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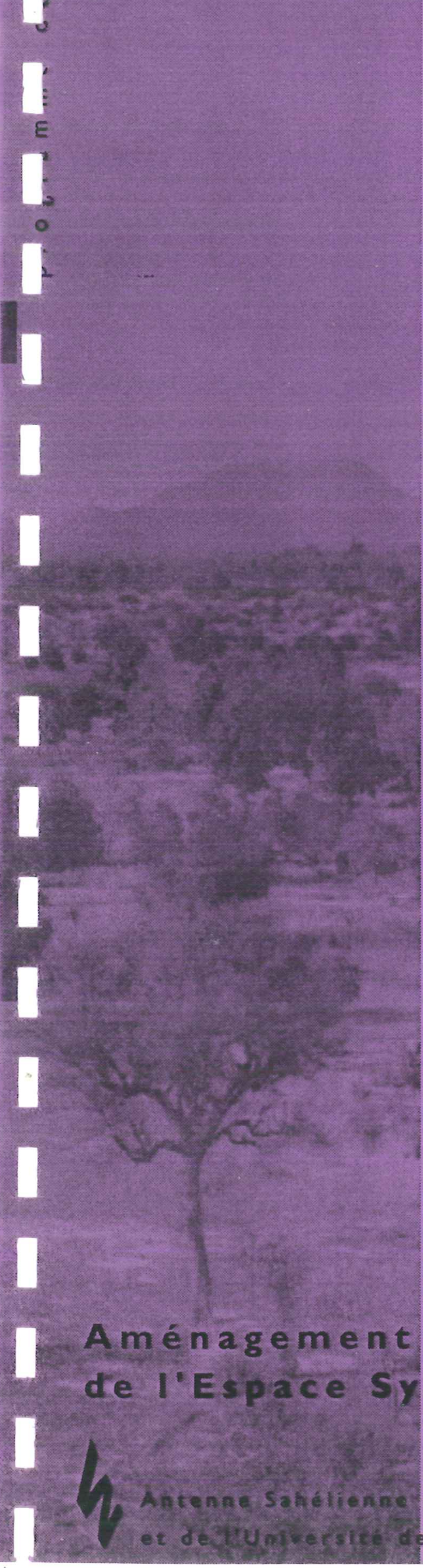

# PHYSICAL PROPERTIES OF SOILS IN THE KAYA AREA, BURKINA FASO


MSc-thesis in Soil & Water Conservation,
Department of Irrigation and Soil & Water Conservation,
Wageningen Agricultural University

J.D. WIJNHOUD and A.J. OTTO



August 1994


**Aménagement et Gestion de l'Espace Sylvo-Pastoral au Sahel**


Antenne Sahélienne de l'Université Agronomique Wageningen Pays-Bas
et de l'Université de Ouagadougou Burkina Faso

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# PHYSICAL PROPERTIES OF SOILS IN THE KAYA AREA, BURKINA FASO



(MSc-thesis in Soil & Water Conservation (K200-711) 840 sbu, Department of Irrigation and Soil & Water Conservation, Wageningen Agricultural University)

**by J.D. Wijnhoud and A.J. Otto**
**August 1994**

# FOREWORD

This is the report of research of physical properties of soils in the Kaya area, Burkina Faso. The research formed one of the last subjects of study for our studies physical geography at the University Utrecht. It was carried out as a subsidiary subject for the Department of Irrigation and Soil & Water Conservation of the Wageningen Agricultural University. We would like to thank Mr L. Stroosnijder and Mr W.B. Hoogmoed for their supervising and the coordination of the research in Wageningen, the Netherlands. We would like to thank Mr W.F. van Driel for his supervising and advices and Mr R. Kaboré and Mr D. Legger for their help and advices during the research in Ouagadougou, Burkina Faso. We would like to thank Mr F. Hièn for his help by the translations into French. We would like to thank Mr J.W. Nibbering and Mrs M. Slingerland for their help with the logistics in Burkina Faso. We would like to thank Mr A. Bélemvire for his introduction in the field and advices in the laboratory and Mr B. Bélemvire for helping us in the field. Further we would like to thank a lot of people in Burkina Faso, especially the co-operators and students working for Antenne Sahélienne and our neighbours in Ouagadougou, for giving us a great time.

J.D. Wijnhoud and A.J. Otto, August 1994.

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SUMMARY

In a research carried out in the Kaya area, Burkina Faso, the soil physical properties texture, bulk density (BD), saturated hydraulic conductivity (Ksat) and soil moisture characteristic (SMC) were studied. The purpose was to study the spatial variability in soil physical properties. An other purpose was to study relations between the different soil physical properties.

Soils are strongly related to geology in the research area. A geological soil map made by Legger et al. (1994), of which annex A is a simplified version, was used as basis for sampling. Four geological soil units 'granitic area, valley bare' (GRvb), 'greenschist area, valley bare' (GSvb), 'greenschist area, valley stone' (GSvs) and 'redschist area, valley bare' (RSvb) were sampled. One unit could be divided in a 'degraded' and 'non-degraded phase' which both were sampled so that the influence of soil degradation on soil physical properties could be studied.

A strategy related to nested sampling was used (Webster and Oliver, 1990). The units, including the two distinguished phases of unit GRvb, were sampled by clusters of 3 sample pits. Within one cluster, pits were located some 50 metres from each other. Two clusters present within a unit, were located some hundred metres to some kilometres from each other. Where possible samples were taken at 3 depths:5-10 cm (layer A), 30-35 cm (layer B), and 60-65 cm (layer C). At each depth one bag sample was taken for texture analysis and 3 ring samples with a height and diameter of both 5 cm were taken for measuring the other soil physical properties. By sampling in this way variation measured between units, stadia of degradation, clusters, sample pits, soil depths and samples taken from the same layer in a pit can be studied.

Most units are characterized by relatively coarse textured soils of loamy sand and sandy loam. However, texture of unit GRvb (non-degraded phase) tends to be a bit coarser than that of units GSvb and RSvb. Only in the sub-soil of the degraded phase of unit GRvb and in the sub-soil of unit GSvs, moderately fine textures of sandy clay loam and clay loam were measured. The sand fraction for the soils of all units mainly consists of fine sand. Texture usually becomes finer with depth and in most sample pits the highest clay percentages are found within the C-layer (55-60 cm), caused by the illuviation of clay eluviated from the soil layers located on top of this soil layer.

For a certain depth within a unit standard deviations for the BD of more than 0.09 g/cm3 were measured sometimes, which is an usual phenomenon for BD-analysis. BD-values for the unit GRvb (non-degraded phase) (resp. 1.60 , 1.59 and 1.62 g/cm3 for the A-, B- and C-layer) tend to be higher than those for units GSvb (resp. 1.44, 1.48 g/cm3 and 1.54 g/cm3 for the A-,B- and C-layer) and RSvb (resp. 1.51, 1.43 and 1.45 g/cm3 for the A-, B- and C-layer). Differences in particle density and soil structure are thought to be mainly responsible for the difference in BD-values. The degraded phase of unit GRvb in the sub-soil is characterized

by a relatively high BD-value of 1.67 g/cm3. Unit GSvs is characterized by BD-values of 1.62 g/cm3 in the A- and B-layer and 1.71 g/cm3 in the C-layer, which are relatively high values for the textures present. A compact soil and the presence of gravel may explain the high BD-values here. In general BD-values tend to increase with depth, which however is not the case for unit RSvb.

