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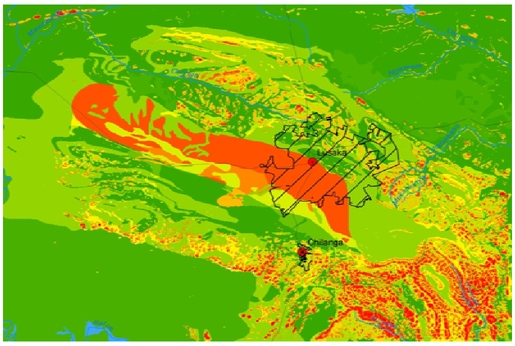
Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

TECHNICAL NOTE NO. 9

REGIONALIZATION OF SOIL PHYSICAL PARAMETERS IN THE LUSAKA REGION

Volker Hennings, Jan Willer, Sesele Sokotela, Angela Bwalya & Tewodros Tena

Hanover, August 2012



Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

REGIONALIZATION OF SOIL PHYSICAL PARAMETERS IN THE LUSAKA REGION

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Abbreviations

awc	(soil) available water capacity
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
DTM	Digital Terrain Model
DWA	Department of Water Affairs
EU	European Union
FAO	Food and Agriculture Organization (of the United Nations)
GSDER	geometric standard deviation of the error ratio
HYPRES	Hydraulic Properties of European Soils
ISRIC	International Soil Reference and Information Center
ksat	saturated hydraulic conductivity
pF	logarithm of the soil-water matric potential
PI	protectice cover and infiltration factor
PTF	pedotransfer function
SAGA	System zur Automatischen Geoökologischen Analyse
SAR	synthetic aperture radar
SRTM	Shuttle Radar Topography Mission
TWI	Topographic Wetness Index
VDC	vertical distance to channel net
WISE	World Inventory of Soil Emission Potentials
WRB	World Reference Base for Soils
ZARI	Zambian Agricultural Research Institute

List of reports compiled by the project in Phase II

Date	Authors	*Title*	Type
Apr. 2009	Museteka L. & R. Bäumle	*Groundwater Chemistry of Springs and Water Supply Wells in Lusaka - Results of the sampling campaigns conducted in 2008*	Report No. 1
Oct. 2009	R. Bäumle. & S. Kang'omba	*Development of a Groundwater Information & Management Program for the Lusaka Groundwater System: Desk Study and Proposed Work Program Report*	Report No. 2
March 2010	Hahne K. & B. Shamboko-Mbale	*Karstification, Tectonics and Land Use in the Lusaka region*	Report No. 3
Oct. 2010	Mayerhofer C., Shamboko-Mbale B. & R.C. Mweene	*Survey on Commercial Farming and Major Industries: Land Use, Groundwater Abstraction & Potential Pollution Sources-*	Report No. 4
2012	Hennings V.	*Assessment of annual percolation rates in the Lusaka region*	Report No. 5
2012, in prep.	Bäumle R., Krekeler T., Shamboko-Mbale B. & C. Siwale	*Water Balance Estimates for Sub-catchments of the Chongwe and Mwembeshi Rivers in the Lusaka region*	Report No. 6
Feb. 2008	Bäumle, R. & J. Nkhoma	*Preliminary Assessment of the Hydrogeological Situation around Lusaka South Local Forest Reserve No. 26*	Technical Note No. 1
Nov. 2010	Tena, T. & A. Nick	*Capacity Building and Awareness Raising Strategy for Phase II (2010-2012)*	Technical Note No. 2
Nov. 2010	Nick A., Museteka L. & Kringel R.	*Hydrochemical Sampling of Groundwater in the Lusaka Urban Area (April/May 2010) and Preliminary Findings*	Technical Note No. 3
Feb. 2011	Bäumle R.	*Results of pumping test evaluation and statistical analysis of aquifer hydraulic properties*	Technical Note No. 4
Apr. 2011	Kringel R., Fronius A., Museteka L. & A. Nick	*Assessment of CVOC- and BTEX-contamination level in Lusaka ground-water in 2010 based on developing and testing a method to sample and analyse groundwater containing organic volatile substances after extended storage*	Technical Note No. 5
Aug. 2011	Nick A.	*Compilation of a vulnerability map according to the PI-method – A documentation and manual.- Ministry of Energy and Water Development*	Technical Note No. 6
Dec. 2012.	Krekeler T. & C. Siwale	*Discharge measurements and rating curves in the rivers Chalimbana, Chilongdo, chongwe, Chunga, Kapwelyomba, Mwembeshi, ngwerere and Laughing Waters Spring*	Technical Note No. 7

List of reports compiled by the project in Phase II (continued)

Date	**Authors**	***Title***	**Type**
June 2012	Bäumle R., Anscombe, J., Siwale C. & A. Nick	*Results of drilling and test pumping at three selected sites in Lusaka, Kafue and Chibombo Districts*	Technical Note No. 8
Aug. 2012	Hennings, V., Willer, J., Sokotela, S., Bwalya, A. & T. Tena	*Regionalization of soil physical parameters in the Lusaka region*	Technical Note No. 9

Summary

Authors: Volker Hennings, Jan Willer, Sesele Sokotela, Angela Bwalya & Tewodros Tena

Title: Regionalization of soil physical parameters in the Lusaka region

Key words: soil texture class, available water capacity, saturated hydraulic conductivity, digital relief model, Lusaka

In preparation of future applications of a simulation model of the soil water balance a regionalization of soil physical parameters in the Lusaka region is required for the entire study area. Because fine-scale soil maps of full coverage are missing, soil properties were derived from digital relief models and pedotransfer functions. In a first step, depth of soil development was estimated by a relief-based prediction model. Secondly, typical soil texture classes of the root zone were interpreted from lithological units of available geological maps. All published results of laboratory measurements of water retention characteristics inside the study area were stored in a central database and used for validation of international pedotransfer functions. Estimates of topsoil saturated hydraulic conductivities could not be checked, but estimates of available water capacities were modified on the basis of local measurements. At the end, a thematic map showing the available water capacity of the root zone was compiled.

Extended Summary

Within the framework of the technical cooperation project “Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems” soil physical parameters in the Lusaka region were regionalized for the entire study area. The resulting thematic maps are required for future applications of a simulation model of the soil water balance. Because fine-scale soil maps of full coverage are missing, soil properties were derived from digital relief models and pedotransfer functions. In a first step, depth of soil development was estimated by a relief-based prediction model. The best performance was reached when four variables were combined: total curvature, a wetness index calculated by the SAGA model, vertical distance to channel net and slope. Secondly, typical soil texture classes of the root zone were interpreted from lithological units of available geological maps. Soil developed from limestone and dolomite are often characterized by clay as the dominant texture class while soils from schist and other parent materials rich in quartz are equally distributed between loamy sand, sandy loam and sandy clay loam. Bulk densities are comparatively high in the Lusaka region, and 1.6 g/cm^3 was used as an overall mean for pedotransfer function applications. All published results of laboratory measurements of water retention characteristics inside the study area were stored in a central database and used for validation of international pedotransfer functions. For assessing topsoil saturated hydraulic conductivity four pedotransfer functions were applied: Brakensiek et al. (1984) and Vereecken et al. (1990) in case of sandy loam, sandy clay loam and sandy clay, Saxton et al. (1986) and Cosby et al. (1984) in case of clay. Additionally estimates according to the 4th and 5th edition of German soil mapping guidelines were taken into account and overall means per texture class were calculated. For assessing available water capacity estimates according to Vereecken et al. (1989), Woesten et al. (1998) and the 4th edition of German soil mapping guidelines were compared and evaluated. Final estimates represent means of pedotransfer function results and local measurements, e.g. 8.5 mm/dm in case of sandy clay. At the end, a thematic map showing the available water capacity of the root zone was compiled. For this purpose, maps of soil depth and texture class were overlaid, available water capacity values for topsoil and subsoil horizons were summed up and available water capacities of the root zone were calculated. Maximum values close to 120 mm are connected with deeply developed sandy (clay) loam soils in flat positions. Minimum values are connected with steep slopes independently of the type of rock that acts as parent material. The accuracy of the final map is mainly dependent on the relief-based algorithm that is used for regionalization of soil depth; on the average, depth of soil development is expected to be slightly overestimated. The Lusaka plateau in the centre of the study area is characterized by spatial patterns of short-range variability and therefore represents the area of poorest model performance or map reliability.

1. Project objectives

Within the framework of the technical cooperation project “Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems” between the Department of Water Affairs (DWA), Ministry of Mines, Energy and Water Development, Zambia and the Federal Institute for Geosciences and Natural Resources (BGR, Hanover/Germany) the main objectives are to facilitate an effective groundwater resource planning and management and to strengthen the capacities in the Zambian water sector. At the end of the project, among others two outputs are expected for the Lusaka area: the amount of groundwater that can be sustainably abstracted is quantified, i.e. the mean annual percolation rate from the soil is estimated, and groundwater quality and its vulnerability to pollution are known. To reach these two goals a simulation model of the soil water balance as well as a classification scheme to assess the protective effectiveness or filtering effect of the rock and soil cover were applied as appropriate tools. Results are published as Technical Note No. 6 (NICK 2011) and Report No. 5 (HENNINGS 2012). For both activities knowledge about hydrological properties of local soils was required. The most relevant soil hydrological parameters determining soil water fluxes and the susceptibility to contamination result from water retention characteristics and can be derived from specific pF curves. Soil available water capacity represents one of these water-retention parameters and acts as an input variable to simulation models of the soil water balance as well as a to classification schemes for assessing groundwater vulnerability; against this background available water capacity (awc) had to be regionalized for the entire study area.

Because fine-scale soil maps of full coverage are missing, required soil properties were estimated by application of auxiliary tools such as digital relief models and pedotransfer functions. In a first step, depth of soil development was estimated by a relief-based prediction model. Secondly, typical soil texture classes of the root zone were interpreted from lithological units of available geological maps. This information on soil texture was used to derive estimates of topsoil saturated hydraulic conductivities and available water capacities by international pedotransfer functions. In a last step, awc values for topsoil and subsoil horizons were summed up and available water capacities of the root zone were calculated.

2. Available soil data and maps

An exploratory soil map of Zambia at the 1:1 million scale for national planning purposes was compiled at the inducement of the Zambian Ministry of Agriculture in 1991, and indicates soil type’s distribution and classification based on the Revised FAO Soil Map of the World Legend, at the sub-group level. The study area is subdivided into five main mapping units (Table 1). Additionally vertisols cover parts of the Kafue flats but do not belong to the study area.

The map shown in Fig. 1 offers an overview of regional soil associations and some coarse-scale information on basic soil characteristics. For project-internal purposes soil data of higher spatial resolution and detailed information about soil physical properties is needed.

