SOIL VARIABILITY AND LANDSCAPE IN THE MACHAKOS DISTRICT KENYA.

A detailed soil survey as part of the study on the influence of soil variability on the tradeoffs between agricultural production and soil fertility.

G.R. Ellenkamp
February - September 2004
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PREFACE

This thesis Soil Inventarisation and Landevaluation formed the last episode of my study at Wageningen University. It was part of a bigger project which aimed to adjust the Tradeoff (TOA) model to Kenyan conditions. This model enables policy makers to quantify the tradeoff between agricultural development and a wide range of possible sustainability indicators, including productivity, environment and human health (Stoorvogel et al., 2001).

The goal of this study was to develop a detailed soil map of Machakos District, which would serve as input for the TOA-model. To do this, three months of fieldwork were conducted from February till May 2004. During this time knowledge was obtained about the landscape and soils in a tropical area and about the relations between them. But it also meant a step into a new world. Living and working in Kenya among the local people for some time changed my view of the world and it gave me lots to philosophize about. I met many people and many of them are now my friends. Although communication is difficult, I hope these friendships will last over time and can be picked up again when I revisit Kenya. All in all I can say that it was one of the most impressive and educational times of my life.

All my work and findings during this research would never have taken place without the help of many people. First of all I want to thank Stephen Matimbi and Philip Kinama who assisted me day after day, by guiding me literally and figuratively through the Kenyan landscape. They were part of the Katumani staff, to which I also sent many thanks. Two people deserve special thanks since they kept me fed every day. Wilson Wambua and Pricilla Matimbi, thank you! Further I want to thank the staff of the International Potato Centre (CIP) in Nairobi, for their support in many ways. Especially the friendly, organizational support of Charles Crissman kept me going. For their supervision overall I want to thank Alejandra Mora Vallejo and Jetse Stoorvogel. Finally I want to give a personal thanks to Jeannette van de Steeg and Paulo van Breugel for their hospitality and the trips we made to many game parks.

Reinier Ellenkamp
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SUMMARY

This study provides a digital soil map of the study area located in Machakos District, Kenya. This is done to supply soil data input for an application of the Trade-off Analysis (TOA) model adjusted for African conditions. The soil map and accompanying database give better insight in the relation between soil variability and landscape.

The study area is located in Machakos district, Kenya between 1°37' S and 1°45' S latitude and 37°15' E and 37°23' E longitude. Geologically the area consists of Basement System which is part of the Mozambique Belt: a complex of metamorphic, igneous and sedimentary rocks. In a process of etching and stripping, which correlated with times of uplift and planation in Eastern Africa, a landscape of inselbergs surrounded by etchplains evolved. The inselbergs are composed of relatively resistant granitoid gneisses, whereas the surrounding plains and uplands are composed of the relatively easily weatherable schists and gneisses. The soils in the area show a strong coherence to the different rock types and landforms. Mainly Cambisols, Ferralsols, Luvisols and Vertisols are found.

Based on a geological map and a soil map the area is transected to make catenas. From observations, made during the transects, insight in the genesis of and soil variability in the area is obtained. The result of this is the determination of 14 landscape units: Mountain Crest (MC), Mountain Shoulder (MSH), Mountain Saddle (MSB), Mountain Middle Slope (MMS) east and west, Mountain Lower Slope (MLS), Mountain Footslope Upper part (MFU), Mountain Footslope Lower part (MFL), Gully (G), Dissected Upland Crest (DUC), Dissected Upland Slope (DUS), Valley (V), Plain (P) and Alluvial Fan (AF). These landscape units are the result of a combination of parent material and geological processes. Within each transect augerings are made which together describe the catena's. The augerings are described according to the FAO guidelines for soil description and sampled for chemical and physical analysis: texture, soil pH, organic Carbon content, moisture content, CEC and nutrient contents. The results from this analysis show a high variability of soil characteristics in the area.

Both the results of the soil description and the chemical and physical analysis are used to determine the functional horizons. A functional horizon has characteristic physical and chemical properties (Finke et al., 1992) and is distinguishable by its macro morphological characteristics. The aim is to make groups of horizons, whereby the characteristics show a high similarity within the groups and a high variation between the groups. Each group represents a functional horizon. Eventually 20 functional horizons are made based on horizon code, texture, color and field observations. With the final functional horizons an average of 51.3% of the variability of the soil samples is explained.

Next the determined functional horizons are related to the topographical data from the FAO descriptions to determine the relations with the landscape units. The landscape units AF, DUC, DUS, V, MC/MSH, MSB, MMS and P show a clear relation to the functional horizons. The soils on these units are built from a combination of the most occurring functional horizons on each landscape unit. The anomalies in occurring functional horizons to a large extent come down to variations in color or texture, caused by differences in parent material and soil development. Due to their geomorphological genesis the landscape units MLS, MFU, MFL and G show a high variation in the occurring functional horizons and consequently show a high variability in soil characteristics. Moreover factors like natural vegetation, agricultural use or terracing can also cause a lack in coherence.

With the final phase of data analysis the relations between soil depth and topography are determined. Based on field observations, soil depth of the A horizon is expected to relate to the
landscape unit on which the soil has developed. This expectation is proved to be true. In a graph soil depth is plotted against the sequence of landscape units as determined in the field. The relation shows a wavy course with shallow A horizons on the unstable landscape units which suffer from active erosion and deposition (MMS, MLS, V and DUS) and deeper A horizons on the stable landscape units (MC, MFU, MFL and DUC). However, within the smooth western mountain middle slope soil depth is a function of slope percentage according to the formula: 

\[
\text{depth} = -0.721 \cdot \text{slope} + 51.866.
\]

Finally, all results are processed with ArcView to develop a detailed soil map of the study area. This map displays the spatial distribution of the landscape units and their soil profiles, composed of the functional horizons. In the accompanying database the specific soil characteristics are stored and available for querying.

This study, has improved the understanding of the soil variability and landscape in the Machakos district, Kenya. A detailed soil map is produced which describes the soils by their functional characteristics using functional horizons. It gives a clear picture of the position of the soil units and their delineation. Moreover the results give insight in the distribution in percentages of the soils in the study area, which makes them applicable in landuse models like the TOA model. Although the method which is used aims to produce a soil map in a time and money saving way compared to traditional soil mapping according to the Soil Survey Manual, the results are satisfactory. However, for a proper statistical analysis the dataset is too minimal and expanding the dataset would be favourable. However, it is questionable whether the effort of adding more detail to the dataset significantly improves the outcomes of any landuse model.
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1. **INTRODUCTION**

1.1 **GENERAL**

Agriculture is an important economic activity in most developing countries. Moreover, pressure on the agricultural systems is rising. In order to feed the growing population using equal agricultural production area, agricultural systems are forced to increase their efficiency. This will further stress the natural resources and expand the impact of agriculture on the environment. To get insight in the economic and environmental impact of agricultural production, Montana State University, Wageningen University and the International Potato Centre have developed the Trade-off Analysis (TOA) Model. The TOA-model is a landuse model which uses quantitative data to get insight in the tradeoff between agricultural development and a wide range of possible sustainability indicators, including productivity, environment and human health (Stoorvogel et al., 2001).

This study is part of a larger project which aims to develop an application of the Trade-off Analysis model for African conditions. At present the Trade-off Analysis methodology is being applied in Machakos district, Kenya, where nutrient depletion from farm activities is a serious environmental problem. To implement the model, bio-physical and econometric data is needed. A large amount of data has already been collected by the NUTMON project. Linking the NUTMON and TOA-models is one of the objectives of the TOA project. However, the NUTMON database lacks more detailed data on soil variability and characteristics and topographic conditions which is required for the application of the TOA-model. The available soil maps do not give insight in the spatial soil variability on the desired level. This study is done to provide a more detailed soil map and accompanying data. Nonetheless the availability of NUTMON data for the Machakos district in Kenya gave rise to choose part of this district as a representative study area for this thesis.

Following the Soil Survey Manual every square centimeter of the eventual map has to be sampled. This is a very time and money consuming method and therefore not convenient when applied in a model which aims to support short term policy interventions. To produce satisfying output in a short time span, a different approach is used. The available small scale soil maps are taken as a starting point to investigate the relations between landscape (morphology and topography) and soil variability. On the basis of these relations a detailed soil map can be derived, using a digital elevation model. The results of this research will be used in a later stage to extrapolate the relations found in the study area and produce a soil map for the whole Machakos district.

1.2 **OBJECTIVE**

The objective of this study is to get insight in the landscape of Machakos district, in an attempt to find a relationship between the soil variability and the landscape, in order to construct a detailed soil map of the study area.

The second objective is to collect data focusing on soil types, (functional) characteristics, and spatial distribution.

Final objective is to digitize and visualize the results and link soil data and topographic characteristics in a soil map. To do this GIS applications are used.
1.3 RESEARCH QUESTIONS

To achieve the objectives, three research questions are formulated:

1. Which soil types are present in the study area and what are their (functional) characteristics? (functional characteristics being the soil properties which determine the functional use of a soil for crops such as horizon thickness and not the genetic soil properties such as significant N-content).

