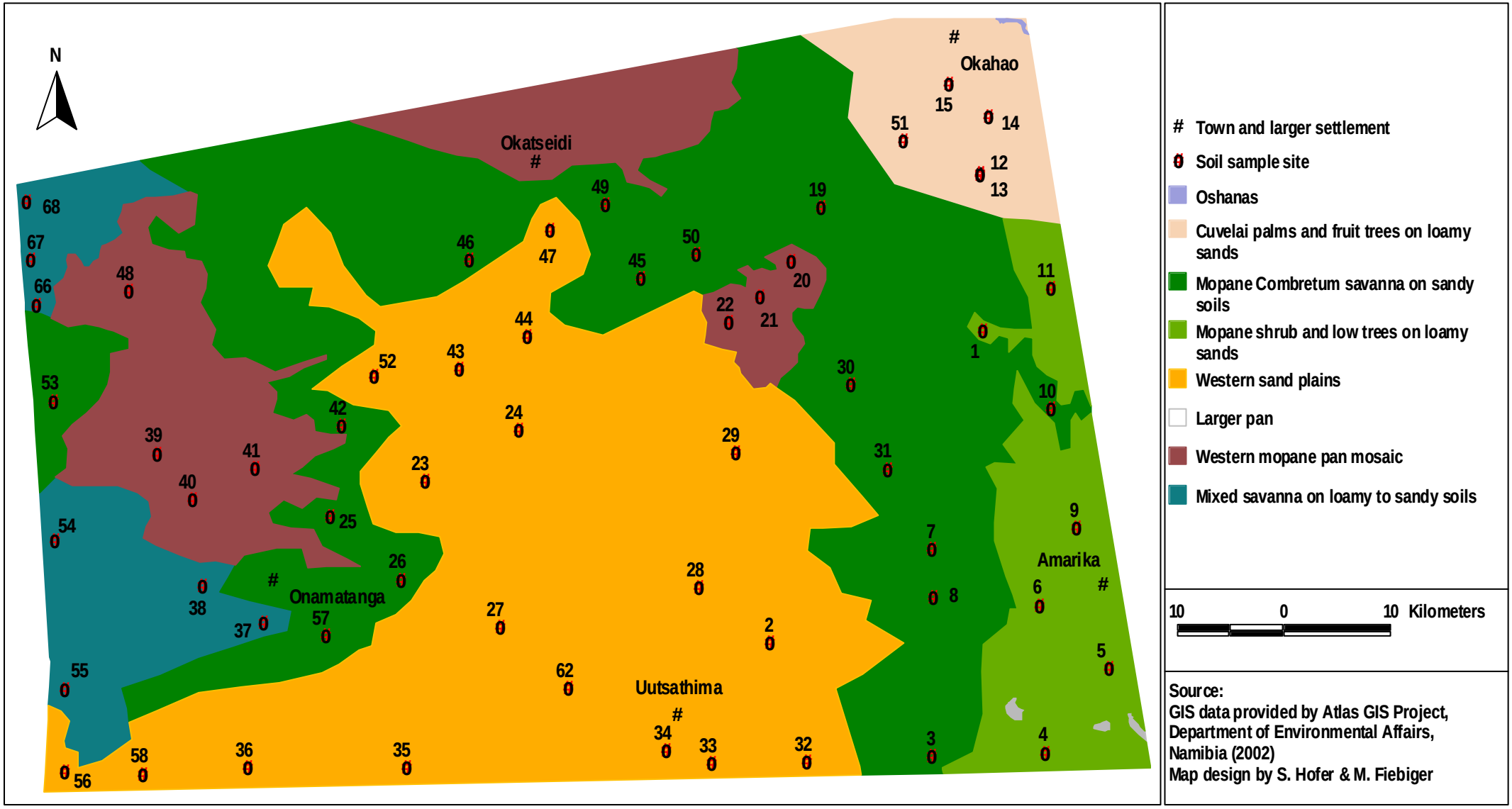
Source:
Topographical maps provided by Surveyor General (1981 & 1975), Namibia
Map design by S. Hofer & M. Fiebiger