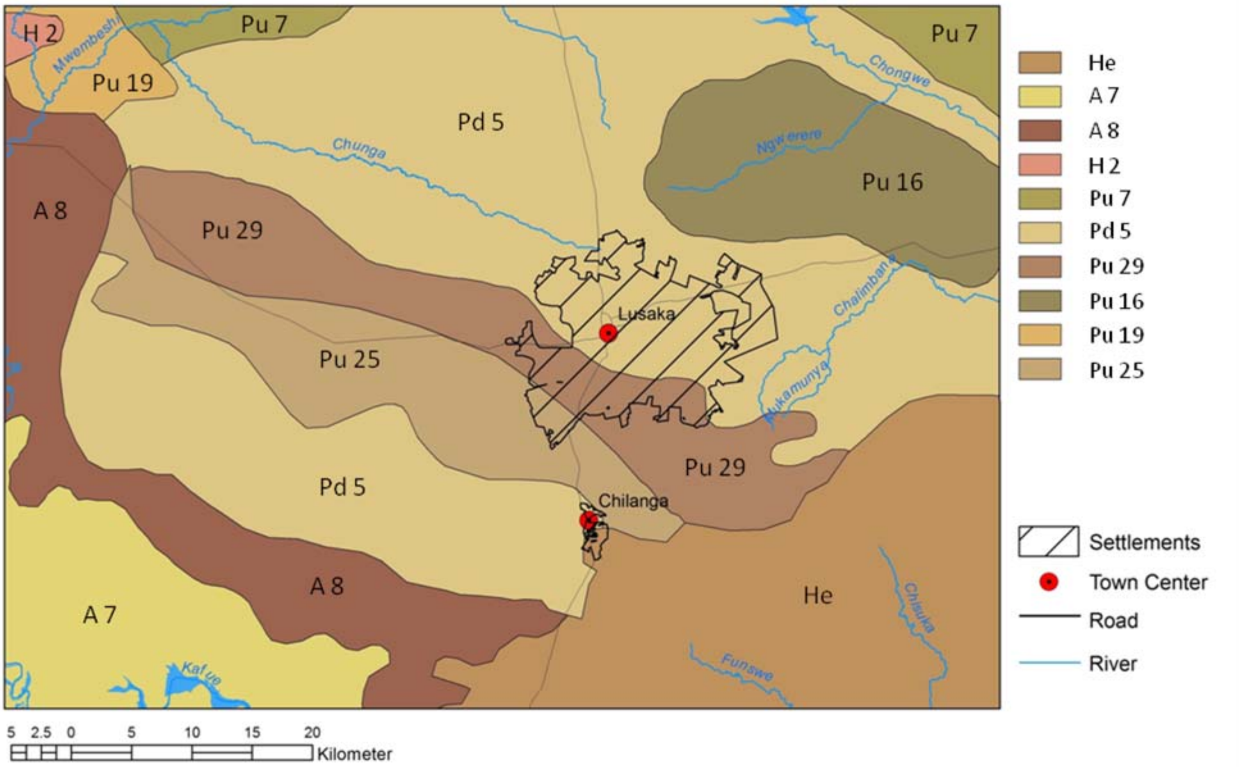

Figure 1: Detail from the "Exploratory Soil Map of Zambia", scale 1:1,000,000 (MINISTRY OF AGRICULTURE 1991); for explanations see Table 1

Table 1: Soil mapping units of the study area according to "Exploratory Soil Map of Zambia", scale 1:1,000,000 (MINISTRY OF AGRICULTURE 1991)

Soil Types	**Parent Material**	**Relief Unit / Slope**	**Description of Dominant and Associated Soils**
Pu 29 Leptosols	Lusaka Dolomite	Plateau 0 – 5 %	shallow, well to poorly drained, loamy soils
Pu 25 Phaeozems	Schists + Quartzites of the Cheta Formation	Plateau 0 – 5 %	very deep, well drained, humous, clayey soils
Pd 5 Leptosols + Lixisols	Limestone/Dolomite of the Cheta Formation Schists of the Chunga Formation	Plateau 5 – 16 %	shallow, loamy to clayey soils with a humous top soil deep, loamy to clayey soils with clay leaching
Pu 16 Alisols + Acrisols	Alluvial Deposits	Plateau 0 – 5 %	deep, humose, clayey soils with clay leaching deep, loamy to clayey soils with clay leaching
A 7 Vertisols	Alluvial Deposits	Floodplains 0 %	very deep, imperfectly drained, calcareous, clayey soils
He Leptosols	changing parent materials	Hills + Scarps variable	shallow, well to poorly drained, loamy soils

A more detailed soil map as a result of former BGR activities in this area is available for the Lusaka plateau where the Lusaka dolomite acts as parent material (VON HOYER et al. 1978). Its spatial resolution is adequate to the 1:100,000 scale, and it covers approximately 20 % of the study area. Local soil series are described by depth of soil development and texture classes.

Within and around the Lusaka area, other demand-driven soil survey projects were carried out. When York Farm was mapped it also served as a benchmark soil site for Makeni series. Several farms were soil surveyed at various levels according to the needs of the farmer by various authors at times dating from the early 70s to recent. Twelve associated reports were researched in the library of the Zambian Agricultural Research Institute (ZARI), and five of their study areas are located within the boundaries of the project's study area: Mt. Makulu Research Station (Soil Survey Report No. 4, LEE 1968), Chalimbana Area (Soil Survey Report No. 1, YAGER et al. 1967), Farm No. 2061 (Soil Survey Report No. 70, CHINENE 1980), Kashima Farm (Soil Survey Report No. 74, VIKAN 1980), and the National Trust for the Disabled Farm Sub 7 of Sub A Number 755 in Makeni West (MAMBO, date unknown). All of last-mentioned reports contain information about laboratory results on soil samples from selected soil profiles, all of them include detailed soil maps or land capability maps at the ≈ 1:10,000 scale, and two of these farm maps (Mt. Makulu & Kashima Farm) were analyzed and interpreted. They cover areas between 1,180 ha (Mt. Makulu) and 1,350 ha (Kashima Farm). Both together, this equals approximately 1 % of the study area.

Detailed profile descriptions of national "benchmark soils" including results from soil physical and chemical measurements in the laboratory are published as part of an excursion guide, edited in connection with the XIth International Forum on Soil Taxonomy and Agrotechnology Transfer (WOODE 1985). Two of them are located within the study area. More site descriptions were collected for the WISE database by the International Soil Reference and Information Center (ISRIC) in Wageningen / The Netherlands, and are available via download from the ISRIC homepage. In total the inventory consists of 80 profile descriptions of Zambian soils, and again two sites are located within the study area.

From all these sources two local databases were created. The first database (named "soil texture") contains all available information on particle size distribution and refers to 67 soil profiles with 390 soil horizons. 339 data sets were ready for data processing and could be used for further statistics, i.e. correlation analysis between parent material and dominant texture class or allocation of typical clay contents or clay gradients to groups of parent material. The second database (named "soil water retention") contains all available information on water retention from pF curves. It includes 13 soil profiles with 126 soil horizons. In soil physics water retention parameters are often estimated by applying pedotransfer functions, i.e. regression equations that are based on easily available soil characteristics such as soil texture, bulk density and organic matter content. The second database was established to check the applicability and validity of well-known international pedotransfer functions in the Zambian study area. Against this background, all data sets without information on all of the independent variables were eliminated. Following this demand, the inventory of the second database was reduced to 87 data sets.

3. Soil survey concept and results

In order to get some more information about local soils and regular patterns of their spatial distribution, a work plan for additional soil survey activities in the Lusaka region was designed. The whole work was scheduled for completion within 15 working days in May 2010. Mapping activities should focus on typical soil associations; therefore representative areas in terms of soil-forming factors should be selected. Available data about soils and soil-forming factors were interpreted and used as a basis for a first conceptual soil map. Four information layers were overlaid: soil mapping units from the Exploratory Soil Map of Zambia, scale 1:1,000,000 (MINISTRY OF AGRICULTURE 1991), lithological units from 1:100,000 geological maps, (degree sheets: 1528 NW (Lusaka) by SIMPSON et al. (1963), 1527 NE (Mwembeshi) by SIMPSON (1962), 1528 NE (Chainama Hills) by GARRARD (1968), 1528 SW (Kafue) by SMITH (1963) and 1528 SE (Leopard Hill) by CAIRNEY (1967)), morphographical units from digital elevation data and an isoline map compiled by R. BÄUMLE, showing the depth to groundwater in April 2009. The relief classification is based on two morphometrical criteria, slope class and absolute altitude. A frequency analysis of all occurring combinations was carried out, and boundaries between morphographical units were derived empirically from histograms. At the end, 12 theoretical relief units were identified. They are not mentioned in detail because the relief-based model performed poorly and was improved later (chapter 4).

From all combinations of these soil-forming factors representative combinations were identified and typical sites were selected. In two steps the total number of 106 data combinations was reduced to 50 typical data combinations and further on to 15 representative data combinations and 15 specific areas. All survey activities were focussed on these selected areas. During field work the BGR project team was accompanied by two representatives from ZARI (Ms. A. BWALYA, Mr. S. SOKOTELA/Head of ZARI's Soil Survey Section and acting as temporary advisor). At selected sites hand-drills were used to describe the soil up to a depth of 1 m below the surface. As a whole, 61 drillings were carried out during 12 field days. It has to be emphasized that the spatial resolution of this mapping procedure does not allow to compile any 1:25,000 or 1:50,000 soil map or to disaggregate the existing 1:1,000,000 map; the sampling or drilling density respectively is not a scale-adequate one and the mapping procedure has still to be characterized as a reconnaissance survey.

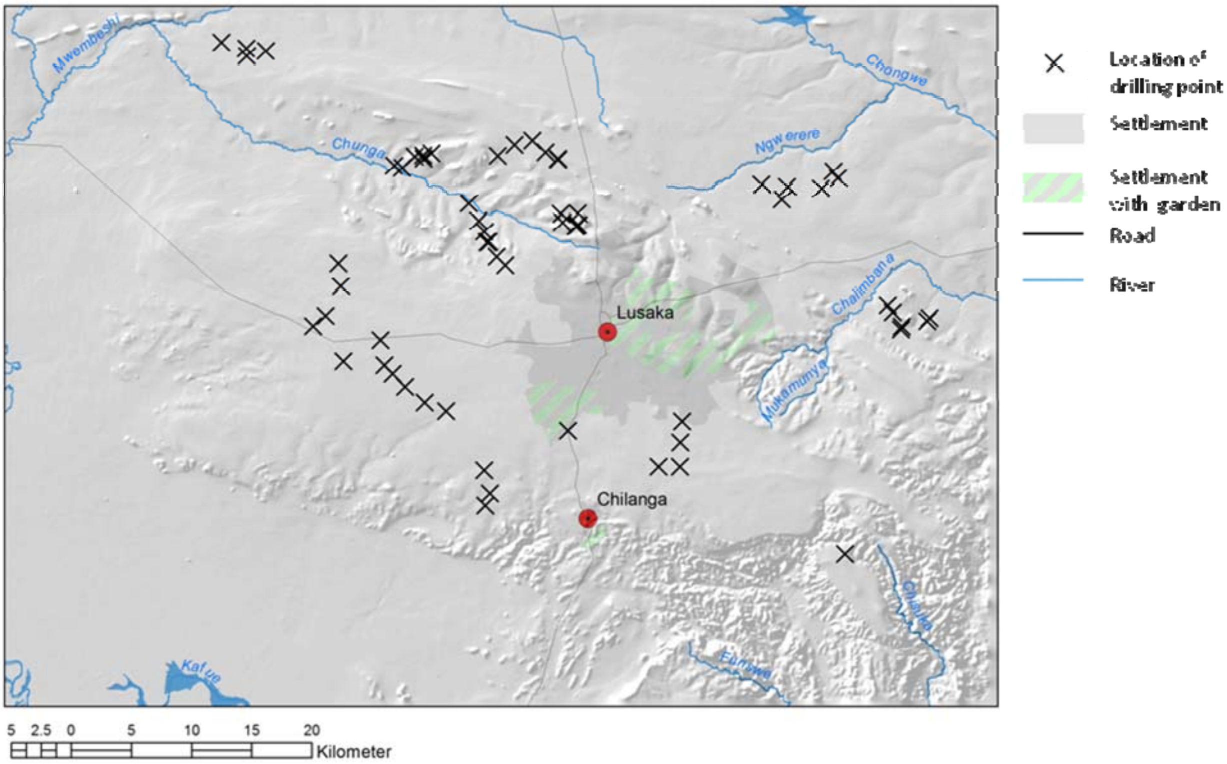

Figure 2: Spatial distribution of drilling points

Local soils of Greater Lusaka can be characterized by some general properties:

--- Soil formation over long periods of seasonal leaching on a maturely eroded landscape tends toward intensively, deeply weathered soils.