2. What is the spatial distribution of the different soil types in the study area?

3. What determines the soil variability in the Machakos district? In other words: What is the relation between the soils and their position in the landscape? (Landscape being the result of parent material and ongoing geological, geomorphological, hydrological, biological and anthropogenic processes).
2. PHYSIOGRAPHY OF THE AREA

2.1 GENERAL

The study area covers an area of 200 square kilometres ranging between 1º37’ S and 1º45’ S latitude and 37º15’ E and 37º23’ E longitude. The area is situated in the central Kenyan highlands and semi-arid uplands. It extends from the east side of the Kapiti Plains (1600 m.a.s.l.) south east of Nairobi to the west side of Mbooni Hills (2000 m.a.s.l.) west of Athi river. The dissected plains surrounding the hills in the study area gently slope down from 1670m in the west to 1450 m.a.s.l. in the east. Figure 2.1 shows the position of the study area in Kenya.

![Figure 2.1 Map of Kenya with the location of the study area.](image)

2.2 CLIMATE

The climatic conditions of the study area are semi-arid, with mean annual temperature varying from 15ºC to 25ºC and a total annual rainfall ranging between 400 mm and 800 mm (NRI, 1990). Depending on altitude and aspect, mean rainfall and temperature vary widely. Mean monthly variation in temperature and rainfall is displayed in figure 2.2 and annual variation in rainfall is displayed in figure 2.3. The graphs are derived from data of Katumani meteorological station which is in the vicinity of the study area.
The mean annual rainfall at the Katumani meteorological station is 602 mm, distributed over a
long (March-May) and a short (October-December) rainy season, separated by a distinct dry
season (figure 2.2). However, this station is located on a low and rolling position in the
landscape, whereas the study area is located 15 km south of Katumani station in a hilly to
mountainous, higher elevated landscape. According to NRI, 1990 "the rains on the southern and
eastern slopes of the mountains tend to be prolonged, more reliable in occurrence and rendered
more effective by persistent low clouds". This results in a high spatial variation in weather
conditions. The eastern and southern slopes receive more precipitation, as do the higher elevated
areas. The average monthly maximum temperature varies between 22.2°C and 27.3°C and the
minimum temperature varies between 11.1°C and 15.2°C.
2.3 **Geology**

2.3.1 **Geology of Kenya**

The main geological units in Kenya are (1) the Rift Valley and its volcanics, (2) the Basement System and (3) the Quaternary sediments. Figure 2.4 shows the geological map of Kenya. The Rift Valley is recognised by the fault pattern from north to south. The Basement System is visible as the clearly perceptible Mozambique belt in which the study area is located. The Quaternary sediments are mainly located in the eastern part of Kenya.

(1) The Kenyan Rift Valley is part of the eastern branch of the Afro-Arabian Rift System which extends over 6500km from Turkey to Mozambique. The Kenyan Rift Valley was formed as a result of updoming of Central Kenya, which started in the end-cretaceous. During the lower Miocene a half graben was formed. Volcanic activity within the rift started during the Miocene. In the Late Miocene flood phonolites overflowed the rift which are now found near the study area (e.g. Kapiti plains and Yatta plateau). In the Pliocene the true rift was formed and in the same period the first volcanic activity took place outside the rift (e.g. Mt Kenya). The rift flank was further uplifted in the beginning of the Pleistocene (Boshoven, 2002). Between 0.9 Ma and 0.4 Ma tectonic activity resulted in the formation of fault patterns in the rift.
(2) The Basement system in Kenya is part of the Mozambique Belt: a complex of metamorphic, igneous and sedimentary rocks. It was formed in the Precambrian during the Katangan period (750-400 Ma). (Boshoven, 2002). Marine sediments were deposited and later folded and metamorphised due to Upper-Precambrian orogenesis. The Basement System is composed of heterogeneous gneisses, granulites and schists (Schoeman, 1951 in Boshoven 2002).

(3) The Quaternary sediments are influenced by the sea. The succession of marine sediments and marine terraces along the coast are the result of sea level changes (Oosterom, 1988). The sediments were later influenced by eolian processes.

2.3.2 GEOLOGY OF THE STUDY AREA

The most important geological feature in the study area is the Basement system, although the domal uplift during the Miocene, which formed the Rift Valley, had a strong influence on the geomorphological development (Maree, 2002).

During the Palaeozoic Eastern Africa was occupied by folded mountains undergoing denudation and sedimentation (Baker et al., 1972 in Buis, 2002). The metamorphic rocks which are found in the study area form the roots of these mountains. In time a process of alternating etching and stripping formed a landscape of dissected plains with extending inselbergs and tors (Driessen et al., 1991). Figure 2.5 shows the development of etchplain levels by etching and stripping.

![Figure 2.5 Two phases of etching (I, III) and stripping (II, IV), (From Driessen et al., 1991)](image)

Etching is the process of gradual deepening of the weathering mantle caused by high infiltration rates and strong chemical weathering (Driessen et al., 1991). During times of uplift the mantle is removed by extensive erosion, revealing the underlying hardrock. This process is called stripping.

The Palaeozoic mountains were eroded down, resulting in the formation of an early Miocene etchplain. This plain is recognizable in the concordance of altitude of the summits in the area (Baker, 1952). An etchplain is characterized by a deep weathering front of saprolite (Driessen et
A broad domal uplift of central Kenya in the Miocene caused a lowering of the erosion base. Incision and erosion of the etchplain exceeded the rate of weathering. As a result the land was stripped of its saprolite mantle, leaving the hardest rocks, mostly metamorphised granitoid gneiss, to stand out as inselbergs in the landscape. This period was followed by a period of extensive planation during the early Pliocene (Veldkamp and Oosterom, 1994 in Maree, 2002). In the study area this resulted in the formation of an early Pliocene etchplain, presumably now visible as the shoulders of the mountains, at a height of 1800 m.a.s.l. The period of planation ends at the beginning of late-Pliocene, with a quick uplift combined with eustatic sea level lowering (Haq et al, 1987 in Maree, 2002). These events result in a lowering of the erosion base causing removal of the weathering mantle and further development of the relief. During the early Pleistocene domal uplift was neutralized by eustatic sea level rise (Haq et al, 1987 in Maree, 2002), leading to the formation of plains surrounding the isolated inselbergs. These plains are now at an average height of 1500 m.a.s.l. Rift faulting 1.7Ma BP caused a rapid uplift, which, combined with eustatic sea level lowering, resulted in a lowering of the erosion base in the area and renewed erosion and incision of the rivers. Until the present day the area is actively being eroded to reach a new equilibrium.

Over time etching and stripping kept a more or less even pace preventing the inselbergs from becoming fully developed. The mountains in the area are characterized by an alternation of deep to shallow weathering mantles and rock outcrops. They lack the smooth domed hardrock surface, which is characteristic for inselbergs.

2.4 Soils

The soils in the study area are strongly related to the geology and geomorphology, with the mountains and plains/uplands as the determining landforms. Figure 2.6 shows the spatial distribution of soils in the study area.

Figure 2.6 Soil map of the study area (from United States department of Agriculture et al, 1978)
Chapter 2  Physiography of the area

The mountains consist of quartz rich granitoid gneisses that were most metamorphised during the folding (paragraph 2.3.2 Geology of the study area). This parent material in combination with a mountainous topography has resulted in the formation of somewhat excessively drained, reddish brown, stony and rocky sandy clay loam soils (HQb), that vary in depth (Siderius, 1978). The plains and uplands that surround the mountains consist of variety of less metamorphised rock (mainly banded gneisses). The flat plains consist of ferromagnesian gneisses in which poorly drained, black cracking and swelling firm clay soils (UFd) are found. In the dissected uplands well drained dark reddish brown clay and sandy clay soils (Unr1) are formed in a gneiss parent material. Differences in the permeability or chemical characteristics of the rock have resulted in the formation of different soils (United States department of Agriculture et al, 1978).

2.5 HYDROLOGY

The study area is drained by two seasonal rivers: Twake and Kaiti. Kaiti river is located in the southern part of the study area (figure 2.6). Twake river is 10km north of the study area, just outside figure 2.6. Both rivers drain into the Athi river, 50km east of the study area. There are several watersheds in the area that determine whether water flows to Twake river in the north or Kaiti river in the south. The area west of Kalama Hills and east of Mbevo Hills belongs to the drainage basin of Twake river. The whole area south of Kalama Hills and east of Mumandu Hill is drained by the Kaiti river.

2.6 LANDUSE

The study area is almost completely cultivated and used as arable land. The farms vary in size from 500m$^2$ to 10000m$^2$ and the majority is terraced. Mixed cropping is the main farming activity, with maize, pigeon peas, beans and fruit trees as the main crops (Onduru et al, 2001). Most farms have some livestock (cows and/or goats) which are kept for manure and diary products.

The natural vegetation has been largely cleared for cultivation, but can be found scattered through the area, mainly in the stream valleys (Gicheru et al, 1987) and on the steepest mountain slopes. The crests of the mountains are covered with government forest. The forest vegetation consists of Eucalyptus trees, shrubs and grasses.

According to Vlaming et al, 2001 within each farm a rough distribution of farm activities over several farm section units (FSU) is found. This distribution is presented in figure 2.7. The homestead is located on the highest part. This FSU also contains the boma where the cattle are kept. The middle and lower FSU are used as arable land. Livestock is considered to temporarily graze outside the farm. However, in the Machakos district the lower FSU is often located near a stream valley and used as grazing area.

Figure 2.7 The farm concept, with FSU's (from Vlaming et al, 2001).
3. MATERIALS AND METHODS

3.1 MATERIALS

The base of this thesis is formed by a literature research on geology and soils and the accompanying maps. From this, insight in the main geology, landscape and soils of the study area and its surroundings is acquired.