For a certain depth within a unit high standard deviations for the Ksat of more than 5cm/h are present. Possibly this may be due to measuring-errors. Ksat-values for unit GRvb (non-degraded phase) (resp. 7.15, 5.09, and 2.49 cm/h for the A-, B- and C-layer) tend to be lower than for unit GSvb (resp. 8.10, 6.92 and 4,34 cm/h for the A-, B-, and C-layer). Unit RSvb is characterized by relatively high Ksat-values (resp. 9.38, 11.55 and 7.00 for the A-, B- and C-layer). These differences in Ksat-values may be mainly due to differences in soil structure and BD-values. The degraded phase of unit GRvb, especially in the top-soil, is characterized by lower Ksat-values (resp. 0.40, 1.80 and 0.54 for the A-, B- and C-layer) than those measured for the non-degraded phase. The very low Ksat-values in the A-layer can be explained by the presence of a surface crust which was partly present in the samples. Soils of this unit are cemented in the whole profile which explains the relatively low Ksat-values for all soil layers. The Ksat-value of especially the C-layer of unit GSvs is low (0.08 cm/h), which partly may be explained by its high BD-value. Possibly, samples were disturbed and underestimation of Ksat-values took place. In general there is a tendency for the Ksat-values to decrease with depth. This is due to the fact that BD-values tend to increase with depth and soil structure is less developed in the sub-soil than in the top-soil.

Standard deviations of more than 3% are present for the 'available water capacity' (AWC) for a certain soil layer within a unit. The SMC for unit GRvb (non-degraded phase) is characterized by a low AWC (resp. 13, 14 and 15 % for the A-, B- and C-layer) and tends to be more unfavourable, than SMC's for the units GSvb (AWC of resp. 21, 19 and 21 % for the A-, B- and C-layer) and RSvb (AWC of resp.18, 16 and 19% for the A-, B- and C-layer). The degraded phase of unit GRvb is, especially in the sub-soil, characterized by low AWC's (resp. 16, 11 and 12 % for the A-, B-, and C-layer). Differences in AWC's may be due to differences in soil structure, BD-values and organic matter levels. Unit GSvs is characterized by a low AWC (resp. 14, 13 and 14 % for the A-, B- and C-layer). This may be due to the high bulk density found for this unit. The sub-soil of this unit is characterized by a high volumetric moisture content (VMC) of 25 % at pF4.2, due to a high clay percentage. There is a slight tendency of measured AWC-values to decrease with depth. This may be due to the fact that BD-values tend to increase with depth and percentages of organic matter tend to decrease with depth.

Inaccuracy and errors made during the processes of sampling, sample management and application of methods used for measuring soil physical properties may cause variation in data results, which may be defined as 'error variation'. 'Error variation' is not part of the spatial variation. A good estimate of the percentage of 'error variation' as part of the overall variation cannot be given, which makes it difficult to judge data quality. Especially the Ksat-data and SMC-data are expected to contain high 'error variation'.

According to the ANOVA analysis, unit GRvb (non-degraded phase) may be distinguished from unit GSvb on account of BD values of the A-, B- and C-layer and Ksat-values of the B-layer, but not on account of Ksat-values of the A- and C-layer. According to the Mann-Whitney test the two units may be distinguished on account of values of the VMC at pF2 and values of the AWC for the A-, B- and C-layer, but not on account of values of the percentage of clay and the VMC at pF4.2 for the A-, B- and C-layer. With both the ANOVA and Mann-Whitney tests it was proved that unit GRvb (non-degraded phase) can be distinguished from unit GSvb on account of soil physical properties. According to the Mann-Whitney test on account of soil physical properties cluster GRvb1-3 (non-degraded phase) can be distinguished from cluster GRvb7-9 (degraded phase), but not from cluster GRvb4-6 (non-degraded phase). This test proves that the degraded phase of sub-unit GRvb is characterized by other soil physical properties than the non-degraded phase.

Regression analysis was carried out to search for relations between soil physical properties. A medium to low negative linear correlation is present between the overall BD- and Ksat-data (R2=0.34). A high positive linear correlation is present between the overall data of the clay percentage and the VMC at pF4.2 (R2=0.84). For unit GRvb (non-degraded phase) a low negative linear correlation was found between these soil properties, which is remarkable. A medium negative linear correlation is present between the overall data of the sand percentage and the VMC at pF2 (R2=0.46). A low negative linear correlation is present between the overall data of the clay percentage and AWC (R2=0.09), but for unit GRvb (non-degraded phase) a negligible positive linear correlation is present between this soil properties (R2=0.02). A negligible positive linear correlation is present between the overall data of the sand percentage and the AWC (R2=0.02), but for unit GRvb (non-degraded phase) a negative linear correlation is present between these soil properties. It appears that only for soils containing a relatively high percentage of sand, like the soils of unit GRvb (non-degraded phase), a higher percentage of sand causes a lower AWC and a higher percentage of clay causes a higher AWC.

Since data quality is not optimum and the sampling strategy was not completed, not all aims of the research were reached and no effort was made for finding a 'transfer-function' between texture and the SMC. In spite of these short coming the research still yielded a lot of useful data and information. Although 'error variation' is present in the data results, most variation is also caused by the 'natural' spatial variability of soil physical properties. Spatial variability of soil physical properties often may be high within small distances. This makes research of them difficult. Supplementary geostatistical research need to be carried out for getting a better insight in the spatial variability of soil physical properties in the area.

*RESUME*

*Dans la région de Kaya (Burkina Faso), nous avons étudié les propriétés physiques du sol: la texture,la densité apparente (BD), la conductivité hydraulique saturée (Ksat), les caractéristques de la réserve en eau du sol (AWC:Réserve Utile), et le taux d'humidité volumique à quelques valeurs du pF (VMC). L'étude a pour objectifs de determiner les valeurs et la variabilité spatiale de ces propriétés physiques et d'examiner les relations entre les propriétés physiques de differents sols.*

*Dans la zone de recherche, les sols sont fortement liés à l'histoire géologique. Une carte géologique dressée par Legger et al. (1994), dont l'annexe A est une version simplificée, a servi de base à l'échantillonage. Quatre unités géologiques de sols ont été sondées: "Les vallées nues sur granite" (GRvb), les "vallées nues sur schistes vertes" (GSvb), les "vallées caillouteuses sur schistes vertes" (GSvs) et les "vallées nues sur schistes rouges" (RSvb). Une unité, GRvb, est divisée en une phase "dégradée" et une "non-dégradée". Toutes deux couvertes de façon à étudier l'influence de la dégradation sur les propriétés physiques du sol.*

*La stratégie utilisée est tirée du "nested sampling" (Webster et Oliver, 1990). Les unités, incluant les deux phases distinctes de l'unité GRvb, ont été échantillonnées par groupes de trois trous. Au sein de chaque groupe, les trous ont été placés à quelque 50m les uns des autres. Deux groupes differents d'une même unité étaient placés de quelques centaines de mètres à quelques kilomètres l'un de l'autre. Si possible, les échantillons ont été prélevés à 3 profondeurs: 5-10 cm (couche A), 30-35 cm (couche B) et 60-65 cm (couche C). A chaque profondeur, un échantillon perturbé est mis en sachet pour l'analyse de la texture en même temps que 3 échantillons non perturbés sont prélevés à l'aide d'anneaux de 5 cm de diamètre sur 5 cm de hauteur pour l'étude des autres propriétés physiques. De la sorte, les variations à l'interieur et entre les unités, les phases de dégradation, les groupes, les trous d'échantillonnage, les profondeurs du sol et les différents échantillons d'un même couche peuvent être apprèhendes séparément.*

*La pluspart des unités sont caractérisées par des sols à texture grossière: sables limoneux ou limons sableux. Ce pendent la texture de l'unité GRvb (phase non-dégradée) semble plus grossière que celle des unités GSvs et RSvb. C'est seulement dans la couche C des unités GSvs et GRvb (phase non-dégradée) que des classes de texture plus fines (limon sablo-argileux et limon argileux) ont été rencontrées. La fraction sableuse des sols de toutes les unités consistent principalement en sable fin. La texture devient généralement plus fine avec la profondeur et, dans la pluspart des échantillons, les taux d'argile les plus élévés ont été rencontrés dans la couche C (55-60 cm). Une*