--- Soils are free of calcium carbonate even at places where limestone acts as parent material.

--- Soils are characterized by comparatively low organic matter contents. Even in the uppermost layer of the topsoil humus contents rarely exceed 2 %.

--- Particularly on unconsolidated rocks and flat surfaces soils are characterized by eluvial processes and accumulation of clay minerals in an argic subsurface horizon and by a low base saturation level. These Acrisols and Alisols correlate with red-yellow podzolic soils of other classification systems. Clay content in subsoil can be up to 25 % higher than clay content in topsoil.

--- As a consequence of high bulk densities, total pore volume, field capacity and available water capacity of local soils are limited.

--- At some places soils can be found that are completely built up from iron and manganese concretions (Fig. 6). They represent pre-stages of Plinthosols or soils where crust development has not taken place. According to definitions of the FAO or WRB classification system these soils have to be named as ferric ...sols.

Figure 3: The soil survey team at work

Figure 4: Lixisol developed from limestone

Figure 5: Groundwater affected soil with gleyic properties from the area northwest of Lusaka International Airport

Figure 6: "Plinthic" material at the surface

Figure 7: Outcrops of dolomite on the Lusaka plateau

4. Regionalization of soil development depth

Regionalization of soil hydrological parameters requires regionalization of soil development depth as the first step. The following work is based on the hypothesis that there is close correlation between topographical position and depth of soil development, i.e. the intensity of soil forming processes is mainly dependent on relief position. For the greater Lusaka area such regular spatial patterns are reported by CLAYTON (1974). For eastern Zambia the success of a geomorphologically based reconnaissance soil survey was assessed by DALAL-CLAYTON & ROBINSON (1992). The previous relief classification as described in chapter 3, based only on slope class and absolute altitude, was evaluated as not sufficient because the prediction potential of morphographic units was poor. For this purpose a new relief classification was required. Several concepts were compared and evaluated. All of them represent deterministic approaches and cannot explain all observed features. Particularly on the Lusaka plateau where soils are developed from dolomite the accuracy of any relief-based model is limited. Here highly erratic structures of short-range variability are predominant, and even the most appropriate approach performs poorly.

Relief analysis was carried out on digital elevation data from Shuttle Radar Topography Mission (SRTM) of 90 m spatial resolution. SRTM data were pre-processed by noise reduction using a Multi Direction Lee Filter. This filter is an enhanced Lee Filter which looks into 16 directions for the direction with the minimum variance and applies a Lee Filter on this direction. Afterwards this filter is used for removing speckle noise in SAR images or DTMs. On DTMs this filter preserves the slope and narrow valleys. For details on the Lee Filter, see LEE (1980). Only for channel net calculation a depression filling algorithm according to PLANCHON & DARBOUX (2001) was applied. In total, six different relief models were applied and six different indices were calculated:

--- Topographic Wetness Index (TWI) according to BÖHNER & KÖTHE (2003),
--- Convergence Index according to KÖTHE & LEHMEIER (1996),
--- Mass Balance Index according to MOELLER et al. (2008),
--- multi-resolution Valley Bottom Flatness Index according to GALLANT & DOWLING (2003),
--- vertical distance to channel net (VDC index),
--- Flow Path Length according to FREEMAN (1991).

The performance of relief models within the study area can be evaluated and prediction results can be validated on the basis of two fine-scale soil maps at the farm level which are available for Mt. Makulu Research Station and Kashima Farm. From both map legends information about soil development depth can be extracted. Furthermore results from the soil survey campaign were used for model validation. Most attention was paid on drilling results from schist ridges northwest of Lusaka, from unconsolidated rocks from the area close to Lusaka International Airport and from limestone areas west of Chilanga. Soil development depth was divided into five classes.

The best performance of prediction models was achieved when several relief parameters are combined. The most appropriate model integrates the following four parameters:

- --- Total Curvature (Fig. 8): After applying the algorithm developed by ZEVENBERGEN & THORNE (1987) the result was smoothed using a weak gauss filter and transformed into values between -1 and 1 according to FRIEDRICH (1996).
- --- SAGA Wetness Index (SWI) (Fig. 9): the index is similar to the "Topographic Wetness Index" (TWI), but it is based on a modified catchment area calculation ("Modified Catchment Area") which does not regard overland flow as a very thin film. As a consequence, for cells situated in valley floors with a small vertical distance to channels a more realistic, higher potential soil moisture compared to the standard TWI calculation is predicted. The method is documented by BOEHNER et al. (2002).
- --- Vertical Distance to Channel Net (VDC) (Fig. 10): The vertical distance to a channel network base level is calculated. The algorithm consists of two major steps: at first interpolation of a channel network base level elevation grid, secondly subtraction of this grid from the original elevations.
- --- Slope (Fig. 11): slope in degree is calculated, following quantitative analysis of land surface topography by ZEVENBERGEN & THORNE (1987).