Soil maps (1:1.000.000 Siderius, 1978; 1:250.000 United States department of Agriculture et al, 1978) and a geological map (1:125.000 Baker, 1952) are used to determine the major landforms in the landscape. The topographical map of East Africa, 1:50.000, sheet 162/2, is used to locate observation points during fieldwork and to derive a Digital Elevation Model. A digital version of the exploratory soil map of Kenya, 1:1.000.000 (Sombroek et al, 1980) is used for preliminary GIS operations to derive a rough base soil map and geological map of the study area.

3.2 METHODS

3.2.1 EXPLORATIVE FIELDWORK

To get familiar with the study area and define the geomorphology, several explorative fieldtrips are carried out. By linking the gathered knowledge from the literature research to the actual landscape a general overview of the area is obtained. During the explorative fieldtrips the major landforms, extracted from the literature, are discerned in the landscape. Based on distinct topographic features (e.g. slope, curvature and altitude), these landforms are further subdivided into landscape units. Landscape units are clearly distinguishable morphological features that are common, or reoccur, in the study area. They form the building blocks of which the different landforms in the area are composed. Each landscape unit is the result of a combination of parent material, climate, and time. Together with topography, biological activity and human influence, they form the soil forming factors. Consequently the subdivision in landscape units is the first step towards understanding soil variability. The determined landscape units are presented in chapter 4.1. The successive detailed field survey is structured by the landscape units.

In addition several farms from the NUTMON database are visited to collect useful local information and to do some explorative augerings to get insight in the soils. Also these farms are geo-referenced.

3.2.2 TRANSECTS AND SOIL DESCRIPTIONS

This step aims at describing the soil variability and finding relations between the landscape and the soil characteristics. Based on the landforms in the study area several transects are mapped out such that all landforms and the transitions between landforms are included. Each representative landform is transected from high to low and along the contour lines. This way different slopes and curvatures are visited to include as much topographic variability as possible. The transects are structured by the previously defined landscape units. That means the actual augerings are made on every distinct landscape unit within the transect. However, augerings are also made whenever unexpected changes (different from the changes between the predetermined landscape units) in the landscape appeared.

Within each landscape unit a representative location for an actual augering was selected based on explorative augerings and expert knowledge. The augerings are described according to the
FAO-system (FAO-ISRIC, 1990). This consists of a general description, and a horizon description. The 'general description' goes into the relation between the soil and its surrounding environment. The following 'horizon description' describes the soil horizons in terms of macro morphological soil characteristics. During the fieldwork expert knowledge about landscape and soil variability in the study area is collected, which is used to determine the relations between soil and landscape.

To determine the feasibility of extrapolating the found relations in the field to the whole study area, the relevance of the gathered data and knowledge is checked in previously unvisited sites in the study area.

3.2.3 Chemical and Physical Analysis

Soil samples are taken from all representative transect augerings. No pits are made, because the explorative fieldtrips proved that soil variability was too high to describe with pits in the available time span. The samples are stored and analyzed simultaneously at the National Agricultural Research Laboratory (NARL) of the Kenyan Agricultural Research Institute (KARI) in Nairobi Kenya. A fertility analysis is done for all samples: pH, texture, Organic Carbon, Nitrogen, Phosphorous, Potassium, Calcium, Magnesium, Manganese, Copper, Iron, Zinc and Sodium. Analysis for moisture content (pF 2.0 and pF 4.2), CEC and EC are done for the most relevant soil samples, selected by expert knowledge.

3.3 Data Analysis

3.3.1 Functional Horizons

In order to describe soil variability in the study area in a quantitative way, the functional horizon concept is used. A functional horizon has a unique combination of texture, color and organic matter content which results in characteristic physical and chemical properties (Finke et al., 1992 in Overmars, 1999). This concept allows to describe soils with predetermined functional horizons which have fixed characteristics.

The determination of functional horizons is based on similarity in macro-morphological characteristics like color and texture (Finke, 1993). The collected data is stratified in groups with similar characteristics. Each group represents a functional horizon. The main principal is to get minimal variation within each group and distinct differences between the groups.

To derive functional horizons from the dataset, the sample data is sorted in 5 different sets of functional horizons using the following criteria:

1. sorted by texture
2. sorted by texture and color
3. sorted by horizon code, texture and color
4. sorted by horizon code, texture, color and expert knowledge
5. sorted by horizon code, texture, color, pH, organic carbon content and expert knowledge.

A manual grouping is done for each sorting, whereby each group found represents a functional horizon. With a statistical analysis the percentage of explained variation for several chemical and physical parameters within each sorting is determined. To do this, the ANalysis Of VAriance is used to determine the variance for a certain parameter within a group (functional horizon) and between the groups. By dividing the variance between groups by the total variance, and multiplying this result with 100%, the percentage of explained variation is calculated. Based on the results from this analysis a grounded choice can be made for a sorting to be used for the succeeding analysis.
By sorting the dataset according to the final sorting several groups of samples with similar characteristics originate. Each group represents a specific functional horizon. Per group the averages of each characteristic are calculated, leaving the extreme values out. Thus the characteristics of the final functional horizons are derived.

### 3.3.2 Relations Between the Functional Horizons and Landscape Units

The goal of this analysis is to determine relations between the functional horizons and landscapes units. Eventually these relations can be used to describe the soil variability in the area on the basis of the topographic features that characterize the various landscape units. The relations are described by analyzing the dataset on the basis of the predefined landscape units. This is done manually to be able to include expert knowledge.

First a database is built in which all soil samples are labeled with the functional horizon to which they classify and with the landscape unit in which they are taken. This data set is stratified by the landscape units in which the samples are taken. Subsequently is determined which functional horizons are present within each landscape unit. The predominant functional horizons are linked to that landscape unit. The variation within the landscape units, which comes from the divergent functional horizons, is analyzed for significance.

To come to clear relations the amount of landscape units and functional horizons used for the analysis is varied, by merging and separating them. In order to merge the landscape units, field observations are used to determine which units show a large similarity. To merge the functional horizons, the insight in the soil variability obtained from the fieldwork is used. However, merging the functional horizons means a decrease in the level of detail, thus less explanation of the soil variability. A compromise is found by making a new set of functional horizons with a reasonable percentage of explained variation, which at the same moment gives clear relations with the landscape units.

### 3.3.3 Relations Between Horizon Depth and Topography

With this step the relations between the depth of the horizons and topography are described. First the relations between depth vs. slope, depth vs. curvature and depth vs. aspect are examined. Plotting soil depth against these variables in an excel-graph displays any present relations.

However, in an area with high topographic and soil variability soil depth is often related to a combination of topographic features. Here expert knowledge is essential to determine where to expect relations, whereas statistics are used to test and prove the relations. During fieldwork insight is obtained about the variation of soil depth along the transects. Based on this knowledge some relations are expected between topography and soil depth. By plotting soil depth against the expected determining combination of parameters these expected relations are tested on verity. In this case soil depth is related to the sequence of landscape units. Polynomial relations can be described with expert knowledge. Some relations became clear, others are found by examining the topographic characteristics within the landscape units.

### 3.4 GIS Application

Finally GIS applications are used to link the soil data to the landscape and display the results. First an aerial photograph analysis of the study area is done to locate the landscape units. These interpretations are digitized using ArcView and converted into a shape file with the
coordinate system UTM zone 37 using ArcInfo. With ArcView soil data is connected to the delineated landscape units in this map. To do this the relations found between the functional horizons and landscape units (see paragraph 3.3.2) are used. To derive a Digital Elevation Model (DEM) the isometrics on the topographic map of the study area are digitized. These shape files are converted to grid files with the coordinate system UTM zone 37 using ArcInfo. Overlaying the two files in ArcView allows delineating the determined landscape units in the DEM. With the determined relations between landscape unit and functional horizons soils in the delineated areas can be described. Finally soil depth can be derived based on the relations between horizon depth and topography (see paragraph 3.3.3) by selecting specific topographic characteristics within the delineated landscape units using the DEM.

The results from these GIS operations are processed into a digital soil map with accompanying database, using ArcView.
Chapter 4  Results

4. RESULTS

4.1 LANDSCAPE UNITS

The division of the landscape in landscape units is the result of the explorative fieldwork (chapter 3). The basis of this division is made during the literature research with the determination of three major landforms for the area: mountains, plains/uplands and valleys. During the explorative fieldwork these landforms are distinguished in the study area. The subsequent subdivision of the major landforms on the basis of distinct topographic characteristics resulted in the following landscape units (figure 4.1):

- MC  - Mountain Crest
- MSH - Mountain Shoulder
- MMS - Mountain Middle Slope
- MLS - Mountain Lower Slope
- MFU - Mountain Footslope Upper part
- MFL - Mountain Footslope Lower part
- DUC - Dissected Upland Crest
- DUS - Dissected Upland Slope
- P  - Plain
- V  - Valley

Figure 4.1 Schematic cross section (W-E) of the study area, displaying the landscape units and their position in the landscape.