Map 3: Major landscapes of the central and western Omusati region



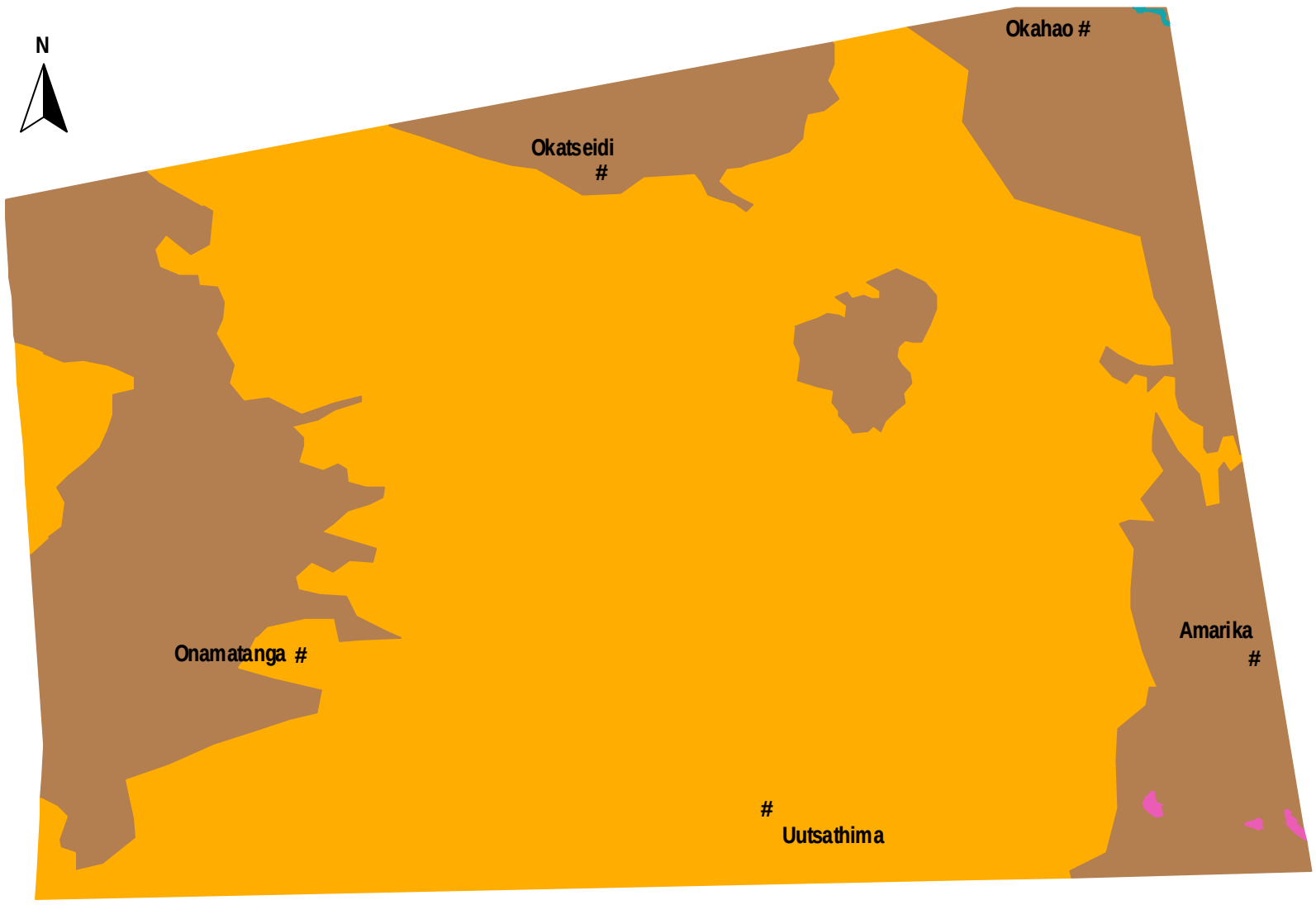
Source:
GIS data provided by Atlas GIS Project, Department of Environmental Affairs, Namibia (2002)
Map design by S. Hofer & M. Fiebiger

Map 4: Vegetation units of the central and western Omusati region and position of soil sample sites



Source:
GIS data provided by Atlas GIS Project, Department of Environmental Affairs, Namibia (2002)
Map design by S. Hofer & M. Fiebiger