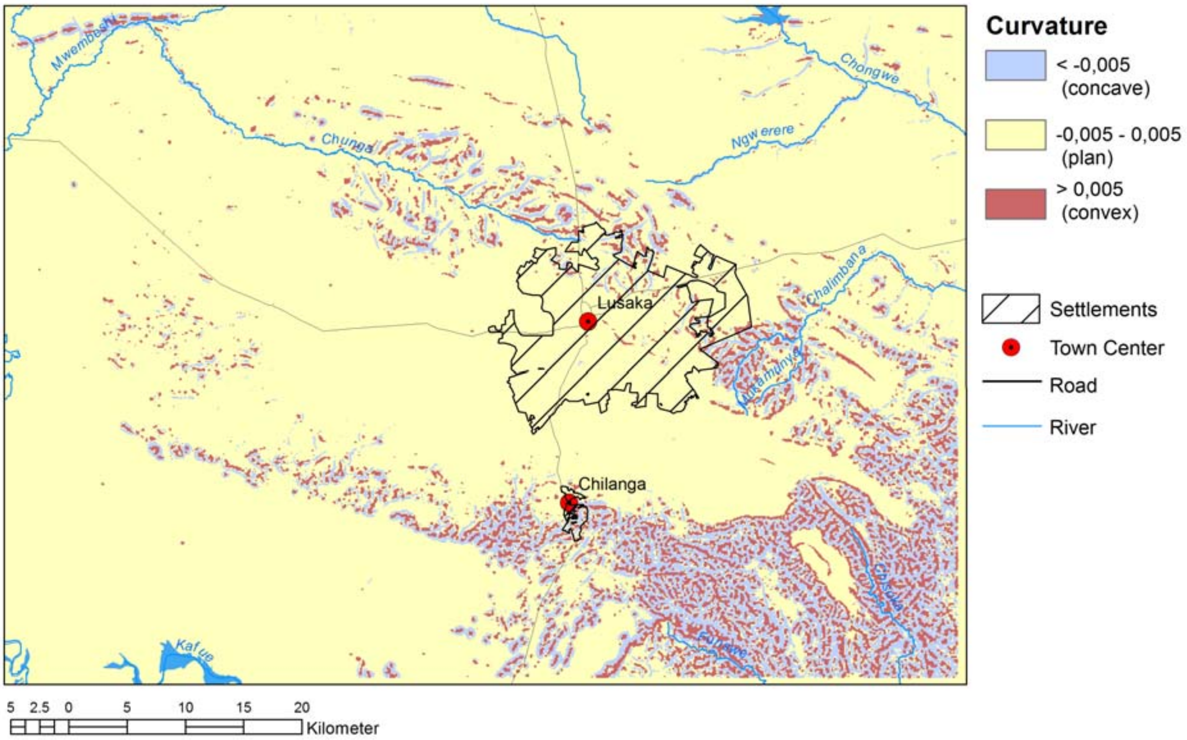

Figure 8: Regionalization of curvature within the study area

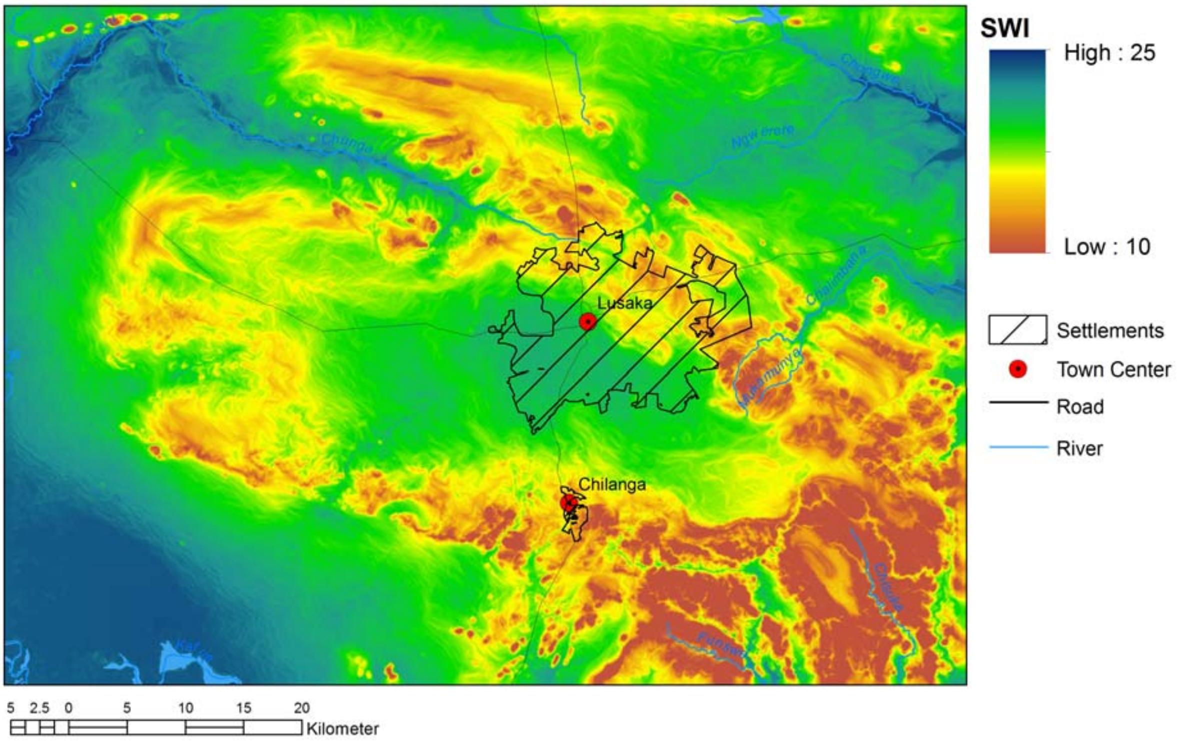

Figure 9: Regionalization of the SWI index within the study area

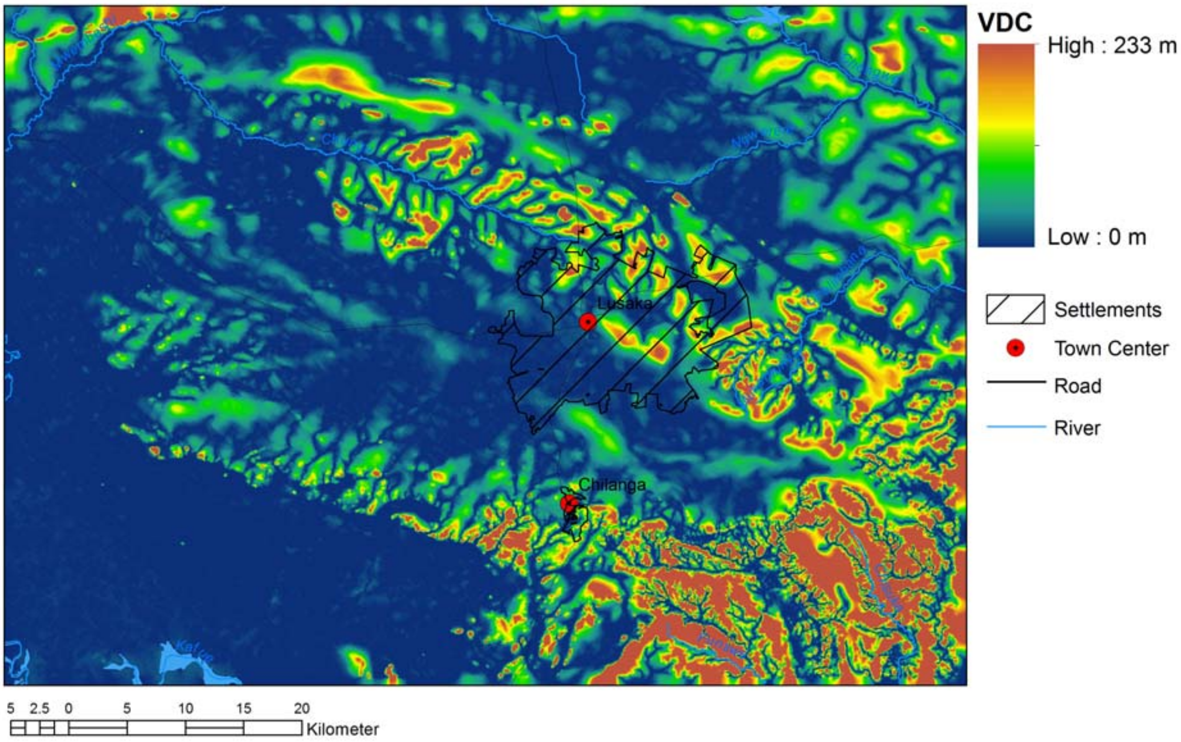

Figure 10: Regionalization of the VDC index within the study area

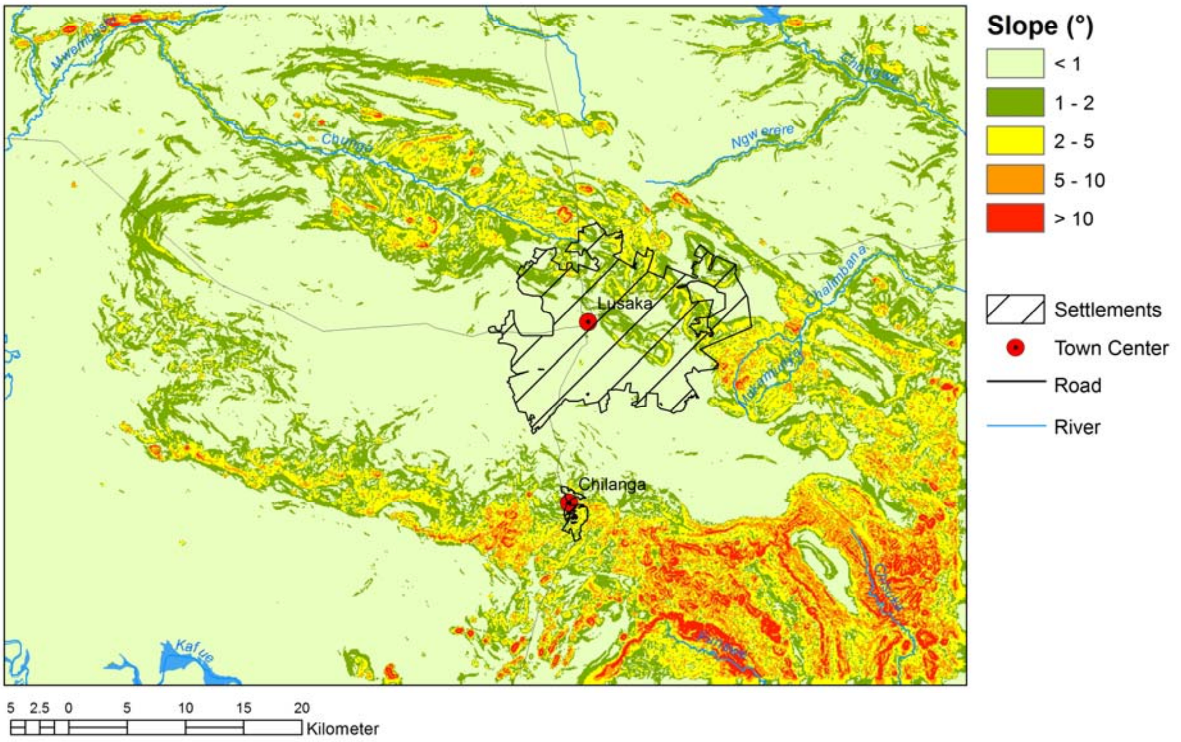

Figure 11: Regionalization of slope degree within the study area

All possible combinations of four curvature classes, four SWI classes, five VDC classes and five slope classes (200 variants) were considered and allocated to five soil depth classes. By this way for every raster cell the most frequently occurring soil depth class can be predicted. Results are given on an ordinal scale only and don't allow to express soil depth on a continuous scale (70 cm, 71 cm, 72 cm, ...). If the user wants more detailed information for water balance calculations mean values of the above-mentioned classes can be given (Fig. 12).

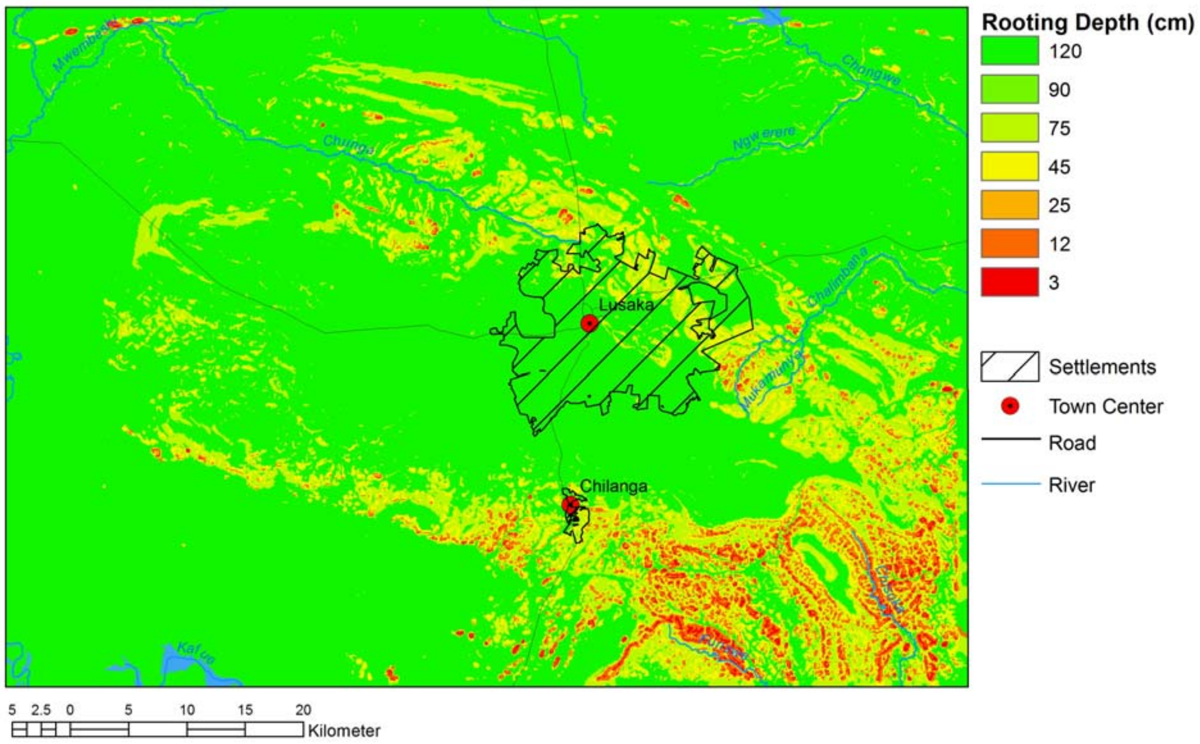

Figure 12: Best-possible prediction of soil depth within the study area, based on a relief classification using four parameters

Qualitatively the accuracy of Figure 12 can be assessed when model results are compared to reality. On a detailed scale this can be done for the area around Mt. Makulu Station: detailed mapping results (Fig. 13) stand versus model predictions (Fig. 14). The general spatial pattern as predicted by relief-based models corresponds well to survey results, but in some parts of the area under consideration also some deviations can be observed. For example, in the northeastern and southeastern corner of the surveyed area a soil depth of < 15 cm was found; here the model assumes deeper developed soils. On the average, depth of soil development as shown in Fig. 14 is slightly overestimated.