The mountain crests in the study area are the remnants of an early Miocene etchplain (chapter 2.3.2). Because of their granitoid parent material, which is the most resistant rock type in the area, they stand out as the highest, more or less solitary geomorphological features: inselbergs. Besides the crests, the mountain shoulders also show a concordance in height. They presumably represent the remnants of an early Pliocene etchplain (chapter 2.3.2). The mountain middle slopes mainly consist of rock faces. They are probably the result of a quick uplift combined with eustatic sea level lowering at the beginning of late-Pliocene. This combination caused severe erosion throughout the area, resulting in the steep mountains slopes and rock outcrops. This observation is substantiated by the concordance in the altitudes of the rock faces. The landscape unit mountain lower slope is formed by the colluvium of the fore mentioned landscape units. This unit is located below the rock faces, grading into the footslopes. Mass movements probably formed the footslopes. Their shape matches with the distinct tongue shape of landslides and the larger footslopes often seem to originate from depression on the mountain crests (saddle top).
The footslopes are slid over what is now the landscape unit dissected upland crest. The uplands and plains surrounding the mountains, or inselbergs, in the area probably represent an etchplain resulting from early Pleistocene planation (chapter 2.3.2). A rapid uplift 1.7Ma BP caused a lowering of the erosion base. Rivers started to incise the upland forming the valleys and dissected upland slopes in the present day landscape.

In addition to the main landscape units, several smaller and less common landscape units are identified and used with the data analysis: alluvial fan (AF), mountain saddle (MSB), hill upper slope (HUS) and gully (GM/GS, gully middle/slope). The alluvial fan is the result of erosion of the regolite zone on the mountain and deposition of the erosion material on the plains. The mountain saddle probably results from a mass movement, leading to removal of a part of the mountain crest and the formation of a landslide. The gullies find their origin at mountain middle slope, due to rapid run off on the rock outcrop, and dissect the mountain lower slope and foot slope, eventually leading to the valleys. They are formed due to an increased aridity during the last decades, causing a decrease in vegetation and an increase in soil erosion (Baker, 1952).

The eastern side of the mountains can clearly be subdivided in different landscape units. Whereas the western side often consists of a smooth, even slope, with less variation in the topographic characteristics. As a result the western slope is not always dividable in different units, thus being a different landscape unit then the eastern slope. In case of a smooth western slope it is indicated differently as slope (S).

4.2 CATENA'S

To describe the topographic and soil variability on the major landforms in the study area, 11 different catenas are made by transecting the study area. Figure 4.2 indicates the position of the transects in the study area. The names of the catenas correspond with the names of the augering descriptions and the profile names of the horizon samples (annex 2). The following catenas are made:

1. Mum: covering the eastside of the mountain Mumandu Hill from crest to footslope, encompassing landscape unit MC, MSH, MMS, MLS, MFU, MFL and V.
2. Kgul: covering the eastside of the mountain along the contour lines, to include various curvatures, encompassing landscape unit MLS, GM/GS and MFU.
3. 2Kgul: covering the dissected upland, nearby the mountain, from crest to valley, encompassing landscape unit DUC, DUS and V.
4. Kat: covering the dissected upland from crest to valley, encompassing landscape unit DUC, DUS and V.
5. Konz: covering the transition of the mountain into the plains, encompassing landscape unit P, AF and MFL.
6. Kav: covering the westside of the mountain along the isometrics, to include various curvatures, encompassing landscape unit MMS, GM/GS and MSH.
7. Musaddle: covering the mountain crest to include various crest types (MC and MSB).
8. Ktmz: covering the westside of the mountain Kyamwimbu from crest to footslope, encompassing landscape unit MC, MMS, MFU, MFL and P.
9. Kyw: covering the westside of the mountain along the isometrics, to include various curvatures within the landscape unit MMS.
10. KMC 010: covering the crest and upper slope of a low mountain, or hill, encompassing landscape unit HUS.
11. Kasu: covering the dissected upland, nearby the plains, from crest to valley, encompassing landscape unit DUC, DUS and V.
Within each transect several actual augerings are made whenever a difference in topography or a change in landscape unit occurred. Together the augerings form the catena. The results of the soil descriptions of each augering are found in annex 1.

The most important observations made during the transects are listed below:

1. Mum. The following sequence is found when transecting the mountain from crest to valley:
   Deep, red loamy soils on the crest and shoulder. Rock outcrops with thin soil in weathering rock, but often bare rock at middle slope. Moderately deep reddish brown sandy stony soils in the colluvium directly below the rock face at lower slope, grading into very deep loamy red soils at the footslopes. In the gullies dissecting the footslopes a shallow dark gray clayey soil is found, which shows some similarities with the shallow black clayey soils at the transition of the footslope to the valley. Figure 4.3 shows the field situation.

Figure 4.2 Hillshade overview of the area with the transects indicated in red.

Figure 4.3 Mumandu Hill. Reddish soils on the mountain and a rim of black soils around the footslopes in the valleys.
- 2. Kgul. Along the contour lines of the mountain a sequence is found of very deep loamy red soils on the footslopes and shallow dark gray clayey soils in the gullies. On the transition between footslope and gully dark clay soils overlain with a reddish loamy toplayer are found. The gullies consist of a braided complex of smaller gullies. In the center of the complex a dark gray clayey soil is covered with a sandy top layer, whereas on the edges of the gully it is covered with a layer of reddish loamy soil which is found at the footslopes.

- 3. 2Kgul. This transect incorporates 2 north facing slopes, two valleys, two south facing slopes and two crests in the dissected upland. The following sequence is found: Deep, dusky red loamy soils at the crest, grading into deep, red sandy loam soils with many stones and quartz grains throughout the profile at the north facing slopes, becoming less deep at midslope. In the valleys shallow to deep, dark clayey soils often covered with a (thin) layer of red soil erosion material is found. The actual valley bottom consists of bare rock, saprolite and eroded rock fragments. Next at the bottom of the south facing slopes shallow gray clay soils or bare rock are found which grade into shallow to deep red loamy stony soils at the south facing lower and mid slopes. The soils become deeper, less stony and redder when ascending the slope, grading into the deep dusky red loamy soils at the crest. The south facing slopes are less steep than the north facing slopes. This can be explained by the strike and dip of the underlying rocks, schematically displayed by figure 4.4.

- 5. Konz and 6. Kav. From the mountain crest steep slopes descent to the plains. Massive rock outcrops are virtually absent. From top to bottom the slopes have a nearly straight curvature. As a result there seem to be no differences in soil type along the slope profile. The footslopes appear to grade into the more gentle slopes of the Konza Plains. Also this western side of the mountain is dissected by many erosion gullies. From a high viewpoint a north-south border is visible, with black soils on the western side and reddish soils on the eastern side. This border forms the transition of the mountain to the plains. The western side of the mountain covered with transect Kav, is very complex. The mountain has two extensions that embrace a major concavity in between them. This concavity has a more or less straight profile curvature, which is dissected by many gullies. As a result the

Figure 4.4 Schematic cross section of a stream valley in the dissected upland.

In the valley bottom, bare rock cuts are visible dipping down to south (facing south). That means that the valley side facing south is sloping down in the same direction as the rocks. When the weathering mantle gets saturated during heavy rain, it can slide down over the underlying rock. It is less stable than the north facing valley side, which is perpendicular on the south sloping rock, resulting in a stabilization of the soil by the rock layers. Outcrops may even catch soil that has slided down and prevent it from being washed by the river.

- 5. Konz and 6. Kav. From the mountain crest steep slopes descent to the plains. Massive rock outcrops are virtually absent. From top to bottom the slopes have a nearly straight curvature. As a result there seem to be no differences in soil type along the slope profile. The footslopes appear to grade into the more gentle slopes of the Konza Plains. Also this western side of the mountain is dissected by many erosion gullies. From a high viewpoint a north-south border is visible, with black soils on the western side and reddish soils on the eastern side. This border forms the transition of the mountain to the plains. The western side of the mountain covered with transect Kav, is very complex. The mountain has two extensions that embrace a major concavity in between them. This concavity has a more or less straight profile curvature, which is dissected by many gullies. As a result the
concavity shows a high alternation of minor concave erosion valleys and convex areas in between. Some concave valleys show a strange disturbance. They are not perfectly concave, but show a straight plan curvature. The soils on these anomalies also differ. They are brown and much sandier. It appears these features are concave valleys which are filled in with erosion material by a mass movement. Figure 4.5 shows this feature in a top aspect. As a result of all these slope processes the soil variability within this transect is very high. Due to the scale of this study, this variability can not be mapped out.

Figure 4.5 Schematic overview of a filled-in valley on the western side of Mumandu Hill.

8. Ktmz: The mountain in this transect appears to be eroded down resulting in colluvium or landslides as its footslopes. Again rock outcrops are present at the east side of the mountain, but less prominent on the western side. On the westside the soils grade into the black clays of the plains, via a transition soil. This transition is the extension of the border which is observed within transect Kav.

4.3 CHEMICAL AND PHYSICAL SOIL DATA

Samples are collected for each augering in a representative landscape unit. The results of the chemical and physical laboratory analysis of these soil samples are found in annex 2. Table 4.1 shows the summary statistics of the chemical and physical characteristics of the soil samples.