Map 5: Major soil types of the central and western Omusati region

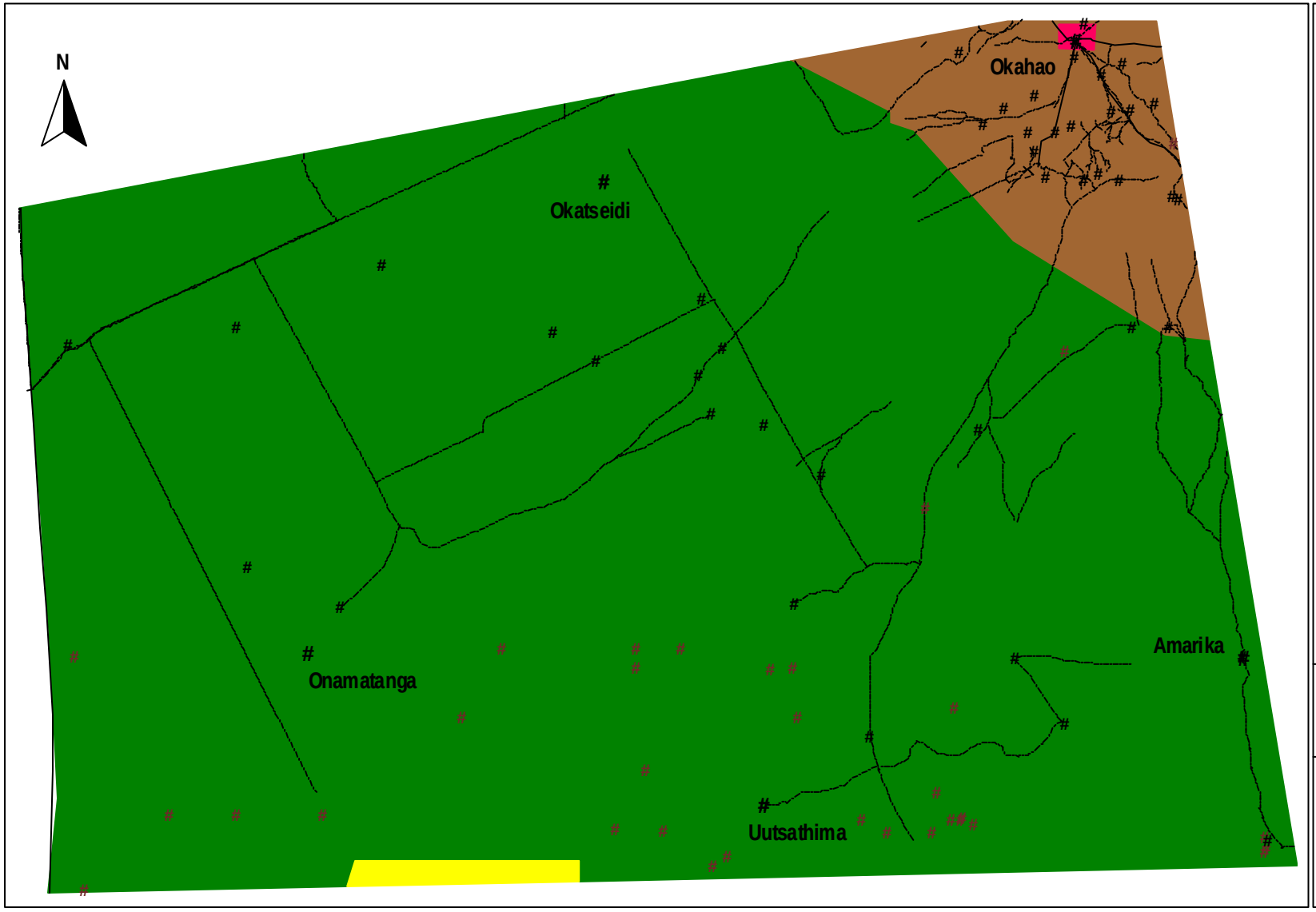


Town and larger settlement
Clayey sodic sands
Deep sands
Sands and loams
Silts

10 0 10 Kilometers

Source:
GIS data provided by Atlas GIS Project, Department of Environmental Affairs, Namibia (2002)
Map design by S. Hofer & M. Fiebiger