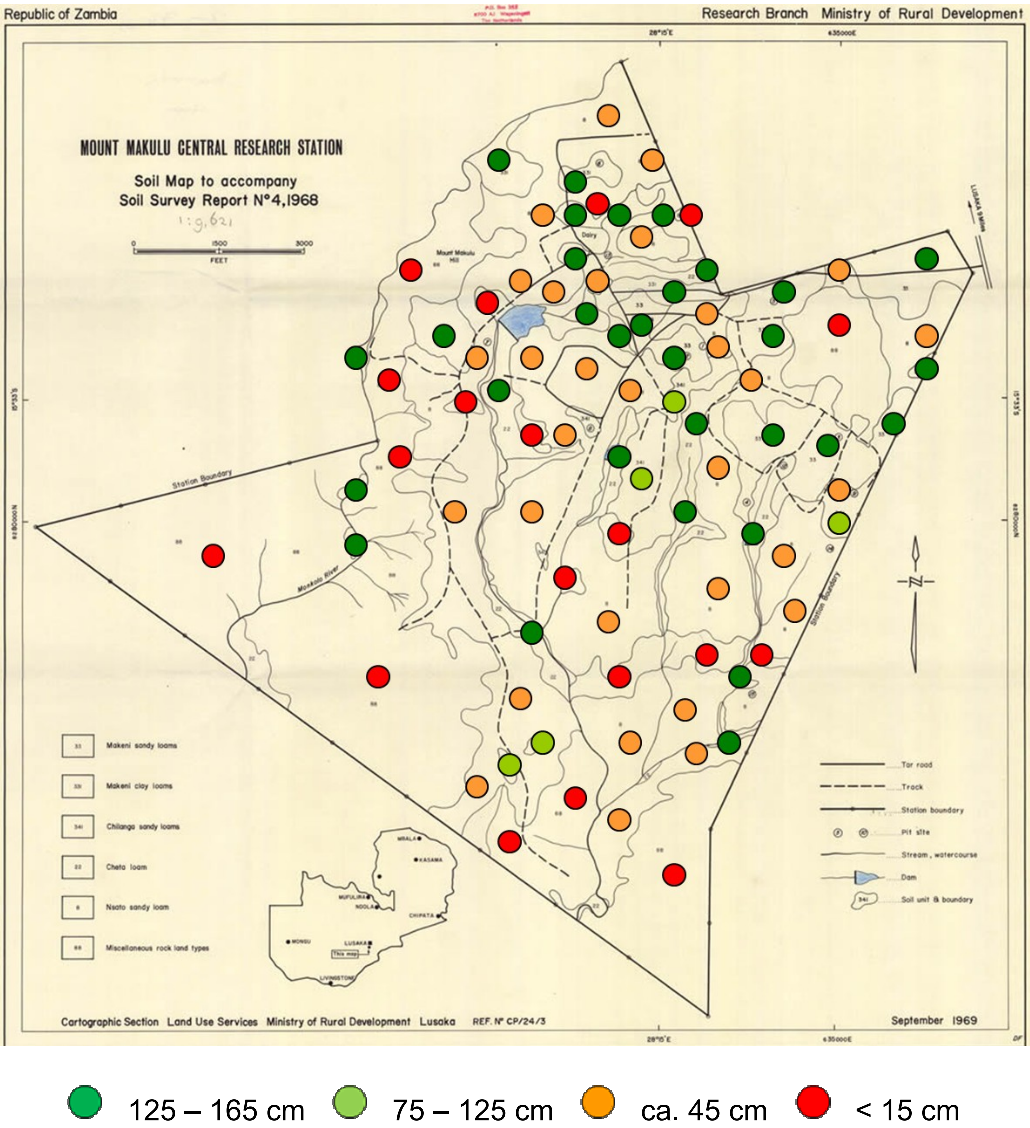

Figure 13: Soil depth around Mt. Makulu Station according to Lee (1968)

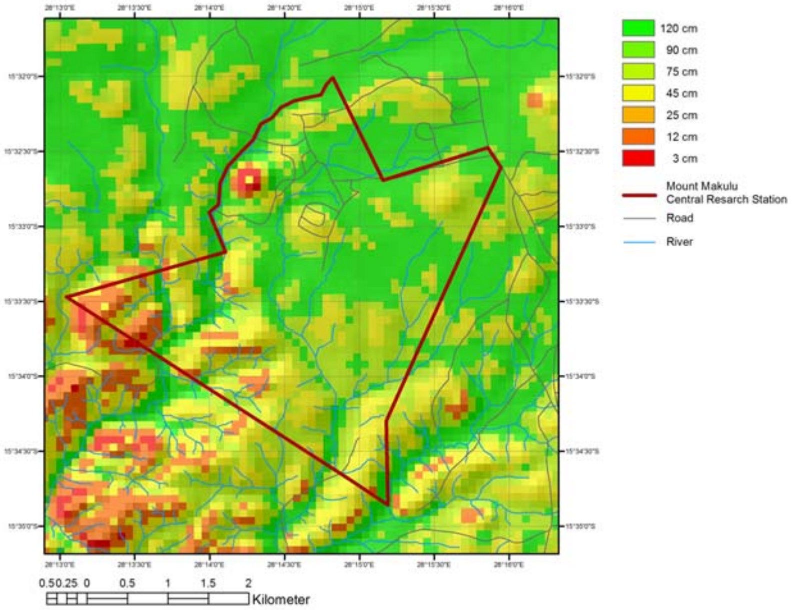

Figure 14: Soil depth around Mt. Makulu Station according to a relief-based prediction model

Because of the extremely heterogeneous soils developed from Lusaka dolomite the described relief classification cannot be utilized for the prediction of soil properties on the Lusaka plateau. The only alternative offers the old BGR soil map from 1978, compiled by von Hoyer et al. at the 1:100,000 scale. Therefore the von Hoyer map was inserted into Fig. 13. In 1978, these authors used another classification of soil depth, differing from that one used in Fig. 13. For that reason the legend of the von Hoyer map can not be adapted directly to the legend of the map from Fig. 13. The final map of Fig. 15 differentiates into seven classified values.

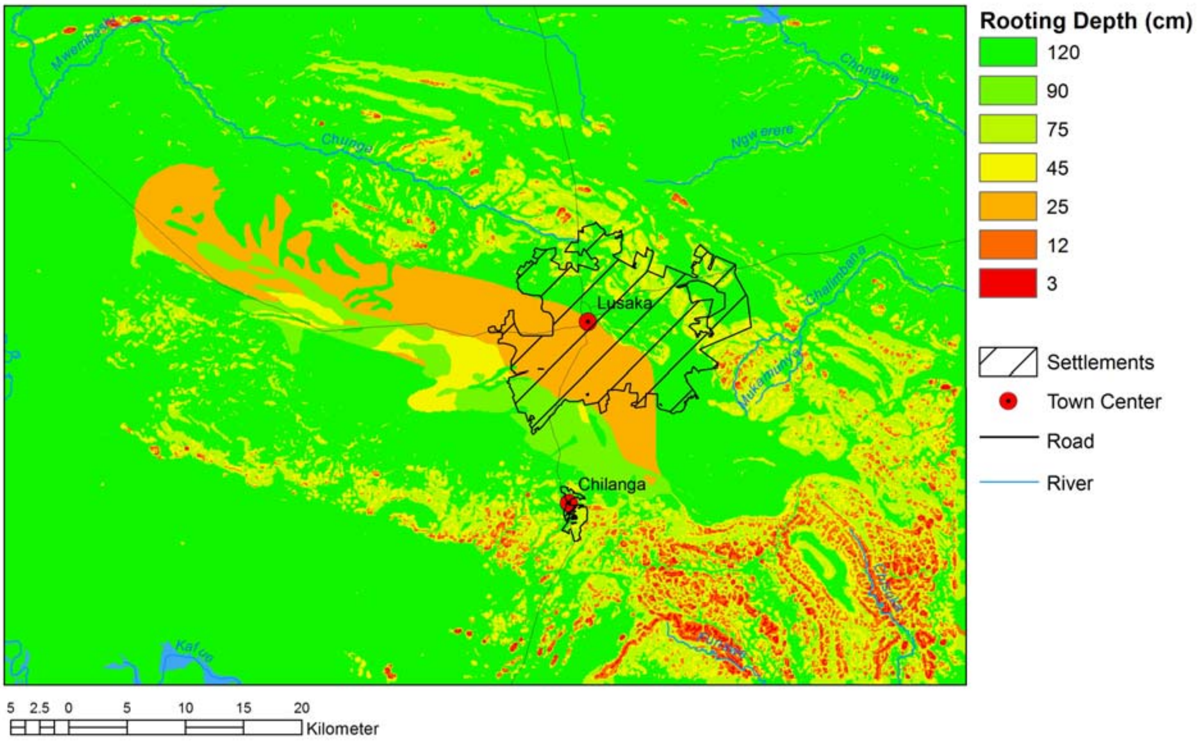

Figure 15: Final map of soil development depth in the study area

5. Regionalization of soil texture classes

In a second step typical soil texture classes have to be allocated to raster cells of Fig. 15. Information about soil texture is available at different scales (see chapter 2). A coarse-scale map can be derived from the 1:1,000,000 Exploratory Soil Map of Zambia, additionally site-specific information is available from different sources. Because of their sparse distribution these profile descriptions don’t allow any spatial interpolation of soil properties. Alternatively a medium-scale map that covers the entire study area can be compiled from geological maps, using lithological units as basic information. The inventory of the project database "soil texture" (see chapter 2) can be used for allocating dominant texture classes to groups of parent material (Fig. 16).

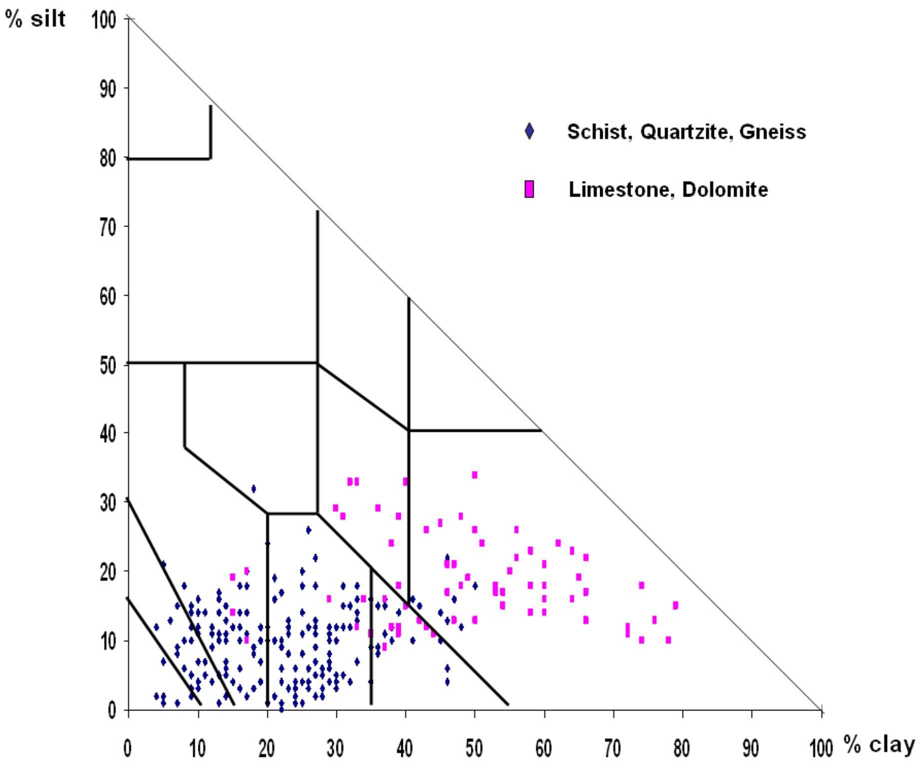

Figure 16: Clay and silt content of selected soils of the study area (n = 273), plotted in the FAO particle-size triangle

From Fig. 16 it can be clearly seen that soils developed from limestone and dolomite and soils developed from schist, quartzite and gneiss significantly differ in their particle-size distribution. Nevertheless, results for soils of one of these groups are scattered over two or three texture classes, e.g. soils from schist and other parent materials rich in quartz are equally distributed between loamy sand, sandy loam and sandy clay loam. This variability mainly results from pedogenesis, i.e. clay migration, and not from weathering processes. Topsoil horizons often consist of loamy sand while Bt horizons are characterized by sandy clay loam (Fig. 17).