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>pH</th>
<th>Organic Carbon</th>
<th>Bulk Density 2.0</th>
<th>Bulk Density 4.2</th>
<th>CEC</th>
<th>EC</th>
<th>Exchangeable Acidity</th>
<th>Nitrogen %</th>
<th>Phosphorus ppm</th>
<th>Potassium me%</th>
<th>Calcium me%</th>
<th>Magnesium me%</th>
<th>Manganese me%</th>
<th>Copper ppm</th>
<th>Iron ppm</th>
<th>Zinc ppm</th>
<th>Sodium me%</th>
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<tr>
<td>Average</td>
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<td>10.8</td>
<td>35.1</td>
<td>5.7</td>
<td>0.5</td>
<td>1.4</td>
<td>25.9</td>
<td>9.5</td>
<td>12.7</td>
<td>0.2</td>
<td>0.4</td>
<td>0.1</td>
<td>11.4</td>
<td>0.9</td>
<td>4.5</td>
<td>2.4</td>
<td>0.4</td>
<td>1.2</td>
<td>11.6</td>
<td>1.6</td>
</tr>
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<td>6.1</td>
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<td>0.3</td>
<td>0.3</td>
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<td>0.4</td>
<td>1.1</td>
<td>14.2</td>
<td>2.3</td>
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</tbody>
</table>

Table 4.1 Summary statistics of the chemical and physical laboratory results of all 144 samples.

Table 4.1 shows a high variability of the soil characteristics within the study area. Texture varies from loamy sand to clay. The sandy soils are mainly found on places where erosional processes
are active (steep mountain slopes) or where erosion material is deposited (alluvial fans). The clayey soils are found on poorly drained positions, such as the flat plains and the valleys. Soil pH shows a similar variation and distribution. Values vary from medium alkaline in black clayey soils to extreme acid in the red loamy soils. Organic carbon content is generally very low with a low standard deviation. The CEC varies from 30.5 me/100g to 2.5 me/100g. The higher CEC’s are found in the alkaline clayey soils, whereas the lowest CEC’s are found in the sandy, more acid soils. The nutrient contents in the soil vary widely, especially for phosphorous and iron which are easily influenced by human activity, like manuring.

Table 4.2 shows the summary statistics per individual landscape unit.

<table>
<thead>
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<th>Characteristic</th>
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<th>Max</th>
<th>Min</th>
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<td>29.62</td>
<td>12.54</td>
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<td>34.15</td>
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<td>49.00</td>
<td>62.00</td>
<td>36.00</td>
<td>9.39</td>
</tr>
</tbody>
</table>

Table 4.2 Summary statistics of the main chemical and physical characteristics per landscape unit.
Chapter 4  Results

The table gives insight in the soil variability within and between the landscape units. The pF, CEC and pH values are highest in the valleys and on the plains which contain the grayish clay soils. Relatively low values for these characteristics are found on the mountain shoulder and middle slope. These landscape units suffer more from erosion, causing the less weathered regolite zone to be near the surface. The erosion is also reflected by the relatively low organic carbon content, since the toplayer, in which organic matter accumulates, is often removed by erosion. As expected from the field observations the soils on the landscape units MLS, MFU and MFL show a high standard deviation for the sand and clay content. The high topographic variability and the resulting high alternation of erosion and sedimentation processes, causes a high variation in soil texture. In general texture shows a high standard variation, which indicates a high variability of parent material in which the soils have developed. Higher clay contents are found in the soils which have developed in the relatively easily weatherable schists and gneisses, whereas the soils developed in the more resistant granitoid gneiss, show a relatively lower clay content and higher sand content.

4.4  FUNCTIONAL HORIZONS

All collected field and laboratory data are analyzed, with the objective to extract a set of functional horizons, based on clusters of samples with a similarity in characteristics. The twenty definitive functional horizons result from a sorting based on horizon code, texture, color and field knowledge about the occurrence and distribution of soil types in the study area. Table 4.3 shows the definitive division in functional horizons with their chemical and physical characteristics.

A1: A black sandy clay loam A-horizon, with a medium acid pH. Organic carbon content is relatively high and the Cation Exchange Capacity (CEC) is somewhat intermediate. The moisture retention capacity (moisture content at pF2.0 minus moisture content at pF4.2) is relatively high.

A2: A dark reddish brown sandy clay loam A-horizon, with a medium acid pH. Organic carbon content is lower then A1, although still relatively high compared to the B and C horizons. The CEC is somewhat intermediate as compared to the other A horizons. The moisture retention capacity is relatively low, however calculated from values with a high standard deviation.

A3: A dark reddish brown sandy clay A-horizon, with a medium acid pH. Organic carbon content is relatively high, although lower then A1 and A2. The CEC is relatively low, as is the moisture retention capacity.

A4: A (very) dark brown sandy clay loam A-horizon, with a strong acid pH. Organic carbon content is together with A7 lowest of all A-horizons, although still relatively high compared to the B and C horizons. The CEC and moisture retention capacity are very low compared to all functional horizons.

A5: A black sandy clay A-horizon with a slight alkaline pH. Organic carbon content is relatively high as is the CEC and moisture retention capacity.

A6: A very dusky reddish brown clay A-horizon, with a medium acid pH. Organic carbon content is relatively intermediate. Both CEC and moisture retention capacity are relatively low.

A7: A very dark gray loamy sand A-horizon, with a medium acid pH. Organic carbon content is relatively high, although lower then A1, A2 and A5. Both CEC and moisture retention capacity are somewhat intermediate as compared to the other A horizons.

AB1: A dark reddish brown sandy clay loam transition horizon, with a medium acid pH and a relatively intermediate organic carbon content. The CEC is relatively low, but is average compared to the other AB-horizons. The moisture retention capacity is relatively intermediate.

AB2: A dark reddish brown sandy (clay) loam transition horizon, with a medium acid pH. Organic carbon content is relatively intermediate. Both CEC and moisture retention capacity are relatively low.
Table 4.3 The functional horizons and the means of their chemical and physical characteristics. Numbers marked in gray are calculated from values with a high deviation from the mean. Bulk density is inaccurate since it is measured on disturbed samples.

<table>
<thead>
<tr>
<th>Functional horizon</th>
<th>Hue</th>
<th>Value</th>
<th>Mean sand %</th>
<th>Mean silt %</th>
<th>Soil pH</th>
<th>Phosphorus ppm</th>
<th>Potassium me%</th>
<th>Calcium me%</th>
<th>w/w at pH 2.0</th>
<th>Moisture content %</th>
<th>Bulk density g/cm3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2 7.5-10YR</td>
<td>5-7</td>
<td>YR</td>
<td>2.5</td>
<td>2.5</td>
<td>5-7</td>
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<td>2.5</td>
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<td>YR</td>
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<td>YR</td>
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<tr>
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<td>1.41</td>
</tr>
<tr>
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<td>YR</td>
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<tr>
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<td>12.75</td>
<td>0.50</td>
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</tr>
</tbody>
</table>

Chapter 4  Results
AB3: A dusky reddish brown clay transition horizon, with a medium acid pH. Organic carbon content is relatively high and the CEC is relatively low. Moisture retention capacity is not measured.

AB4: A dusky reddish brown sandy clay transition horizon with a medium acid pH. Organic carbon content is relatively intermediate to high, although lower then the A-horizons. Both CEC and moisture retention capacity are relatively low to intermediate.

AC1: A very dark gray (sandy) clay transition horizon, with a medium alkaline pH and accompanying high Calcium content. Organic carbon content is relatively intermediate. Both CEC and moisture retention capacity are relatively very high.

B1: A dark reddish brown to dark red sandy clay loam B-horizon, with a strong acid pH. Organic carbon content is relatively low to intermediate. The CEC and moisture retention capacity are relatively intermediate.

B2: A dusky reddish brown to dark red clay B-horizon, with a medium acid pH. Organic carbon content and moisture retention capacity are relatively intermediate. The CEC is relatively low.

B3: A dark reddish brown sandy clay B-horizon, with a medium acidity. The organic carbon content and the CEC are relatively low. The moisture retention capacity is relatively intermediate.

B4: A dark reddish brown sandy loam B-horizon, with a medium acid pH. Organic carbon content is relatively low. The CEC is relatively low and the moisture retention capacity is relatively high. However, both characteristics are calculated from values with a high standard deviation.

B5: A dark brown sandy clay loam B-horizon, with an extreme acid pH. Organic carbon, CEC and moisture retention capacity are all relatively intermediate.

C1: A dark (greenish) gray clay C-horizon, with a slight alkaline pH. Organic carbon content is relatively low to intermediate. Both CEC and moisture retention capacity belong to the highest of all functional horizons.

C2: A brown sandy clay loam C-horizon, with a strong acid pH. Organic carbon content is relatively low as is the CEC. The moisture retention capacity is relatively very high.

C3: A dark (greenish) gray sandy clay loam C-horizon, with a slight alkaline pH. Organic carbon content is lowest of all functional horizons. Both CEC and moisture retention capacity are relatively intermediate to high.

The methodology to define the final functional horizons resulted from a process of trial and error. Initially five sortings are produced (chapter 3.3.1). Based on the results of the statistical analysis for the percentage of explained variation (table 4.4) and on the utility of the sorting in the field, a sorting is chosen to be used for further analysis. Although sorting 5 has a relatively high percentage of explained variation, both for pH and Nitrogen% (table 4.4), and resulted in a smaller amount of functional horizons (27), it is not used. This sorting requires laboratory results to determine the functional horizons which makes it difficult to use in the field. Based on the relatively high percentage of explained variation and the high utility in the field sorting 4 is used for further analysis. The high number of functional horizons (39) that results from sorting 4 corresponds with the high soil variability experienced in the field. The results of the statistical analysis, done to derive table 4.4, are found in annex 3.