*explication possible de cete observation serait un phénomène d'illuvation de l'argile en provenance des couches situées au-dessus.*

*Pour une profondeur donnée au sein d'une unité, des écart types de 0.09 g/cm3 ont été obtenus sur les mésures de densité apparente. Ce qui est un phénomène courant dans les analyses de densité apparente. Les valeurs de la BD pour unité GRvb (phase non-dégradée) (1.60, 1.59 et 1.62 g/cm3 respectivement pour couche A, B et C) semblent plus élevées que celles des unités GSvb (respectivement 1.44, 1.48 et 1.54 g/cm3) et RSvb (1.51, 1.43 et 1.45 g/cm3). On pense que les différences dans la densité des éléments constituants des sols et la structure de ceux-ci seraient à la base de ces differences de densité apparente. La phase dégradée de l'unité GRvb, dans la couche C est caractérisée par une valeur de densité apparente relativement élevé: 1.67 g/cm3. L'unité GSvs présente des densités apparentes de 1.62 g/cm3 dans couche A et B et 1.71 g/cm3 dans couche C. Ces valeurs paraissent rélativement élevées pour les textures en place. La compacité du sol ainsi que la présence de graviers seraient à la base de densités apparentes si élevées. En général les valeurs de densité apparente augmentent avec la profondeur, alors que ce n'est pas le cas de l'unité RSvb.*

*Pour une profondeur donnée au sein d'une unité des écart types pour le Ksat, de 5 cm/heure ou plus, ont été observés. De telles valeurs peuvent être dues a des erreurs de mesure. Les valeurs de Ksat dans l'unité GRvb (phase non-dégradée) qui sont respectivement de 7.15, 5.09 et 2.49 cm/heure pour couche A, B et C, semblent plus basses que celles de l'unité GSvs qui sont respectivement de 8.10, 6.42 et 4.32 cm/heure. L'unité RSvb est caractérisé par des valeurs élevées de Ksat (9.38, 11.55 et 7.00 cm/heure respectivement pour couches A, B et C). Ces différences dans les valeurs de Ksat seraient la conséquence de différences dans la structure des sols et entre les valeurs de densité apparente. La phase dégradée de l'unité GRvb, spécialement dans le micro-horizon affleurant, est caractérisée par des valeurs de Ksat plus faibles (0.40, 1.80 et 0.50 cm/heure pour couche A, B et C) que celles de la phase non-dégradée. La présence de la croûte en surface expliquerait ces valeurs très basses dans la couche A. Les sols de cette unité GRvb sont compacts tout le long du profil; ce qui expliquerait cette faible conductivité saturée pour tous les couches. Les valeurs de Ksat dans l'unité GSvs, en particutée dans la couche C (0.08 cm/heure), sont faibles en raison probablement des densités apparentes élevées. D'autres explications possibles seraient une sous-estimation des valeurs de Ksat consécutive à des perturbations des échantillons au cours du transport. En général, les valeurs de Ksat ont tendance à diminer avec la profondeur. Ceci est lié à p'acenissement des valeurs de densité apparente avec la profondeur et au faible développement de la structure dans les couches profondes.*

*Des écarts types supérieurs à 3% ont été observés entre les valeurs de réserves utiles (AWC) d'une couche donné à l'interieur d'une même unité. La réserve utile en eau de l'unité GRvb (phase non-dégradée) est faible (taux d'humidité volumique de 13, 14 et*

15 % respectivement dans couche A, B et C); elle semble encore plus défavorable que celle des unités GSvb (21, 19 et 21%) et RSvb (18, 16 et 19%). La phase dégradée de l'unité GRvb est caractérisée, spécialement dans la couches profonde, par de faibles réserves utiles: 16, 11 et 12% respectivement pour couche A, B et C. De telles différences résideraient dans les différences de structure, de densité apparente et du niveau de la matière organique. L'unité GSvs quand à elle, présente des valeurs de réserve utile de 14, 13 et 14% pour couche A, B et C; valeurs probablement liées aux densités apparentes élevées qui caractérisent cette unité. Les couches profondes de cette unité sont caractérisées par un taux d'humidité volumique élevé de 25% à pF4.2, en raison de leur haute teneur en argile. Les valeurs de la réserve utile présentent une légère tendance à la baisse lorsque la profondeur augmente. Ceci provendrait de l'accroissement de la densité apparente et de la baisse du taux de matière organique avec la profondeur.

Les imprécisions et erreurs lors de l'échantillonnage, le traitement même des échantillons et les manipulations lors des analyses physiques peuvent être à la base de variations dans les résultats. Ce type de variations peut être qualifié de "variation due aux erreurs" Celle-ci ne représente aucune part de la variation spatiale. Malheureusement il n'est pas possible de donner une bonne estimation de la part de "variation due aux erreurs" dans les variations globales. C'est la raison pour laquelle il est difficile de porter un jugement sur la qualité des résultats obtenus. En particulier, les données de Ksat et de réserve en eau sont susceptible de contenir de grandes "variations dues aux erreurs".

D'après l'analyse ANOVA, l'unité GRvb (phase non-dégradée) peut être distinguée de l'unité GSvb sur la base des valeurs de densité apparente des couches A, B et C et des valeurs de Ksat de la couche B, mais pas sur les valeurs de Ksat des couche A et C. Selon les résultats du test Mann-Whiney, les deux unités peuvent se distinguer sur la base du taux d'humidité volumique à pF2 et des réserves utiles des couches A, B et C, mais pas à partir de la teneur en argile ni du taux d'humidité à pF4.2 des mêmes couches. L'analyse ANOVA et les tests de Mann-Whitney ont démontre que l'unité GRvb, phase non-dégradée, se distingue de l'unité GSvb, sur la base des propriétés physiques du sol. Selon le test Mann-Whitney, le groupe GRvb1-3, phase non-dégradée, se distingue du groupe GRvb7-9, phase dégradée, mais pas du groupe GRvb4-6, phase non-dégradée, si on s'en tient aux propriétés physiques du sol. Ce test montre que l'unité GRvb, phase dégradée, présentent des propriétés physiques autres que la phase non-dégradée.

Une régression linéaire a été tentée pour mettre en évidence des rélations éventuelles entre différentes propriétés physiques du sol. Une correlation négative moyenne à faible existe entre la densité apparente (BD) et le Ksat pour l'ensemble des échantillons ($R2=0.34$). Une correlation hautement positive existe par contre entre la teneur en argile et le taux d'humidité volumique à pF4.2 ($R2=0.84$). Ce qui est surprenant, c'est la *correlation légèrement négative entre ces propriétés physiques dans l'unité GRvb, phase non-dégradée. Une correlation négative modérée apparait entre l'ensemble des données de teneur en sable et les taux d'humidité volumique à pF2 (R2=0.46). Une faible correlation négative existe entre le taux d'argile et la réserve utile (R2=0.09). Cependent pour l'unité GRvb, phase non-dégradée, une correlation positive négligeable existe entre ces propriétés du sol (R2=0.02). Une correlation positive négligeable existe entre l'ensemble des données de teneur en sable et la réserve utile (R2=0.02); mais pour l'unité GRvb, phase non-dégradée, une correlation linéaire négative existe entre les mêmes propriétés du sol. Il semble donc que c'est seulement comme ceux de l'unité GRvb, phase non-dégradée, qu'une teneur élevée en sable entraîne une faible réserve utile aussi élevée.*

*En raison de la qualité non optimale des données collectées et du fait que la stratégie de sondage n'était pas complète, tous les objectifs de cette étude n'ont pu être réalisés. De même aucun effort n'a été pas fait dans le sens de rechercher une relation de cause à effet entre texture et réserve en eau des sols. Malgré cela, l'étude a produit de nombreuses données et informations utiles. Même si des "variations dues aux erreurs" sont présentes dans les résultats obtenus, la pluspart des variations constalées sont aussi liées à la variabilité spatiale naturelle des propriétés physiques des sols. Cette variabilité spatiale peut être souvent élevée sur de courtes distances. C'est cela qui est souvent la cause des difficultés dans de telles études. Des travaux (géostatistiques) supplémentaires méritent d'être effectués en vue d'obtenir un meilleur aperçu de la variabilité spatiale des propriétés physiques du sol dans cette région.*

## 1 INTRODUCTION

'Antenne sahélienne' is the research institute in Burkina Faso of the Wageningen Agricultural University in cooperation with the University of Ouagadougou, Burkina Faso. The institute carries out multidisciplinary research with an interdisciplinary character.