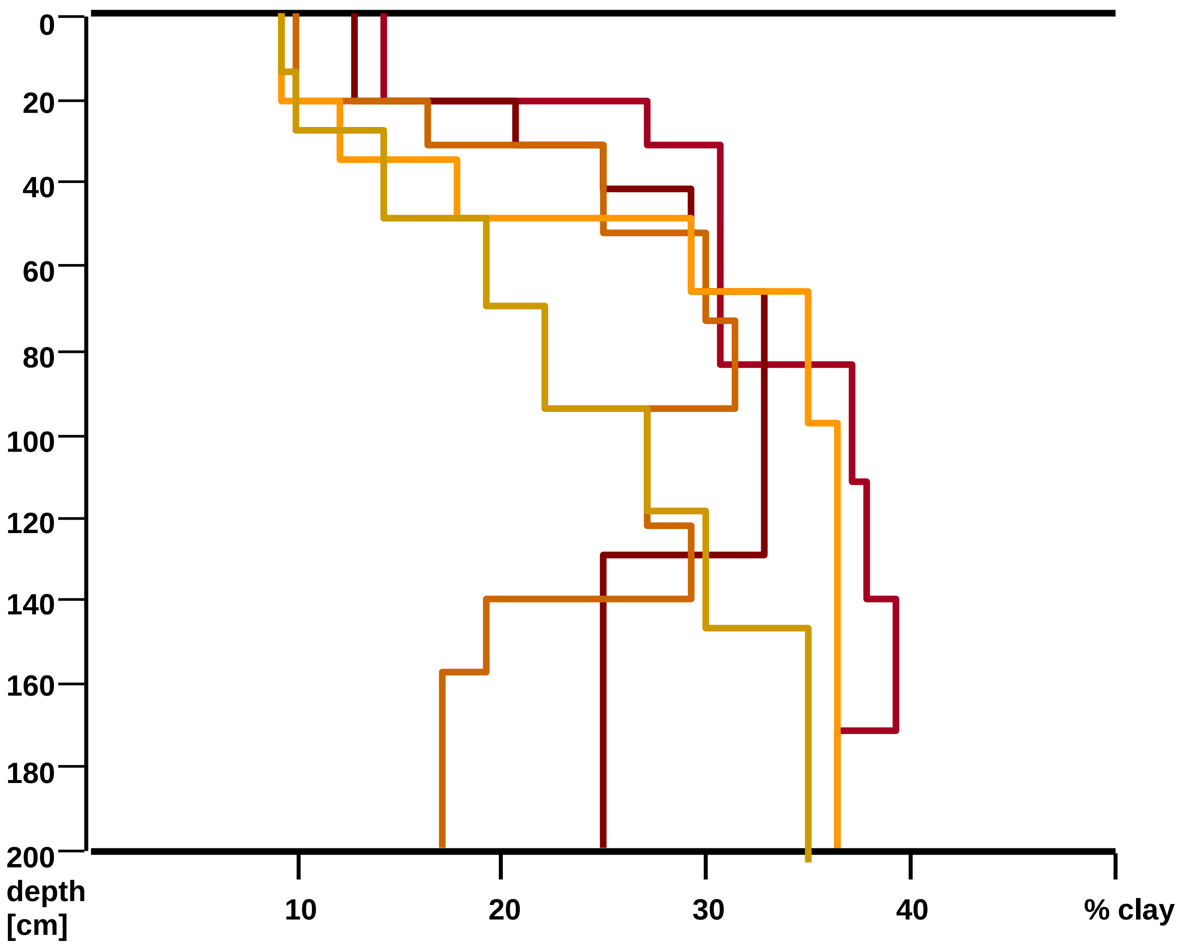

Figure 17: Clay content as a function of depth for selected soil profiles of the study area, developed from schist and gneiss

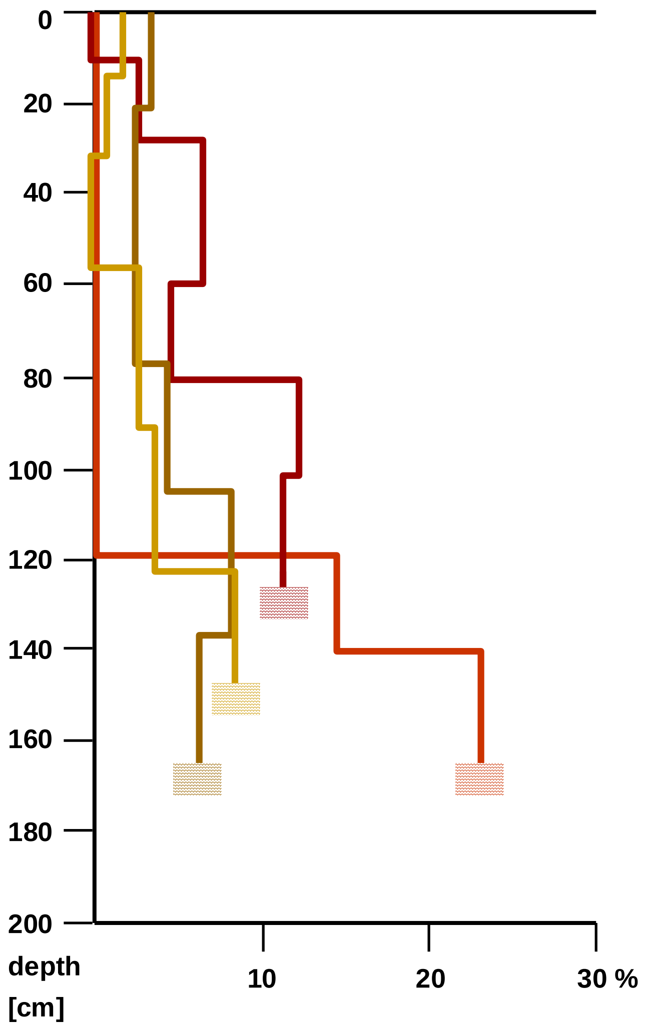

Figure 18: Proportion of coarse fragments as a function of depth for selected soil profiles of the study area

In this study information about soil texture is only needed for estimating soil hydrological properties such as the available water capacity of the root zone. Against this background, knowledge of clay contents and proportions of coarse fragments of all relevant soil horizons is important and is needed to summarize the available water capacity over the entire interval of consideration, but has not to be presented in separate thematic maps for every geological stratum or soil horizon. In Table 2 the general rules for interpreting the local geological map and underlying assumptions for the spatial estimation of typical soil texture classes and mean clay and silt contents are given, and Fig. 19 shows the final regionalization result for the study area. Properties of soils developed from igneous rocks are unknown, and therefore these rocks/soils are excluded from the map in Fig. 19.

Table 2: Rules for predicting soil texture classes from lithological units

Parent material	Dominant texture class	Mean clay content [%]	Mean silt content [%]
Limestone	clay	48	18
Dolomite			
Schist	sandy clay loam	22	10
Psammite			
Quarzite			
Granite	sandy loam	17	10
Igneous Rocks	?	?	?
Unconsolidated Rocks	sandy clay	40	10

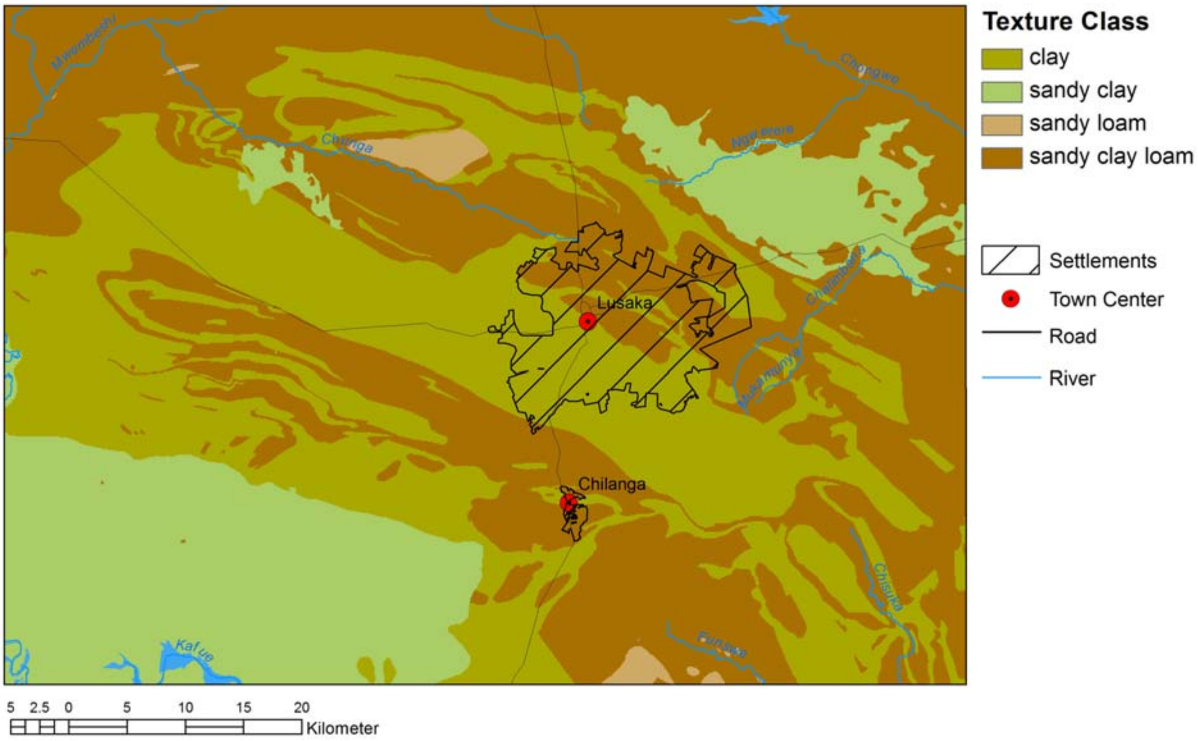

Figure 19: Typical soil texture classes of the root zone in the study area

In addition to soil texture or clay content, bulk density and organic matter content also act as input variables to pedotransfer functions. Organic matter contents of local soils are generally low, and can therefore be neglected. Bulk densities are comparatively high, even in topsoil, and no distinction between topsoil and subsoil is necessary. Mean values of intensively investigated soils were calculated, and 1.6 g/cm^3 was used as an overall mean for pedotransfer function applications. When available water capacities of the root zone were calculated by

PTF equations, estimates were slightly reduced because of coarse fragments, and this final correction was carried out on the basis of typical profiles as shown in Fig. 18.