<table>
<thead>
<tr>
<th>Sorting</th>
<th>No. of func horz</th>
<th>Percentage of explicated variation</th>
<th>pH</th>
<th>N%</th>
<th>Org C%</th>
<th>Sand%</th>
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<td>19</td>
<td>59</td>
<td>59</td>
<td>29</td>
<td>37</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4.4: The number of functional horizons and the percentage of explained variation resulting from different sortings.
The table shows two additional sortings: 6 and 7. They resulted from an interactive process between the analysis for the functional horizons and the analysis for relations between the functional and the landscape units. A first analysis to determine the relations between the functional horizons, resulting from sorting 4, and the landscape, gave a very poor result. Due to the large amount of functional horizons, the relations with the landscape did not become clear. To get insight in these relations a new sorting (sorting 6) is made based on field knowledge about the soil types that are found on the different landscape units. This resulted in the formation of groups of samples with a rough similarity in characteristics. With only 16, less detailed, functional horizons the relations with the landscape units became clear. However, this sorting has a relatively low percentage of explained variation (table 4.1). In a process of trial and error through re-sorting the soil data and analyzing the relations with the landscape, a compromise is found: sorting 7. Sorting 7 is the result of resorting sorting 6 based on its relations with sorting 4 and on expert knowledge.

### 4.5 RELATIONS BETWEEN THE FUNCTIONAL HORIZONS AND LANDSCAPE UNITS

The relations between the functional horizons and the landscape units are found in table 4.5. The results of the cluster analysis, done to derive table 4.5, are found in annex 4.

<table>
<thead>
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<th>DUS</th>
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<th>MMS</th>
<th>MSB</th>
<th>P</th>
<th>MLS</th>
<th>MFU</th>
<th>MFL</th>
<th>GM/GS</th>
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<tr>
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</table>

Table 4.5 The distribution and occurrence of the functional horizons per landscape unit. The functional horizons marked in gray form the soils on the specific landscape unit.

As described in the previous paragraph determining the functional horizons and finding the relations between functional horizons and landscape units eventually went hand in hand. The relations are determined by stratifying the sample data by landscape unit and describing the patterns of correspondence in functional horizons per landscape unit. In the case of the functional horizons resulting from sorting 4 relations do not become clear. Resorting the soil data into groups with less similarity within the groups and less difference between the groups results in a smaller number of functional horizons with less detail (sorting 6) which causes clearer relations between landscape and soil data. With a low level of detail (i.e. a rough division in functional horizons) the relations between landscape units and functional horizons are clear, but
the percentage of explained variation for the chemical and physical parameters of the functional horizons is low. With a high level of detail the opposite is true. The final functional horizons, resulting from sorting 7, are a compromise in the level of detail with a reasonable percentage of explained variation and clear relations with the landscape units (table 4.4 and 4.5).

A clear relation is found in the dissected uplands. On the crests (DUC) a soil is found composed of the functional horizons A2, AB3 and B2. A variation in A horizon is observed (A6 and A3), that comes down to a difference in texture. On the slopes (DUS) the soil is composed of functional horizons A6 and B2. The divergent B horizons (B1 and B3) differ in texture. In the valleys a combination of the functional horizons A5, AC1 and C1 forms the soil. The variation in the C horizon comes down to a difference in texture.

On the mountains relations are less clear. The field surveys proved that similar soils are found on the mountain crest (MC), upper slope (MUS) and the shoulder (MSH). This observation is vouched by the data analysis. By merging these landscape units a clear relation was found. The soils on this merged unit are mainly composed of the functional horizons A2, AB4 and B3. For the A horizon a slight variation in texture or color is possible (A1, A3, A4). Whereas the AB horizon can slightly differ for texture and color together (AB1). For the B horizon a slight difference in texture is possible (B1, B4). The soil on the middle slope of the mountain (MMS) is predominantly composed of A2, AB1 and B1 functional horizons. Both the A and AB horizon can slightly differ in color and texture (A3, AB2), whereas the B horizon can slightly vary in texture (B2, B3). On the lower slopes of the mountain, composed of the landscape units MLS, MFL and MFU, no clear relations are found. Different ways of combining and separating these units did not result in any clear relations. A wide variety of functional horizons is found. This corresponds with the fact that the lower slopes contain a high topographic variability. Convex, completely cultivated areas are alternated with valleys and dissected by gullies with natural vegetation. Therefore the combination of these landscape units will be indicated as an association.

In the plains the soils are composed of the functional horizons A5, AC1 and C1. Both for the A and C horizon a variation is observed in the texture (A1, C3).

For the smaller and less common landscape units in the study area, mountain saddle (MSB), hill upper slope (HUS) and gully (GM/GS), no relations are determined, since only one observation is done in each unit. Although only a limited number of observations is done on the unit alluvial fan (AF) a relation with the functional horizons can be described. The soils consist of an A8, AC3 and C2 functional horizon. The soils on the alluvial fan are relatively sandy compared to the other soils in the study area.

Finally a remark on some observations which are based on erosion and not on landscape units. As can be seen in annex 4, the two observations made on highly eroded areas show a similarity in color and texture. The soils have less red hue compared to the other soils on the mountain, originating from a set back in soil development, caused by erosion.

4.6 RELATIONS BETWEEN HORIZON DEPTH AND TOPOGRAPHY

The goal of this analysis is to extract relations between soil depth and topography. However, on the footslopes and dissected uplands soil depth exceeded augering depth and could not be measured. Thus making it impossible to determine any relations. Since the A horizon is the most important horizon for nutrient provision of agricultural crops, the depth of this horizon is used for analysis.
First the relations between horizon depth and the topographic characteristics slope, curvature and aspect and the relations between horizon depth and combinations of these topographic characteristics are analyzed. By clustering the dataset according to the fore mentioned characteristics and combinations of characteristics, patterns in the variation of horizon depth can be described. Although this method gave clear relations in the mountainous area around La Encañada in Peru (Overmars, 1999) no clear relations are found in this area. Due to the high topographic variability (slopes varying from 0 to 55% and curvatures from convex to concave, all within short distances), soil depth depends on a complexity of topographic characteristics.

To find relations between horizon depth and topography a different approach is used. Based on observations from the field (chapter 4.2) a rough expectation is made for the soil depths on each landscape unit. Table 4.6 represents the expected relation from high (i.e. mountain crest) to low (i.e. valley) in the landscape.

<table>
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<th>Moderately</th>
<th>Very deep</th>
</tr>
</thead>
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</tr>
<tr>
<td>MSH</td>
<td>X</td>
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<td>DUC</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>DUS</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 Soil depth on the different landscape units, determined by field knowledge.

By structuring the dataset according to landscape unit and analyzing the variation in soil depth, the expected relation is substantiated. To display the results of this analysis three graphs are made in which topography is related to depth of the A-horizon. Figure 4.6a and b show the relation between landscape units and depth. Figure 4.6a is a plot of all measured depths per landscape unit, whereas figure 4.6b provides a clearer picture of the relation by showing the means of the depth in relation to the landscape units. Figure 4.7 shows a specific relation which is found for the soils on the western mountain middle slope. This relation is clarified with a trendline. The data source tables of these figures are found in annex 5.

![Figure 4.6 Relation between A-horizon depth and the landscape units. A. Measured A-horizon depths plotted per landscape unit. 1=MC, 2=MSH, 3=MMS, 4=MLS, 5=MFU, 6=MFL, 7=V, 8=DUS, 9=DUC. Some points overlap and are not visible. B. Mean A-horizon depth as a function of the landscape units.](image-url)
Figure 4.6 shows the relation between horizon depth and the sequence of landscape units on the mountain and the dissected upland. Figure 4.6b shows a relation which correlates to the expected relation from table 4.6. On the mountain crest and shoulder, depth of the A-horizon is more or less the same (30-35cm). On the middle slope the depth becomes very shallow. The depth has a value 0 on the eastern middle slope, since this slope exists of rock outcrops on which virtually no soil is present. On the steep outcrops no observations can be done. The western slope shows a different relation which is presented in figure 4.6. On the lower slope soil depth is still relatively shallow. On the stable footslopes the A horizon is deepest. In the valleys (landscape unit 7) shallow soils are found. Going up from the valleys to the slopes of the dissected upland the A-horizon remains relatively shallow. Within the dissected upland the deepest A horizons are found on the crests.

\[ y = -0.721x + 51.866 \]
\[ R^2 = 0.3452 \]

Figure 4.7 Horizon depth in the landscape unit MMS(w), as a function of slope. Some points overlap and are not visible.

For the western middle slope the horizon depth is found to be a function of slope. Figure 4.7 shows a clear linear relation between horizon depth and slope percentage: \( y = -0.721x + 51.866 \). The depth of the A horizon increases with decreasing slope.

As a result of a limited number of observations for the landscape units P, AF, GM/GS, and MSB no clear relations between topography and horizon depth could be derived. Table 4.7 shows the average depths of the A horizon for all determined landscape units.