Map 6: Landuse in the central and western Omusati region

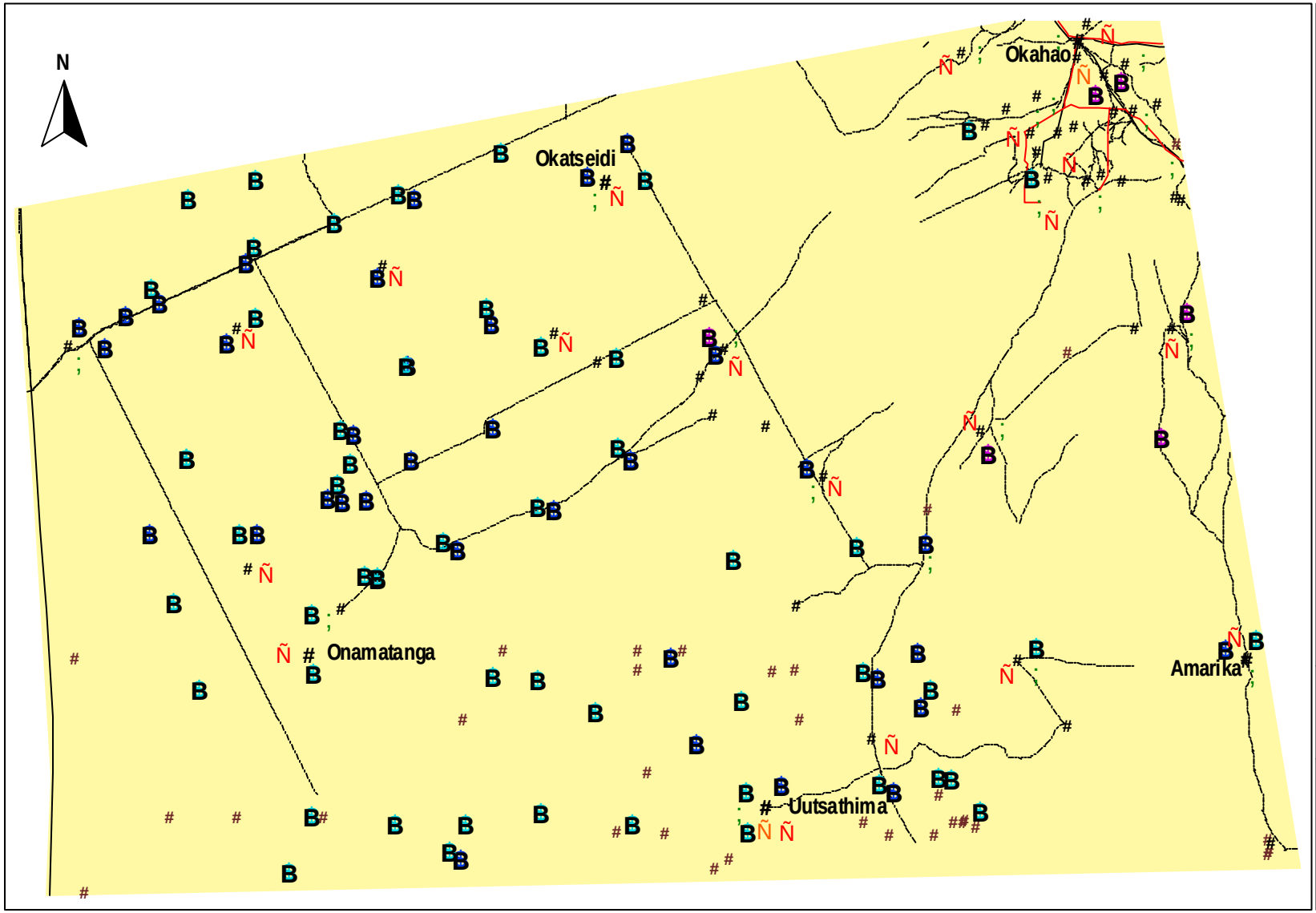


Town and larger settlement
Village
Cattlepost
Mainroad
Track
Municipal area
Small-scale farming
Communal grazing
Quarantine farm

10 0 10 Kilometers

Source:
GIS data provided by Atlas GIS Project, Department of Environmental Affairs, Namibia (2002)
Map design by S. Hofer & M. Fiebiger

Map 7: Infrastructure of the central and western Omusati region



Town and larger settlement
Village
Cattlepost
; School
Ñ Health facility
Ñ Veterinary service
B Well
B Borehole & waterpoint
B Borehole with pump
Water-pipeline
Mainroad
Track

10 0 10 Kilometers

Source:
GIS data provided by Atlas GIS Project, Department of Environmental Affairs, Namibia (2002)
Map design by S. Hofer & M. Fiebiger