6. Regionalization of saturated hydraulic conductivity

One objective of the local project is the compilation of a groundwater vulnerability map. As one parameter determining the protective effect of the soil cover, the saturated hydraulic conductivity (ksat) of the topsoil is required when the PI method (GOLDSCHEIDER 2002) was chosen as the appropriate approach. The target variable can be estimated by applying pedotransfer functions on typical soil texture characteristics from Fig. 19 and associated soil properties such as bulk density and humus content. Unfortunately measured ksat values for local soils in the Lusaka area are not available; neither the WISE database nor ZARI's Soil Survey Reports contain any results from laboratory measurements on this topic. That means that topsoil ksat can only be estimated from empirical knowledge but cannot be validated.

Table 3: International pedotransfer functions to estimate saturated hydraulic conductivity: best-suited approaches for selected texture classes

Texture class	Appropriate PTF	Input data
sandy loam	BRAKENSIEK et al. (1984)	clay content, silt content, bulk density
	CAMPELL (1985)	contents of at least three particle size fractions, bulk density
sandy clay loam	VEREECKEN et al. (1990)	clay content, silt content, bulk density, organic matter content
sandy clay	?	
clay	SAXTON et al. (1986)	clay content, silt content
	COSBY et al. (1984)	clay content, silt content

Several approaches to predict saturated hydraulic conductivity from soil characteristics such as clay content, bulk density and organic matter content are presented by TIETJE & HENNINGS (1996). Additionally mean ksat values per texture class can be obtained by applying class pedotransfer functions from the 4th edition (AG BODEN 1994) or 5th edition of German soil mapping guidelines (AD-HOC-AG BODEN 2004). TIETJE & HENNINGS compare and evaluate existing approaches on the basis of almost 1200 data sets from the laboratory database of the Lower Saxony Soil Information System. Main results of their study can be summarized as follows:

--- The prediction of the saturated hydraulic conductivity using a pedotransfer function is inaccurate. The geometric standard deviation of the error ratio (GSDER) is about 4 to 20 and is about the same as the standard deviation of the data.

--- Pedotransfer functions based only on grain-size distribution and represented by a simple regression equation (e.g., COSBY et al., 1984) lead to results that are similar to those of more complex models (e.g., BRAKENSIEK et al. 1984).

--- Integration of additional independent variables, such as bulk density and organic matter content, does not significantly reduce the GSDER.

--- The variability of the measured data within the textural classes showed good agreement with the variability of the error ratios of the pedotransfer functions. This indicates that the inaccuracy of the ksat prediction is due to the inherent variability of the saturated hydraulic conductivity (including measurement error, spatial variability, and sample error).

--- The pedotransfer function should be chosen on the basis of the textural class for which a ksat prediction is to be made.

The last conclusion or recommendation to choose texture class specific PTFs was picked up and is reflected in Tables 3 and 4. For example, on sandy clay loam only the models from BRAKENSIEK et al. (1984) and VEREECKEN et al. (1990) were applied. All calculations are based on bulk densities of 1.6 g/cm^3 and organic matter contents of 0.1 %. Table 4 offers up to four different estimates for every texture class and the final value that was assessed as a realistic local value. In a final step, typical soil texture classes from Fig. 19 were linked with estimates from Table 4. Results for the study area are presented in Fig. 20. General accuracy of PTF results can be assessed by utilizing results from TIETJE & HENNINGS (1996). Additional errors resulting from macropores and preferential flow phenomena don't have to be taken into account because vertisols only occur on Kafue flats outside the study area.

Table 4: Ksat estimates of selected pedotransfer functions for typical soil texture classes

Texture class	Most appropriate PTF	Ksat estimate of selected PTF [cm/d]	Ksat estimate according to German soil mapping guidelines, 4th edition [cm/d]	Ksat estimate according to German soil mapping guidelines, 5th edition [cm/d]	Final ksat estimate [cm/d]
sandy loam	Brakensiek et al. (1984)	136	34	67	42
sandy loam	Vereecken et al. (1990)	14			
sandy clay loam	Brakensiek et al. (1984)	70	16	42	28
sandy clay loam	Vereecken et al. (1990)	11.5			
sandy clay	Brakensiek et al. (1984)	1.8	---	11	6
sandy clay	Vereecken et al. (1990)	7.9			
clay	Saxton et al. (1986)	3	1	6	2
clay	Cosby et al. (1984)	20			

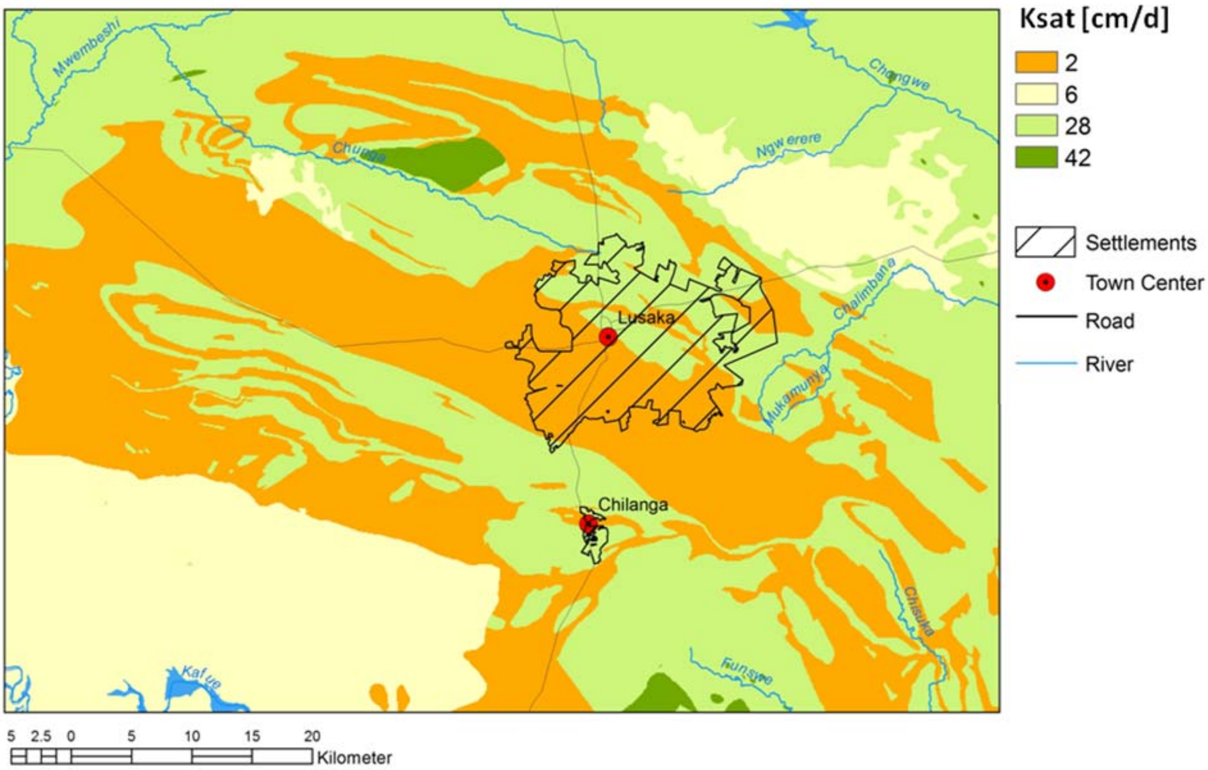

Figure 20: Estimated topsoil saturated hydraulic conductivities in the study area

7. Regionalization of soil available water capacities

Field capacity is conventionally quoted as moisture content in vol. % at a soil-water matrix potential of pF = 1.8 (equivalent to mm head of water per dm soil thickness), in most tropical and subtropical countries at pF = 2.5. The permanent wilting point, conventionally quoted as matrix potential of pF = 4.2, is the limit at which crops begin to wilt irreversibly. The available water capacity is defined by two soil-water matrix potentials: above pF = 4.2 all the moisture is held in the fine pores and is not available for plants, and below pF = 2.5 the moisture is relatively readily removed from the pores. The available water capacity (awc) can therefore be defined as proportion of the field capacity available to plants. Water retention parameters such as awc often serve as input data for simple functional models to simulate the soil moisture regime or for empirical nomograms and regression equations for determining of the mean annual percolation rate.

Usually the water retention parameters are determined in the laboratory by using undisturbed samples and ceramic cells. To avoid costly and time-consuming measurements pedotransfer functions are applied to estimate the required parameters from easily mappable soil characteristics such as texture class, bulk density, and organic matter content. In the same way as it was done for hydraulic conductivities, available water capacities can be estimated by pedotransfer functions from regionalized soil physical properties as available from maps like Fig. 19. To characterize a complete soil profile, the available water capacity is usually summed over the effective rooting depth, in this case over the depth interval of soil development as shown in Fig. 15.

Table 5: Available water capacity estimates (awc) of selected pedotransfer functions for typical soil texture classes of the study area and mean local measurement results

Texture class	**Awc [mm/dm]**				
	FAO	VEREECKEN et al. (1989)	WOESTEN et al. (1998)	German soil mapping guidelines, 4th edition	Means from local measurements
sandy loam	16	10	9.2	10.5	7.7 (n = 36)
sandy clay loam	13	10.5	9.5	10.5	8.6 (n = 26)
sandy clay	9	8.3	11.8	8.0	7.5 (n = 10)
clay	12	6.4	9.1	7.0	7.2 (n = 14)

In Table 5 results of three international and one German PTF are compared. The FAO approach is based on knowledge of texture classes only, and no distinction is made with respect to bulk density. The models from VEREECKEN et al. (1989) and WOESTEN et al. (1998) represent continuous pedotransfer functions and consist of several regression equations to estimate the parameters of the van Genuchten model. The WOESTEN approach results from the HYPRES database which has been developed as an integral part of the EU funded project "Using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning". The approach from the 4th edition of the German soil mapping guidelines (AG BODEN 1994) is type of a class pedotransfer function and provides mean estimates for texture classes and bulk density classes. Local means per FAO texture class were calculated using the inventory of the self-created "soil water retention" database (see chapter 2).