<table>
<thead>
<tr>
<th>Landscape unit</th>
<th>Mean depth A horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>33.33</td>
</tr>
<tr>
<td>MSH</td>
<td>31.67</td>
</tr>
<tr>
<td>MMS(e) rock face</td>
<td>0</td>
</tr>
<tr>
<td>MMS(w)</td>
<td>35</td>
</tr>
<tr>
<td>MLS</td>
<td>22.5</td>
</tr>
<tr>
<td>MFU</td>
<td>45</td>
</tr>
<tr>
<td>MFL</td>
<td>37</td>
</tr>
<tr>
<td>V</td>
<td>20</td>
</tr>
<tr>
<td>DUS</td>
<td>25</td>
</tr>
<tr>
<td>DUC</td>
<td>43.75</td>
</tr>
<tr>
<td>P</td>
<td>20</td>
</tr>
<tr>
<td>MSB</td>
<td>20</td>
</tr>
<tr>
<td>GS</td>
<td>10</td>
</tr>
<tr>
<td>AF</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Table 4.7 Mean depth A horizon per landscape unit. Numbers marked in gray, represent a single observation.
4.7 GIS

4.7.1 General

Several products have resulted from the GIS application. First of all the digitized aerial photographs are produced. These files form the base of the final soil map. Since there is a clear relation between the functional horizons and the landscape units, the delineated landscape units on the digitized aerial photographs represent the major soil units. Secondly the digital elevation model is produced. One result of a GIS operation with the DEM is shown in figure 4.2 (hillshade overview of the area). With the use of the digital elevation model (DEM) the major soil units are further subdivided on the basis of the depth of the A-horizon. The final result, a soil map of the study area based on the relations found between the soil data and the topography, is presented in figure 4.7. In its GIS format this map is connected to a table in which the soil profiles are described by the functional horizons.

4.7.2 Final soil map

The soil map presented in figure 4.7 displays the landscape units, including the functional horizons which are found on these units, as determined in chapter 4.5. The following description and the soil map can not be seen separately.

On the mountain crest a soil is found with a dark reddish brown sandy clay loam top horizon (A2), a dusky reddish brown sandy clay transition horizon (AB4) and a dark reddish brown sandy clay sub horizon (B3). The top horizon has an average depth of 33cm. On the mountain saddle a soil is found with a (very) dark brown sandy clay loam top horizon (A4) with an average depth of 20cm. The transition horizon is a dark reddish brown sandy (clay) loam (AB2) and the sub horizon is a dark brown sandy clay loam (B5). As can be seen on the map the landscape units mountain middle slope are mainly located west of the mountain crests, whereas the eastern sides mainly consists of rock faces and erosional areas. This corresponds with the results presented in chapter 4.1: the eastern and western mountain middle slope are different units. On the mountain middle slope a very homogeneous soil is found with a dark reddish brown sandy clay loam top horizon (A2), a dark reddish brown sandy clay loam transition horizon (AB1) and a dark reddish brown to dark red sandy clay loam sub horizon (B1). The top horizon has an average depth of 35cm. However, in this landscape unit soil depth is a function of slope: depth= -0.721·slope + 51.866. Since soil depth is a determining factor for soil classification this landscape unit is indicated as an association. On the rock faces sometimes a very shallow soil <50cm is found, but they mostly consist of bare rock. On the erosional areas no augerings are made. These area's represent non-cultivated or abandoned land. As a result of their position on the steep mountain slopes erosion has removed all soil and the weathering mantle, or regolite zone is exposed. The mountain lower slope represents the colluvium zone of the mountain. Due to the high alternation in the supply of fresh colluvium from the mountain a soil complex is found on this landscape unit. A second result of the supply of fresh colluvium is the shallow average depth of the top horizon: 23cm. On the mountain footslopes almost all A, AB, and B horizons are found, as can be seen in table 4.5. These landscape units are the result of landslides, which are turbulent events, resulting in a mixture of the soils. Together with the differences in cultivation this has resulted in a high variation in soil characteristics, indicated as a complex. However, since the footslopes are now stable positions in the landscape, soil development and cultivation have resulted in a deep top horizon with an average depth of 41cm. On the gully slopes a complex mixture is found of black clayey soils, found in the valleys, overlain with reddish clay loam soils, from the footslopes. Depth of the top horizon depends on the amount of erosion and deposition that has taken place.

On the dissected upland crest a soil is found with a dark reddish brown sandy clay loam top horizon (A2), a dusky reddish brown clay transition horizon (AB3) and a dusky reddish brown to
dark red clay sub horizon (B2). With an average depth of 44cm the top horizon is deepest of all soils in the area. On the dissected upland slope a soil is found with a very dusky reddish brown clay top horizon (A6) to an average depth of 25 cm. The sub horizon is a dusky reddish brown to dark red clay (B2).

Although the plains and valleys represent different landscape units, the soils which are found on these units are similar. The top horizon is a black sandy clay (A5), the transition horizon is a very dark gray (sandy) clay (AC1), and the sub horizon is a dark (greenish) gray clay (C1). The top horizon has both in the valley and on the plain an average depth of 20cm. On the alluvial fan, which is overlying the plain, a soil is found with a very dark gray loamy sand top horizon (A7) and a brown sandy clay loam sub horizon (C2). The top horizon has an average depth of 27cm.
Chapter 5 Discussion and Conclusions

5. DISCUSSION AND CONCLUSIONS

5.1 GENERAL

The study of the soil maps in combination with the augerings and their descriptions, showed the presence of Cambisols, Luvisols, Ferrasols and Vertisols in the area. With the functional horizon concept and the relations between soil and landscape a more detailed soil map is produced. The soils are described by their functional characteristics, using functional horizons. The functional horizons can be derived from the dataset based on different criteria. The more criteria are used, the more detail is added to the division and the closer they get to describing the actual variability. However to increase the utility of the functional horizons it is important to keep a certain level of abstraction. The definitive functional horizons are a generalisation of the reality, but explain an acceptable percentage of the variability of the soil characteristics in the study area.

The soil data shows a large coherence with the determined landscape units. Consequently the distribution of soils in the area is reflected by the distribution of the landscape units. However, by using this method it is difficult to determine the distribution of classified soil types, such as Cambisols etc. During the data analysis the sample data of every augering is disconnected from their original soil classification. Only the characteristics of each soil are used to make the functional horizons, thus filtering any kind of soil classification out. Eventually these functional horizons are used to describe the soils in the area. Therefore in this case it is better to speak of the (spatial) distribution of soils, than of soil types.

The final soil map, produced with GIS tools, shows the spatial distribution of soils as determined by this study. On the scale of this study, eventually covering an area of 10 km by 7.5 km it gives insight in the position of the soil units and their delineation. Moreover the results give insight in the distribution in percentages of the soils in the study area, which makes them applicable in landuse models like the TOA model.

5.2 MATERIALS AND METHODS

5.2.1 FIELDWORK

Many different positions in the landscape are visited in order to get insight in the soils and landscape of the study area. This proved a very time-consuming activity. This time could otherwise have been used to make more observations on the main landscape units, to enlarge the dataset and be able to better analyze the data in a statistical way. Later many of the observations were left out of the data analysis because of their unique character. However, due to this method of fieldwork great insight is gained in the geomorphology and soil variability in the study area, which proved very useful during the data analysis.

While making transects, smooth transitions between landscape units made it difficult to determine the separate landscape units in which an augering should be made. In these cases the scale of the landscape was too big to get an overview while standing in the middle of it. Moreover a detailed geological map was absent and the aerial photographs were not available at the time of fieldwork, which made it impossible to determine the landscape units during the fieldwork preparation. This may have influenced the reliability of the data set. In order to improve the results of the fieldwork it is useful to make an explorative trip to determine the landscape units in the area to be transected, before starting with the actual transect.
The augering descriptions according to the FAO proved very useful. This standardized description allows comparing datasets from different areas. The detailed general description about the topography made it possible to quickly check up on the topographic characteristics at the observation locations. With the soil horizon descriptions many soil characteristics are described and although eventually only the necessary information is used for analysis the extra gathered data can be used for further analysis and application. However, the FAO description is intended for profile pits. Since this study is done based on augerings, some of the soil characteristics could not be described accurately. Although these characteristics are not used in this study, the inaccuracy could influence the possibilities for further analysis.

The way soil samples were taken also influenced the data set. Since it was not feasible to make pits within the available time span, samples were taken from the auger. This means samples were not undisturbed, which increased the error of the sample analysis.

5.2.2 DATA ANALYSIS

The data analysis was a complex process during which the dataset is analyzed several times in different ways in order to obtain satisfying results. Eventually it proved to be rewarding. However, the fact that a lot of expert knowledge is needed to find relations in the data reduces the utility of this method. It is very difficult to extract functional horizons and their relations with topography from an existing dataset, when extensive field knowledge is absent. However, during the analysis it became clear that on the landscape units MLS, MFU, MFL, G and AF not enough observations are done to draw any conclusions on the relations between the soils and the landscape. A second round of fieldwork could solve this problem.

5.3 RESULTS

5.3.1 LANDSCAPE UNITS

The division of the major landforms in smaller landscape units (chapter 4.1) proved to be very useful. Each unit has his own place in the landscape and a specific influence on the soil variability in the study area. However, it is disputable whether the landscape units MSH (mountain shoulder) and MFU (mountain foot slope upper part) are useful. Because of their similarities in topographic characteristics with MC (mountain crest) either MFL (mountain foot slope lower part) they are later unified with these units.

5.3.2 FUNCTIONAL HORIZONS

With the final division of functional horizons according to sorting 7, an acceptable percentage of the soil variability is described. Eighty percent of the variation in sand content is explained. Yet this is expected since texture is one of the main discriminating characteristics of the functional horizons. Since color also is one of the main discriminating characteristics the percentage of explicated variation for hue, value and chroma is also expected to be high. However, these values are not calculated. The percentage of explicated variation for the pH is relatively high when considered that sorting 5 was partly based on pH (table 4.1). The variation of the nitrogen content is poorly explicated by all sorting. This is caused by the natural high spatial variability of nutrients in the soil. Since the 29% explicated variation for sorting 7 is in between the percentage for sorting 4 and sorting 6, it is considered acceptable. The low percentage for organic carbon content probably is a result of the irregular distribution of a number of Ap horizons over the clusters which form the functional horizons. These horizons have a relatively high organic carbon content which disturbs the similarity in carbon content within the
respective functional horizons. In total the definitive functional horizons give an acceptable 51.3% explanation of the soil variability.