The central problem field of the research is the degradation of the 'Sahel' region. Soil fertility is decreasing, causing yields and biomass to decrease. As a result, the vegetative cover is diminishing, in turn leading to erosion, and ultimately, to desertification. The living conditions for inhabitants of these regions will marginalize (Stroosnijder and Hoogmoed, 1993).

The central research question of the research therefore reads: under what conditions will users of natural resources be willing

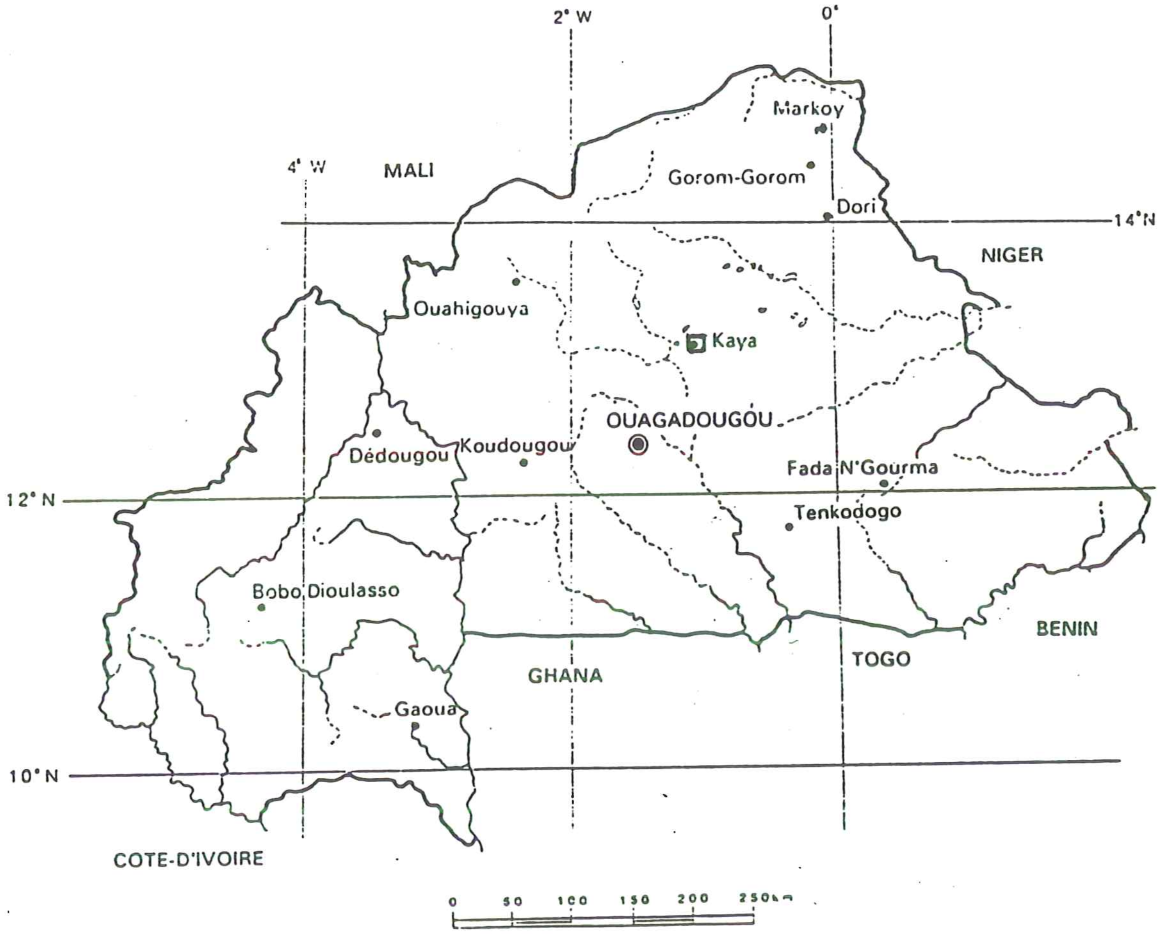


Figure 1.1: Map of Burkina Faso, indicating the most important places, lakes and rivers. The research area is indicated by means of a small square (Source: Poutsma, 1992).

*Figure 1.1: Carte du Burkina Faso, indiquant les localités, les lacs et les fleuves les plus importants. Le terrain de la recherche est marqué avec le petit cadre (Source: Poutsma, 1992).*

and be able to use and manage these resources in a sustainable way, or to rise a higher production level by introducing improvements? (Stroosnijder and Hoogmoed, 1993).

The soil characteristics are a major subject of research. They are investigated by the 'cluster physique' of the research institute. One of the research areas is an area of some 225 square kilometres around Kaya some 100 kilometres northeast of the capital Ouagadougou.

This is the report of research on soil physical properties carried out in this area from August 1993 till January 1994. Figure 1.1 is a map of Burkina Faso in which the research area

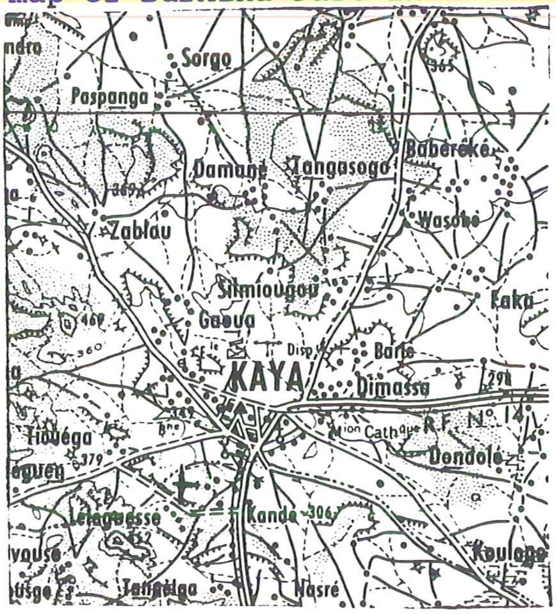


Figure 1.2: Topographical map of the research area on scale 1:200.000.(Source:I.G.N., 1960).
*Figure 1.2: Carte topografique du terrain de la recherche, à l'échelle 1:200.000 (Source: I.G.N., 1960).*

is indicated. Figure 1.2 is a map of the research area. The area was chosen as a representative area for the Mossi-Plateau. This, in comparison with other regions in Burkina Faso, relatively densely populated plateau is located in the centre of Burkina-Faso.

Results of the research in the area may be extrapolated to other parts of the Mossi-Plateau. The use of natural resources on the Mossi-plateau can roughly be divided into on one hand the use of arable land, with on the other hand the use of grasslands and forest, roughly corresponding with sylvo-pastoral areas. Sylvo-pastoral areas in the 'Sahel' are characterized by great heterogeneity. The most prominent heterogenic vegetation is caused not only by existing variation in the soil physical characteristics, but also by local patches of soil degradation, often called desertification (Stroosnijder, 1992). In terms of their use and management, the sylvo-pastoral areas are part of the territory of the sedentary farmers and marginal fields are located here as well. However, they are also part of the extensive grasslands of the nomadic farmers who have old rights to the use of these areas (Stroosnijder and Hoogmoed, 1993).