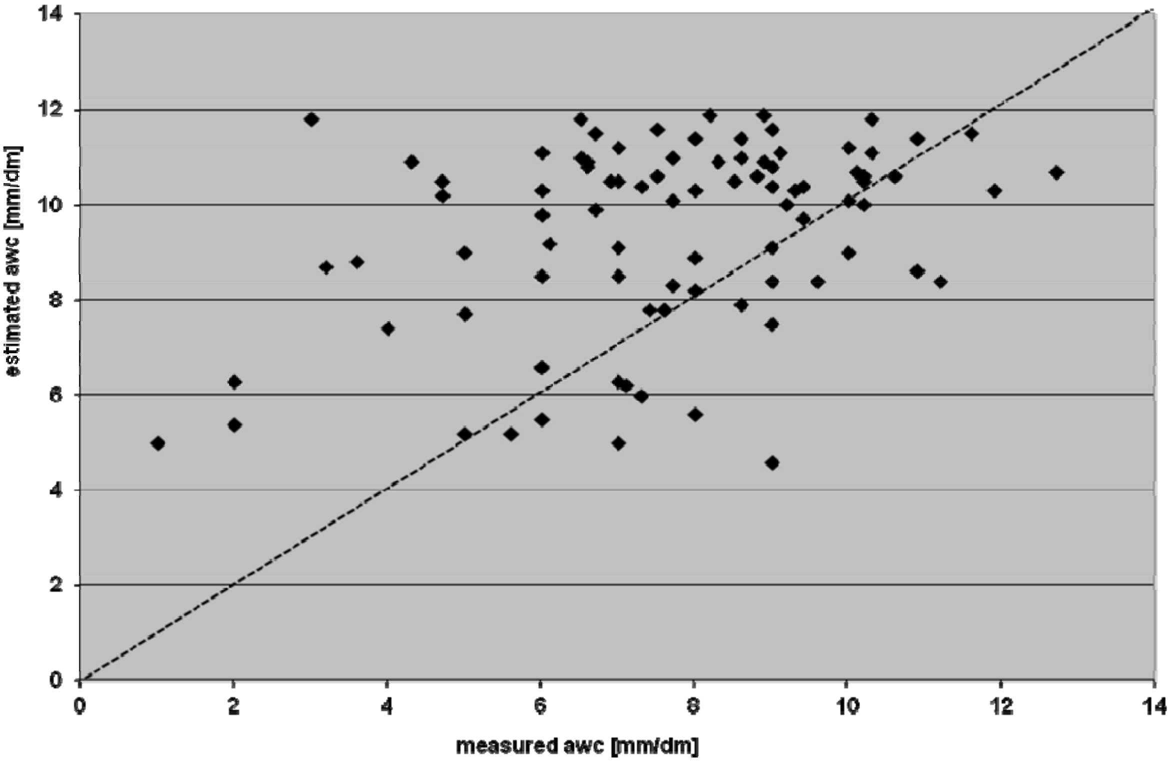

Figure 21: Estimation results of soil available water capacity, using the PTF from VEREECKEN et al. (1989), in comparison to measurement results for selected soil samples from the project area (n = 87)

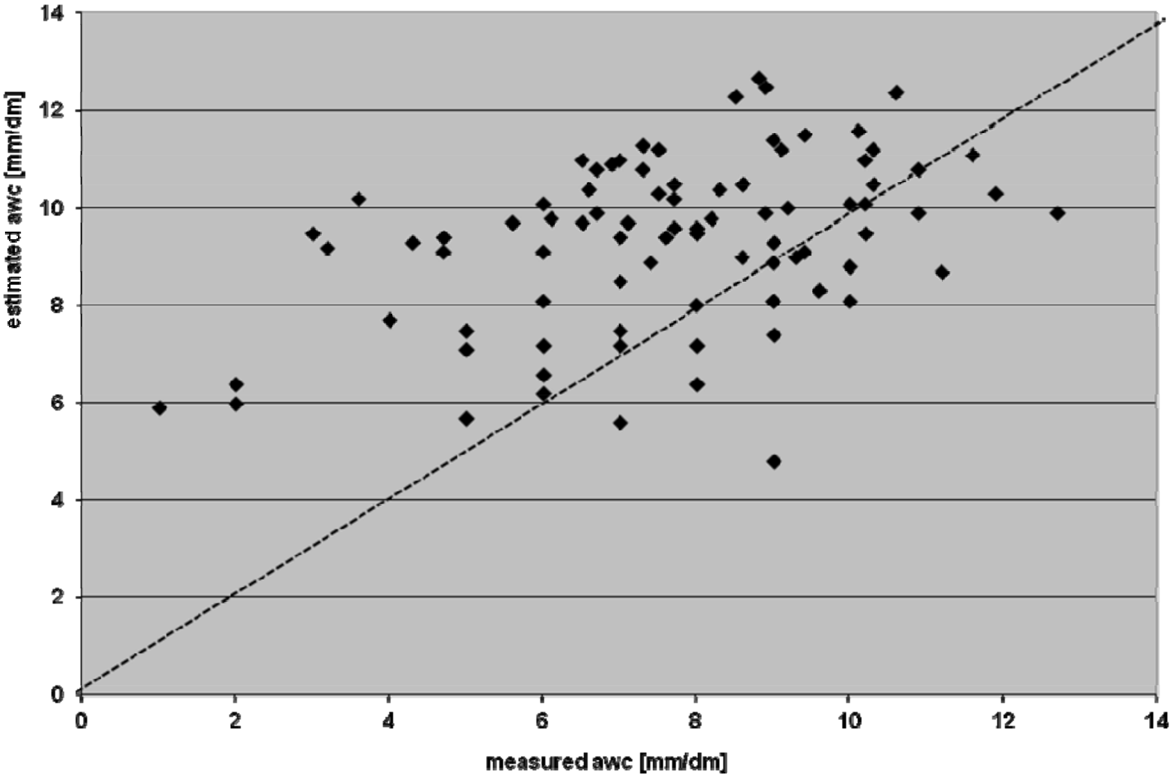

Figure 22: Estimation results of soil available water capacity, using the PTF from WOESTEN et al. (1998), in comparison to measurement results for selected soil samples from the project area (n = 87)

As it can be seen from Table 5, available water capacities among texture classes under consideration differ only slightly, with the exception of the FAO approach. Available water capacities are generally low, because of high bulk densities (see chapter 3). The FAO approach by far overestimates reality and performs poorly. For that reason more attention was laid on the competing approaches from Vereecken and Woesten. Final estimates represent means of PTF results and local measurement results and are presented in Table 6.

Table 6: Final awc estimates for typical soil texture classes of the study area

Texture class	**Awc [mm/dm]**
sandy loam	10
sandy clay loam	10.5
sandy clay	8.5
clay	7.5

In a next to last step, typical soil texture classes from Fig. 19 were linked with estimates from Table 6. Finally available water capacities over the depth interval of soil development as shown in Fig. 15 were added up. This calculation is based on assumptions on typical proportions of coarse fragments as mentioned in chapter 5. Results for the study area are presented in Fig. 23.

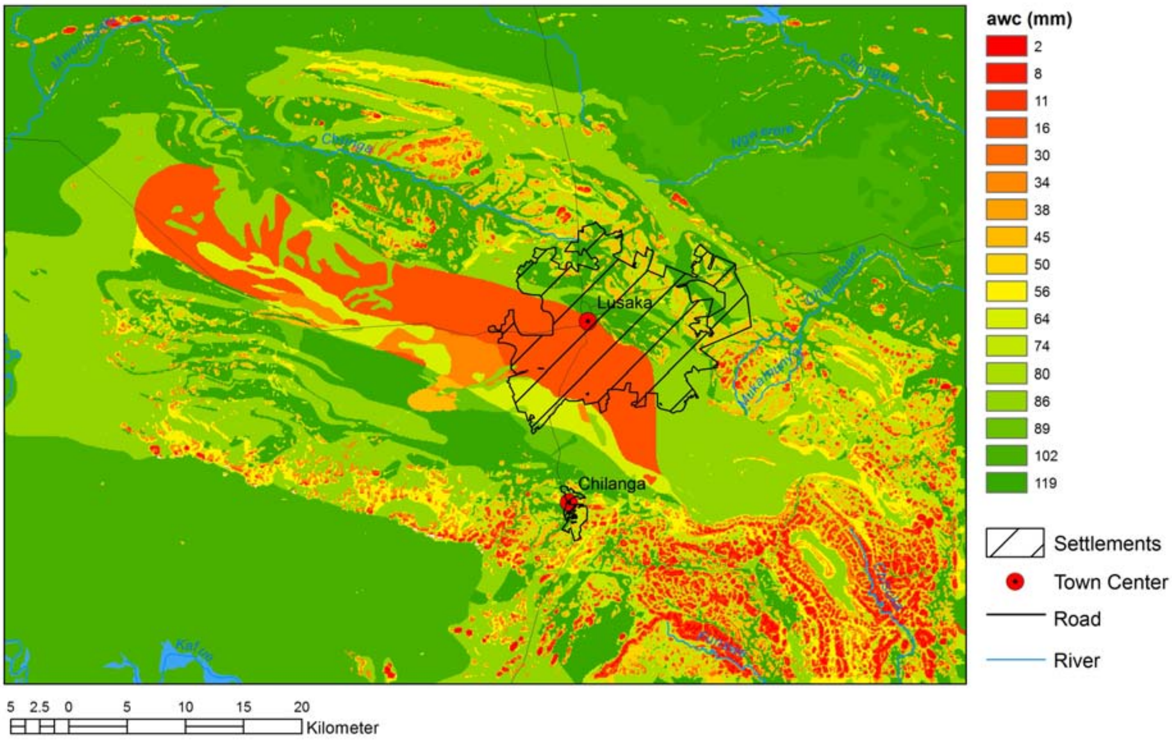

Figure 23: Available water capacities of the root zone of soils of the study area

Maximum awc values close to 120 mm are connected with deeply developed sandy (clay) loam soils in flat positions. Minimum values are connected with steep slopes independently of the type of rock that acts as parent material. Outside the dolomite plateau in the centre of the study area the regionalization of soil depth is based on the relief classification as described in chapter 4, on the Lusaka plateau itself the map from Fig. 23 is based on the old soil map from VON HOYER from the seventies. The awc estimates base upon local pedotransfer functions as presented in Table 6. As a consequence, the accuracy of the awc map of the Lusaka area is dependent on three influencing factors: regionalization of soil development depth, assignment of soil texture classes to lithological units and estimation of soil available water capacity by pedotransfer functions. Because soil texture acts as the dominant input variable to pedotransfer functions the latter two influencing factors are intercorrelated. But the most relevant factor is supposed to be the relief-based algorithm that is used for regionalization of soil depth. On the average, depth of soil development is expected to be slightly overestimated. In general, the reliability of any map of soil depth depends on the degree of correlation between soil depth and relief position. The Lusaka plateau in the centre of the study area is characterized by spatial patterns of short-range variability and therefore represents the area of poorest model performance or map reliability. As a consequence, this statement also refers to local estimates of soil available water capacities. The regionalization of soil physical parameters in the Lusaka area and the accuracy of Fig. 23 could be improved if more knowledge of soil spatial variability will be available and will be incorporated into this map.

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