5.3.3 RELATIONS BETWEEN THE FUNCTIONAL HORIZONS AND LANDSCAPE UNITS

Moreover, with the definitive twenty functional horizons it is possible to describe the soils on the different landscape units. On the landscape units DUC (dissected upland crest), DUS (dissected upland slope), V (valley), MMS (mountain middle slope), P (plain), AF (alluvial fan) and the combination of MC (mountain crest) and MSH (mountain shoulder), there is a big coherence between the functional horizons which are found on each landscape unit. The anomalies to a large extend come down to variations in color or texture. The variations in color are probably caused by differences in soil development, which can originate from differences in erosional conditions. The variation in texture is caused by differences in parent material. As described in chapter 2, the basement system in the study area consists of folded and partly metamorphised sediments. Due to the original layers of different sediments which were later exposed, there can be a high alternation of rock types at short distances, resulting in a high variability in soil texture. Figure 5.1 schematically shows a possible alternation of rock types in the area.

![Figure 5.1 Schematic cross section of a possible alternation of rock types.](image)

As described in chapter 4.5 the functional horizons do not relate to the landscape units MLS (mountain lower slope), MFU (mountain footslope upper part), MFL (mountain footslope lower part) and GM/GS (Gully). However, it is possible that the high amount of different functional horizons found on these units explains the actual soil variability on these landscape units. Due to the alternation of erosion and deposition, and the high variety in topographic conditions, all at short distances, soil variability is very high. Besides, factors like natural vegetation, agricultural use or terracing, which are not included in the analysis, can have a big influence on soil variability. From the augering descriptions can be concluded that on these landscape units all land that is suitable for agriculture is cultivated. Within that area every field with the slightest slope is terraced. The terracing has a big influence on soil erosion. And as a result the relations between soil and topography are disturbed. Therefore terracing can be one of the reasons that it is difficult to find clear relations. However no hard conclusion can be drawn about the influence of terracing since that is greatly dependent on the history of cultivation. On slopes that are terraced recently relations between soil depth and topography are still clear, whereas on slopes that have been terraced and cultivated for 50 years the relations are extensively disturbed.

The last anomaly which is found in the results of chapter 4.3 is the variation in texture for the soils on the plains. This is caused by a series of observations which was nearby and on an alluvial fan, which resulted in a higher sand content.
5.3.4 Relations between horizon depth and topography

The apparent lack of relations between horizon depth and slope, curvature or aspect can have two reasons. 1. The high variability of soil depth and topographic characteristics represents the high variability in the actual landscape. Soil depth is amongst others a function of the resistance of the parent material in which the soil has developed. As shown in figure 5.1 there can be a high alternation in parent material. As a result relations are very complex and do not become clear. 2. The number of observations is insufficient to derive the relations in the area. The second reason is in any case true since the dataset should be expanded to be able to do proper statistical analysis.

The analysis on the basis of field experience gave some results. The relation found between horizon depth and the landscape units of mountain and upland can be explained as follows: The mountains in the area are undeveloped inselbergs (chapter 2.3), composed of the relatively hard granitoid gneiss. Because they are not fully developed (not completely stripped) they still have a weathering mantle in which soils can develop, especially on the flat positions like crest and shoulder, but the hard rock is still nearby. Because water can infiltrate, the soils are reasonably well developed, compared to the soils on the steep slopes. Due to the strike and dip of the rock layers in combination with the active erosion, the eastern mountain middle slopes in the study area are stripped and have developed to rock faces. The majority of this unit consists of rock outcrops. On small patches a thin soil is still present. The soils on the lower slopes are formed in colluvium material. Due to the stony nature of this parent material and the constant supply of fresh colluvium from the rock outcrops, the soils develop slowly and are shallow. The foot slopes have a relative stable character and less steep slopes, compared to the mountain middle slope. As a result erosion is minimal. Water can infiltrate and soils are deeply developed. Moreover, these landscape units have been cultivated for a long time, which contributed to the formation of Ap horizons, with a different structure and high organic matter content.

The valleys are subject to variable water movement. In times of uplift, erosion is severe and valleys are eroded. In times of relative crustal rest the rivers deposit their sediments and sedimentation prevails over erosion. The gullies, on the mountain slopes, which are actively being formed, indicate a period of erosion. Thus the soils in the valleys are also actively eroded, resulting in shallow soils.

The soils on the dissected upland slopes are very stony, as can be determined from the field results (chapter 4.1). This indicates severe erosion. The top layer, which is homogenized and cleared of stones by termite activity, has been removed by erosion and the termite stone line is at the surface, giving the soil its stony character. A termite stone line, as shown in figure 5.2 is the result of termite activity. Termites only move particles smaller than coarse sand. Since these particles are moved up, the remaining particles (coarse sand, gravel and stones) relatively move down and accumulate at the depth where termite activity stops (Driessen et al, 1991). Most of the upland slopes are not terraced, thus erosion can continue and the soil will eventually be completely removed. The stable upland crests are almost flat, which allows water to infiltrate the soil in stead of running off. As a result on these positions a deep

![Figure 5.2 Road cut along Mumandu road, revealing a termite stone line.](image)
weathering mantle with deep soils is developed. Compared to the mountain crest, which has similar topographic characteristics, the mean depth of the A horizon is deeper. The parent material of the dissected uplands (gneisses and schists) is much less resistant to weathering compared to the granitoid gneiss on the mountain crests with their shallow weathering mantle. This less resistant rock type results in a deeper weathering mantle and better developed soils.

The relation between horizon depth and slope which is found on the western mountains middle slope (MMS) can be explained as follows:

The western sides of the mountains consist of a more even slope. Distinct shoulders or steep rock outcrops are absent. Thus variations in landscape unit do not influence the horizon depth. As a result horizon depth depends more on slope percentage. On a steep slope surface run-off of water is more likely then on less steep slopes. Besides, the erosive power of water run-off on a steep slope is much higher then on a gentle slope. Thus on a steep slope more topsoil is removed and soils are shallow.

5.4 **The relation between soil variability and landscape**

The study area consists of Basement Rock, of which the most severely metamorphised rock (granitoid gneiss) is most resistant to erosion, causing these rocks to stand out as the highest mountains in the area. Over time a weathering mantle is formed. Due to the mineralogical composition and the well drained position in the landscape, reddish brown loamy soils have developed. The sand fraction in the soil depends on the quartz content of the parent material.

Alternating etching and stripping have removed the less resistant rock types causing the granitoid gneisses to stand out as inselbergs. On the steep slopes of these mountain the weathering mantle is easily removed which has resulted in stony loamy soils, and rock outcrops. As a result of water saturation of the weathering mantle on the mountains during wet periods, like the beginning of the Holocene (personal comment A. Veldkamp), in combination with the big height differences in the area caused mass landslides. These landslides form the foot slopes of the mountains. Since the whole mantle including the original soil has slided down, the soils on the foot slope could continue developing. The stable topographical position reduced erosion, which in combination with a good drainage resulted in the formation of well developed deep red loamy soils. Parts of the mountain where the mantle is slid down are recognizable as saddle crests. Here the soil and weathering mantle has been completely removed, thus soil formation had to start all over. As a result poorly developed yellow brown sandy loam soils are found and the regolite zone is present at shallow depth.

The landslides have slided over the plains and dissected uplands surrounding the mountains. The soils on these landscape units have developed in schists and gneisses which are less resistant to weathering. Therefore rock outcrops and regolite zones are absent except in the river valleys. The crests and slopes in the dissected upland are well drained, due to which well developed red loamy soils are formed. Due to the stable position on the crests the soils are deep, whereas on the slopes erosion processes have removed the well developed top layer of the soil above the termite stone line. As a result the termite stone line is at the surface, resulting in moderately deep stony, red sandy loam soils.

The plains are less extensively dissected by stream valleys, which causes a poor external drainage. In combination with the poor internal drainage of the schists which form the parent material of the plains, poorly drained black clayey soils are formed.
In the valleys and gullies on the mountains a gray clayey soil is found. These soils are formed during times of regional ponding. The ponding can result from a dam of the drainage system due to a rise of the erosion base caused by a large sediment supply (personal comment A. Veldkamp). As a result basins are formed in which sedimentation prevails over erosion. In these calm environments also clay particles can be sedimented. The gray clayey soils in the gullies and streams are sediments from such a period. This theory appears to be feasible, since Baker, 1952 mentions that in recent times many rivers appear to have choked in their sediment, what could have caused damming of the rivers.

5.5 CONCLUSION

Finding the relations between soil and landscape is difficult. When insufficient data is available it is possible to do additional detailed fieldwork. However, is it useful and desirable? First of all more detailed fieldwork is more expensive. Secondly it is questionable whether the effort of adding more detail to the dataset significantly improves the outcomes of a landuse model. Finally a map represents a simplified image of reality, as does a model and therefore it will always keep a certain level of generalization.

The results of this study have improved the insight in the soil variability and its determining factors in the study area, thus the main objective is achieved.
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