Van Dam (1993) produced a soil map of the research area based on aerial photographs and remote sensing images. At a later stage Legger et al. (1994) produced another soil map with a geological strain. For getting better insight in the process of land degradation and the possibilities of land use and for estimating the production potentials of arable crops and natural vegetation the different soils in the area need to be better characterized.

The purpose of this research was to collect values of some important soil physical properties for the different soils and possibly for the different stadia of degradation within a given soil unit. For this reason different soil physical properties were measured. The soil physical properties that were measured are: the texture, the bulk density (BD), the saturated conductivity (Ksat) and the soil moisture characteristic (SMC). The data obtained may be used as input for a quantified land evaluation model (QLE-model) as described by Driessen and Konijn (1992). However, the accuracy and reliability of the data obtained have to be checked before using them for this purpose.

Since the research area is relatively densely populated and a major town, Kaya, is present, a big part of the area is used for arable farming. Permanent fields are present and a large part of the area does not belong to the sylvo-pastoral areas. The sylvo-pastoral areas are found especially were shallow, stony or degraded soils are found. Since the gathering of soil physical data is virtually impossible in such areas, the research was focused more at the arable land than at the sylvo-pastoral areas.

For getting a realistic idea of the spatial variability in the values of the different soil physical properties it is important that the right sampling method is used. By sampling according to the sampling method chosen, it was pursued to examine the variability of the soil physical properties within soil units and between soil units. Further it was pursued by the application of statistical tests to examine, if the variability in the values of the soil physical properties justify the division into soil units.

It was further proposed to check if there are relations between the different soil physical properties. For this purpose regression analysis was applied. Data quality will determine if reliable relations between soil physical properties can be found. If the data quality is sufficient there will be searched for so called 'pedotransfer functions'. 'Pedotransfer functions' are functions which give relations between different soil physical properties. These functions are often based on multiple regression analysis. Especially the relation between texture and the soil moisture characteristic is of interest. In this way one soil physical property, for which measurements e.g. are time-consuming or expensive, may be predicted from another soil physical property which is easier to measure. In this way data gathering of e.g. input data for a QLE-model may be facilitated.

## 2.1 Climate

Climate and soil are the most important factors for agricultural productivity. This section deals with rainfall and temperature, the most important climate factors for the productivity of crops and the production of grasses and herbs at the rangelands.

A number of relatively dry years after each other will lead to a 'drought' period. Drought is a recurrent element of the climate in the countries located at the edges of the sub-tropical high pressure belt, both in the northern and the southern hemispheres. Burkina Faso is one of the countries where 'drought' is common. A 'drought' period will lead to crop failure or strong reduced yields and will have a very negative influence on livestock production (Bhalotra, 1987).

Table 2.1: Rainfall and temperature data for Kaya. (Source: ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1987).
*Tableau 2.1: Données de la précipitation et de la température à Kaya (Source: ICRISAT (International Crop Research Institute for the Semi-Arid Tropics), 1987).*

| Month | Pmean (mm) | C.V. (%) | Pmax. (mm) | Pmin. (mm) | Tmax. (°C) | Tmin. (°C) |
|---|---|---|---|---|---|---|
| Jan. | 0.0 | 0.0 | 0.0 | 0.0 | 31.8 | 16.9 |
| Feb. | 0.5 | 351.5 | 9.5 | 0.0 | 35.1 | 19.6 |
| Mar. | 3.1 | 353.3 | 83.8 | 0.0 | 37.8 | 22.9 |
| Apr. | 9.4 | 158.7 | 91.0 | 0.0 | 39.1 | 25.4 |
| May | 45.6 | 71.6 | 128.1 | 0.0 | 38.1 | 24.9 |
| Jun. | 97.2 | 46.1 | 252.0 | 15.1 | 35.3 | 22.8 |
| Jul. | 160.5 | 32.9 | 373.4 | 50.2 | 32.3 | 22.0 |
| Aug. | 227.6 | 36.3 | 583.2 | 96.0 | 31.0 | 21.4 |
| Sep. | 122.3 | 43.1 | 256.6 | 9.4 | 32.2 | 21.9 |
| Oct. | 25.4 | 117.5 | 154.2 | 0.0 | 36.2 | 23.2 |
| Nov. | 2.0 | 272.8 | 30.4 | 0.0 | 35.1 | 20.3 |
| Dec. | 0.2 | 782.3 | 11.8 | 0.0 | 32.4 | 17.5 |
| Year | 693.9 | 18.4 | 1007.7 | 458.2 | - | - |

Pmean: Mean amount of precipitation (1920-84) (mm)
C.V. : Coefficient of variation in precipitation (1920-84) (%)
Pmax.: Maximum amount of precipitation (1920-84) (mm)
Pmin.: Minimum amount of precipitation (1920-84) (mm)
Tmax.: Mean maximum temperature (°C)
Tmin.: Mean minimum temperature (°C)

Table 2.1 gives the mean monthly and annual rainfall calculated over the period 1920-1984 for Kaya. The table also shows the maximum and minimum monthly and annual rainfall during the period 1920-1984 for Kaya. Most rainfall occurs in the period from May till October, with a highest mean monthly rainfall in August. The mean annual rainfall amounts 693.9 mm. The rainfall has an annual coefficient of variance of 18.4 % with a highest annual amount measured of 1007.7 mm and a lowest annual amount measured of 458.2 mm. Even with an amount of 458.2 mm rainfall still a reasonable harvest yield for crops adapted to the semi-arid tropics such as sorghum and pearl millet, can be reached. For good harvests it is important that the total amount of rainfall is evenly spread over the growing season so that long dry periods do not occur within the growing season and crop failure is avoided, and that all rainfall infiltrates so that losses due to runoff do not occur.

In table 2.1 the mean monthly maximum and minimum temperatures are given for Kaya. Highest maximum temperatures are reached in April and lowest in January and in August which in the average is the most cloudy month. Lowest minimum temperatures are reached in January and highest in May. Since the area is characterized by relatively high temperatures and high amounts of sunshine, high crop yields and a good rangeland production can be reached, if water availability poses no limit for growth. However, the mean monthly rainfall exceeds the mean potential evapotranspiration (PET) only during 2 or 3 months of the year. In other months crop, grass and herb growth will be reduced because of waterstress (ICRISAT, 1987).

## 2.2 Geology and geomorphology

Legger et. al. (1994) distinguish five geological-soil units which are indicated in table 2.2. For each of these units a code is given with which they further in this report will be indicated. These codes differ from those used by Legger et. al. (1994) and indicate more clearly the units which they represent. Annex A is a map of the research area on which 4 units are indicated. The extent of one geological unit was too small on this map and is included in one of the others. Since a strong relation between geology and soils is assumed, the units are marked as 'geological-soil' units.

The areas with a bedrock of granite and granodiorite are defined as 'granitic area'(GR). Annex A indicates that this unit is found in the northern, eastern and southeastern parts of the research area. At some places granitic or granodioritic outcrops can be found. The area is rather flat, but at some places hills formed by 'cuirasses' can be found. Cuirasses are iron crusts formed by plinthite. They were developed, during wet periods, where dissolved Fe3+ precipitated as Fe2+. When plinthite is irreversibly hardened, the material develops into a petroferric or skeletic phase (FAO, 1988). Since these cuirasses are relatively resistant to erosion they form at many places 'cuirasse-hills'.

Table 2.2: The 5 geological-soil units present in the research area and their codes as used for them in this report (Source: Legger et. al., 1994).
*Tableau 2.2: Les 5 unités géologiques du sol, présent dans la région de la recherche, et leurs codes ainsi que usagés dans ce rapport (Source: Legger et al., 1994).*

| geological soil-unit | code |
|---|---|
| 1 granitic area | GR |
| 2 greenschist area | GS |
| 3 redschist area | RS |
| 4 manganese area | MA |
| 5 alluvium/valley bottoms | AL |

The areas with a bedrock of 'greenschists' are defined as 'greenschist area' (GS). Annex A indicates that this unit is found in areas southwest, west, northwest and north of Kaya. The area is characterized by a relief of rolling hills of different heights.

The areas with a bedrock of 'redschists' are defined as 'redschist area' (RS). Annex A indicates that this unit is found around Kaya, in areas west of Kaya and in the outermost southwest of the research area. Relief exists mainly of cuirasses which cover the 'redschists' at most places. At many places along the eroded slopes of the cuirasses outcrops of 'redschists' are found.

The narrow belts of basic rock containing manganese are defined as 'manganese area' (MA). In annex A, by generalization, this unit is included in the unit of the 'redschist area' (RS), where most of these belts occur, although they occur also in the 'greenschist area' (GS).

The alluvium, corresponding to the valley bottoms, is defined as 'alluvium\valley bottoms' (AL). Annex A indicates that this unit is found as narrow strips in the research area. The unit consists of the river beds with adjacent levees influenced by the rivers, often containing layers of gravel. Since rivers are rather small, the unit forms only a small part of the research area.

## 2.3 Soils

According to the soil map of Africa published by FAO-UNESCO (1977), the soils in the research area belong to the major soil grouping Luvisols. Luvisols are soils having an argic B-horizon, a subsurface horizon which has a distinctly higher clay content than the overlying horizon and which is characterized by relatively high values of both the cation exchange capacity (CEC) and the base saturation (BS). This FAO-UNESCO map was made by very global soil mapping by which a high degree of generalization was applied. The physiography of the research area however is very heterogeneous and next to Luvisols other major soil groupings according to the FAO (1974 and 1978) legend occur. This statement is confirmed, since results of texture analyses (see section 5.2) reveal that many soils in the area cannot be classified as Luvisols.

During field surveys different soil types were recognized. A description will be given of major soil groupings which, according to the FAO (1974 and 1988) legend, occur within the different geological-soil units (see annex A):

In the 'granitic area' (GR) mainly Cambisols, Luvisols, Leptosols and rarely Arenosols are found. Cambisols are moderately developed soils characterized by absence of appreciable quantities of illuviated clay, organic matter, aluminium and/or iron compounds (FAO, 1988). Luvisols are soils having an argic B-horizon which has a CEC equal to or more than 24 cmol(+)/kg clay and a BS of 50 % or more throughout the B-horizon (FAO, 1988). In this area Cambisols and Luvisols have sandy loam textures. However this texture sometimes is interrupted by horizons of loamy sand. Leptosols are soils limited in depth by continuous hard rock or cemented layers within 30 cm of the surface (FAO, 1988). In the research area these cemented layers consist of shallow iron crusts (cuirasses), especially at places where cuirasse-hills are present. Arenosols are soils with a texture coarser than sandy loam to a depth of at least 100 cm (FAO, 1988). Since the parent material is relatively poor in the area all soils contain low amounts of nutrients.

In the 'greenschist area' (GS) along the higher relatively steep slopes of the 'greenschist-hills' Leptosols are found. At the lower slopes next to Leptosols also Regosols, Luvisols and Cambisols all with a sandy loam to clay loam texture are found. Regosols are soils from unconsolidated finely textured (finer than loamy sand) weathering material, having no diagnostic horizons other than an ochric or umbric A-horizon, which are top soil layers containing respectively low and high amounts of organic carbon (FAO, 1988). In the almost flat areas of the valleys and valley bottoms, adjacent to the 'greenschist-hills' only Luvisols and Cambisols with a sandy loam to loamy texture are found. In these areas 'greenschists' form also the parent material for the soils present. Since the parent material in the 'greenschist area' (GS) is richer than in the 'granitic area' (GR), the soils here are richer in nutrients.

In the 'redschist area' (RS) along the slopes of the cuirasses mainly Leptosols and Regosols are found. In the narrow valleys Luvisols, Cambisols and rarely Arenosols are found. The Luvisols and Cambisols mainly have sandy loam textures. They are, because of the relatively rich parent material like in the area with 'greenschists', richer in nutrients than the soils in the 'granitic area'.

In the 'manganese area' (MA) mainly Leptosols are found.

In the 'alluvium/valley bottoms' (AL) mostly Fluvisols are present, often containing layers of gravel. Fluvisols are soils showing fluvic properties. Fluvic properties refer to fluviatile, marine and lacustrine sediments which receive fresh materials at regular intervals causing stratification (FAO, 1988).

## 2.4 Vegetation and land use

Land use in the research area can roughly be divided into 2 major types. Part of the land is used as permanent field for crop production. A permanent field is used each year for crop production. The other part of the land is used for wood gathering and as rangeland for grazing. The last major type of land use occurs within the areas marked as sylvo-pastoral areas (see Chapter 1).

In the lower flat or almost flat parts of the research area, the valleys and valley bottoms (bas-fonds) and at lower slopes arable farming is found on permanent fields. Because of the relatively high population density almost all land suitable for arable farming is used as permanent field.

In the research area the sylvo-pastoral areas, are often degraded, i.e. areas with shallow iron crusts, e.g. the cuirasse-hills, and the steep slopes of the 'greenschists-hills'. An open savanna is found here at most places. This area is characterized by pastureland with scattered trees and shrubs. The natural vegetation was characterized by a higher density of trees, but because of the population density a lot of trees have disappeared.

The overgrazing of the land associated with the high population density is one of the causes that many degraded spots of land are found. Undulating areas with shallow loamy soils at the top of laterite crusts are very sensitive for degradation. This explains the high amount of degraded spots on top of and along the slopes of the cuirasse-hills.

# 3 SAMPLING STRATEGY

## 3.1 Introduction

This chapter contains a discussion on soil maps which may serve as basis for sampling and on soil units which have to be sampled. In addition the method of sampling and the sampling within the different geological-soil units is discussed.

## 3.2 The soil map used as basis for sampling

During the first period of the research a soil map on scale 1:30.000 produced by Van Dam (1993) served as a basis for sampling. This soil map was based on analysis of aerial photographs and satellite images. By means of augerings Van Dam (1993) investigated soil depth and soil texture at many locations.

During the process of sampling for the determination of soil physical properties it appeared that the map of Van Dam (1993) was rather inaccurate. At many locations soil depth and texture differed from those given by the soil map of Van Dam (1993). Because of the lack of a detailed topographical map of the area, exact place determination in the field was rather difficult if not impossible. During this research and the research of Van Dam (1993) only a topographical map on scale 1:200.000 of the area was available. For this reason orientation in the field took place using aerial photographs on scale 1:30.000 of the area. The soil map of Van Dam (1993) is possibly too detailed given the limitation in place determination. The map contains small patches of sub-units which were distinguished by differences in sub-surface characteristics, like soil depth and texture, only. During the sampling for the research of soil physical properties, it was impossible to find the exact locations of these patches in the field.

The conclusion was that it was better to sample a few relatively homogeneous physiographic-soil units. These units were distinguished according to field observations carried out in the first period of the research. These units still partly rely on the research of aerial photographs carried out by Van Dam (1993).

Not long after the decision of leaving the soil map of Van Dam (1993) as basis for soil sampling, a group researchers began field work to produce a new soil map of the area (Legger et al., 1994). They produced a soil map on a scale of approximately 1:22.200, although in their report they published a reproduction of this map on a smaller scale. For this soil map the geology served as the most important input for distinguishing the different map units, which was not the case with the soil map of Van Dam (1993). Since parent material is one of the most important soil forming factors in the research area, distinguishing soil units based on geology was seen as the most favourable option. Fortunately most sample points selected before using the soil map of Legger et al. (1994) as the definitive basis of sampling, still could be used for the new sampling strategy.

Legger et al. (1994) distinguish five major geological-soil units (see table 2.2) in the area, which are described in section 2.2 of this report. Based on the geomorphology and the presence or absence of surface gravel and stones, within these units geological-soil sub-units were distinguished. So within the geological-soil unit e.g. 'greenschist area' (GS) the sub-units 'greenschists valley bare', 'greenschists valley stones' and 'greenschists hill' can be distinguished. Annex A is a schematic representation of the map of Legger et al. (1994), indicating only the major geological-soil units. For information about locations of the different sub-units the map of Legger et al. (1994) should be consulted.

## 3.3 Method of sampling

Most sampling took place in the 'granitic area' (GR) and 'greenschist area' (GS) and some in the 'redschist area' (RS). No sampling took place in the 'manganese area' (MA) and in the 'alluvium/valley bottoms' (AL). These areas form an unimportant part of the research area. The shallow soils in the 'manganese area' (MA) containing high amounts of gravel and stones which makes sampling impossible. The irregular character of the soils in the 'alluvium/valley bottoms' (AL), containing high amounts of gravel, makes sampling impossible here as well. Due to limited time it was impossible to sample fully three major geological units. In table 2.3 the different geological-soil sub-units which were sampled are indicated. This table also gives the codes with which these sub-units further in this report will be indicated.

Table 3.1: The geological-soil sub-units, according to Legger et al. (1994), sampled and the codes used for them in this report.
*Tableau 3.1: Les sub-unités géologiques du sol selon Legger et al. (1994), échantillonées et leurs codes ainsi que usagés dans ce rapport.*

| geological-soil sub-unit | code |
|---|---|
| granitic area , valley bare | GRvb |
| greenschist area, valley bare | GSvb |
| greenschist area, valley stone | GSvs |
| redschist area , valley bare | RSvb |

Most sampling took place on permanent fields. Outside the permanent fields sampling was often difficult or impossible because of the presence of shallow bedrock, shallow ironcrusts or high concentrations of gravel. Random sampling was often applied, using sample locations representative for the geological-soil unit sampled. For reasons of distance and accessibility most sampling however took place in the central eastern and southern part of the research area, as is indicated on the geological-soil map (annex A).

A strategy related to nested sampling was used (Webster and Oliver, 1990). Because of lack of time and the late availability of the soil map of Legger et al. (1994) this strategy, especially in the 'redschist area' (RS), could not fully be applied. However this does not imply that the samples taken cannot give good information about soil physical properties of the different geological-soil sub-units.

Sampling took place using sample pits. The soil sub-units were sampled by clusters of 3 sample pits (with a few exceptions). Within a cluster pits were located some 50 metres from each other forming a triangle. Within the sub-units the different clusters were located some hundred metres to some kilometres from each other. The sample clusters are indicated on the geological-soil map (Annex A). On this map the sub-units, according to Legger et al. (1994), in which they are located are indicated by the cluster-codes.

No complete profile descriptions were carried out. However site characteristics for the clusters and also site characteristics and some soil profile characteristics of the individual sample pits were described, which can be found in annex B.

Where possible in each pit samples were taken at 3 different depths:5-10 cm (layer A), 30-35 cm (layer B) and 55-60 cm (layer C). At some places this was impossible because of the presence of high amounts of gravel, shallow bedrock or an ironcrust. At each depth one bag sample was taken for texture analysis. For measuring the BD, Ksat and soil moisture characteristic 3 small ring samples with a height and diameter of both 5 cm were taken. These rings were hammered carefully into the soil and once filled they carefully were cut out of it. To avoid cracks within the samples dry soils sometimes were wetted before hammering the rings into it.

Using the above described sampling method variation in analysis results at different scales can be studied. Five different types of variation can be distinguished:

1. Variation between soil sub-units.
2. Variation between clusters within the same soil sub-unit.
3. Variation between sample pits within the same cluster.
4. Variation between the different sample depths (horizons) of a certain sample pit
5. Variation between samples taken at the same depth (the same horizon) of a certain sample pit

For sub-unit GRvb also a sixth type of variation can be distinguished, namely the variation between a degraded and non-degraded phase found within the sub-unit (see section 3.4).

Place determination took place for each cluster using a global positioning system (GPS). Place determination is important, because in this way the sample locations are known if the research results will be used for future research in the area. However the coordinates obtained by the GPS are not very reliable, since high deviations between coordinates for known fixed points on the map and those for the same points determined by the GPS, were found. For this reason it happened that clusters according to their GPS-coordinates fell in the wrong unit on the geological soil-map. In some cases therefore clusters are not always indicated in annex A at the place determined by the GPS-coordinates, but at their most likely place according to the units and topography as given on the map.

## 3.4 Sampling in the granitic area

The geological-soil sub-unit 'granitic area, valley bare' (GRvb) was sampled by 3 clusters of each 3 sample pits and one pair of 2 sample pits.

The place of 2 clusters with 3 sample pits (GRvb1-3 and GRvb4-6) was randomly determined within the sub-unit, however places with shallow ironstone and outcrops of granite, as well as profiles which contain high amounts of gravel were neglected. Care was taken that both clusters were not located too close to each other.

Cluster GRvb7-9 was located on a field were the soil looked rather degraded and no crops were grown any more. It was expected that some information about the influence of soil degradation on soil physical properties could be achieved.

The pair of sample pits (GRvb10-11) was located at the lower slope of a cuirasse-hill in an area with a relatively shallow ironcrust. Since the slope was not steep at this place, this location still belongs to the sub-unit GRvb. The location and top-soil roughly corresponded with those of the clusters GRvb1-3 and GRvb4-6, although the concentration of gravel was higher here. The place of the cluster (GRvb10-11) was randomly determined within the sub-unit, neglecting places with outcrops of granite. This cluster was sampled during the first period of the research. At that moment the strategy of sampling by means of clusters of 3 sample pits was not yet developed and the soil map of Legger et al. (1994) was not available. It was decided not to take more samples in areas with a shallow ironcrust, including also the cuirasses, within the soil sub-unit. The high concentrations of mainly iron stone concretions, but also other gravel, made sampling here difficult and unattractive. However for completeness the analysis results are given in this report.

Discussion of analysis results requires separation of the sub-unit in a non-degraded phase represented by the clusters GRvb1-3, GRvb4-6 and GRvb10-11 and a degraded phase represented by the cluster GRvb7-9.

In annex B the coordinates and site characteristics of the clusters are given. Detailed information is given also for each sample pit.

## 3.5 Sampling in the greenschist area

The geological-soil sub-unit 'greenschist area, valley bare' (SVb) was sampled by 3 clusters of each 3 sample pits. The 3 clusters were stepwise located from the foot of the high greenschist-hills in the southwest of the research area to near the centre of the adjacent valley. Cluster GSvb1-3 was located near the foot of the greenschist hills at the edge of the valley. Cluster GSvb7-9 was located near the centre of the adjacent valley. Cluster GSvb4-6 was located inbetween the other two clusters. Depending on slope percentage, the locations of the clusters were chosen. Slope percentage was about 5 % at the location of cluster GSvb1-3, about 3% at the location of cluster GSvb4-6 and about 1-2 % at the location of cluster GSvb7-9 The clusters were located along this relatively gentle valley slope to study the variation along it and to find out if a 'catena' could be discovered.

In annex B the coordinates and site characteristics of the clusters Gsvb1-3, GSvb4-6 and GSvb7-9 are given. Detailed information is given also for each sample pit.

The geological-soil sub-unit 'greenschist area, valley stone' (GSvs) was randomly sampled by 1 cluster (GSvs1-3) of 3 sample pits and another single sample pit (GSvs4). Cluster GSvs1-3 was located at the gentle lower slope of a small greenschist hill. At not too steep places around these small greenschist hills soils deeper than 30 cm with a more clayey texture are found at many places.

The single sample pit (GSvs4), also located on the lower slope of a small greenschist hill, was sampled during the first period of the research. For completeness results are given in this report.

In annex B the coordinates and site characteristics of cluster GSvs1-3 and sample pit GSvs4 are given. Detailed information is given also for each sample pit of cluster GSvs1-3.

It must be stressed that the relatively clayey soils at the locations sampled are not present everywhere in the sub-unit. However, along the small greenschist hills they are expected to be dominant. 'Valley stone' indicates only a surface characteristic, which not always have to be related to sub-soil characteristics.

On the large greenschist-hills and at the top of the small greenschist-hills very shallow stony soils are present which made sampling here impossible.

## 3.6 Sampling in the redschist area

The geological-soil sub-unit 'redschist area, valley bare' (RSvb) was randomly sampled by 1 cluster (RSvb1-3) of 3 sample pits. This cluster was sampled at the moment that the soil map of Legger et al. (1994) was not yet available. No more samples in this sub-unit were taken.

In annex B the coordinates and site characteristics of cluster RSvb1-3 are given. Detailed information is given also for each sample pit.

Sampling in the other sub-units of the redschist area was impossible because of the presence of shallow soils or soils with high concentrations of gravel and stones in their profiles.

# 4 METHODS FOR MEASURING THE SOIL PHYSICAL PROPERTIES

## 4.1 Introduction

In this chapter a short description of the methods used for measuring the different soil physical properties is given. There will be successively dealt with respectively the different methods used for determination of the texture, bulk density, saturated hydraulic conductivity and the soil moisture characteristic.

## 4.2 Method used for measurement of texture

For measurement of texture in all sample pits at each sampling depth one bag sample was taken. Texture was measured one time for each depth.

With texture is meant texture of the 'fine earth', which are all particles < 2 mm. The 'fine earth' was separated from gravel and stones using the a common sieving machine. The Coarsest fraction of the 'fine earth' (1-2 mm) was determined by the same machine. The other fractions were determined by using the sieving machine and/or using the hydrometer method.

This hydrometer method is an analysis method which makes use of the different timespans of settling for each different soil particle-size. The density of a soil in suspension decreases during sedimentation of soil particles. With this method it is possible to carry out rough texture analyses. It is a quick and convenient method, and very suitable for measuring the texture of large numbers of soil-samples.

The sample material was prepared before sieving it. Stove dry sample material was pulverized in a mortar to avoid the presence of large aggregates. Sample material containing particles < 1 mm was used for the hydrometer method. It was prepared by adding 100 ml of a dispersing agent, made of a solution of 50 g sodiumpyrophosphate ($Na_4P_2O_7$) and 8 g sodiumcarbonate ($Na_2CO_3$) in 1 litre water, to 50 g of stove dry sample material.

The following formula was used for calculation of the various fractions (RHLS-Deventer, 1986):

$$\text{Fraction (\%)} = (D - ft - B) * 100/V$$

with: D = the measured density of the suspension (g/l)
ft= temperature correction (g/l)
B = the density of the control solution (g/l)
V = weighted amount of stove-dry soil matter (g)

Table 4.1 is the table used for the temperature correction (ft). The ft-values in this table are rounded off by 0.5, which is permitted for this rough method of texture analysis. Table 4.2 gives the hydrometer values of the control solution (B) by different temperatures, which were determined in the laboratory during the research. The control solution is the solution of 100 ml dispersing agent filled up with water to 1 litre, without soil material. If the temperature rises the B-value decreases. This effect is corrected by an increase of the ft-value if temperature rises.

Table 4.1: Values for the temperature correction (ft) by different temperatures (T) (Source: RHLS-Deventer, 1986).
*Tableau 4.1: Les valeurs de la correction de la température (ft) pour des températures differentes (T) (Source: RHLS-Deventer, 1986).*

| T (°C) | ft (g/l) |
|---|---|
| 25 | 2.0 |
| 26 | 2.0 |
| 27 | 2.5 |
| 28 | 2.5 |
| 29 | 3.0 |

Table 4.2: Values measured with the hydrometer for the control solution (B) by different temperatures.
*Tableau 4.2: Les valeurs qui sont mesurées avec l'hydromètre pour la solution contrôlée (B) à des températures differentes.*

| T (°C) | B (g/l) |
|---|---|
| 25 | 6.8 |
| 26 | 6.4 |
| 27 | 5.9 |
| 28 | 5.5 |
| 29 | 5.1 |
| 30 | 4.6 |
| 31 | 4.2 |
| 32 | 3.8 |

## 4.3 Method used measurement of the bulk density

The bulk densities were measured using undisturbed small ring samples with a height and diameter of both 5 cm. The bulk density was measured three times for each depth. The ring samples were dried in a stove at a temperature of 105 °C for 24 hours. The bulk densities were calculated by dividing the dry sample weight by the volume of the sample ring, i.e. 98,17 cm3.

## 4.4 Method used for measurement of the saturated hydraulic conductivity

The saturated hydraulic conductivity (Ksat) was measured using undisturbed small ring samples with a height and diameter of both 5 cm. Ksat was measured two times for each depth.

The samples were saturated with water, putting them for 24 hours in a tray filled with water so that only the top 0.5 cm of the sample stayed above the water table. After that a constant watertable (constant head) was placed on each saturated sample using a bottle of Mariotte. After some time the flow of water passing through a sample became constant (Q). The constant heads were known and Ksat-values were calculated.

Ksat can be calculated using the following formula:

$$Ksat = Q/iA \text{ where } i = b/a$$

With: Ksat = saturated hydraulic conductivity (cm/min)
Q = constant throughflow (cm3/min)
A = surface area sample ring (cm2)
a = length sample (cm)
b = length sample plus constant head (cm)

## 4.5 Method used for measurement of the soil moisture characteristic

The soil moisture characteristic (SMC) was measured using undisturbed small ring samples with a height and diameter of both 5 cm and using bag samples. The SMC was measured one time for each depth.

The soil moisture characteristic is determined by measuring the moisture content by different suction heads. The suction head can be expressed by the pF-value, which is the 10log of the value of the suction head in centimetres water. The pF-curve gives the relationship between volumetric moisture content and pF-values. A 'pressure cooker' was used to determine the soil moisture characteristic of soil samples. In this pressure cooker samples are placed under different air pressures on ceramic plates. Water from the samples can drain through the ceramic plates until equilibrium with the 'over'-pressure is reached.

The soil moisture characteristic was measured in one direction, i.e. determined by drying up the samples and therefore the pF-curve also may be indicated as desorption-curve. The volumetric moisture content at pF0 initially was determined by weighing saturated samples. This method is inaccurate since the weight of a saturated sample is rapidly decreases after taking it out of the water. So, moisture content at pF0 was calculated, dividing the BD-value by the particle density. For all calculations an average value for the particle density of 2.60 g/cm3 was used.

However if the samples contain high amounts of iron, which seemed sometimes the case, this value may be to low and inaccurate values may have been calculated.

The volumetric moisture content at pF1.7, pF2, pF2.3, pF2.7, pF3 and pF3.5 were determined using ring samples. The volumetric moisture content at pF 4.2 was determined using small amounts of disturbed sample matter taken from the bag samples. Since soil structure does not have influence on the amount of water bound with high suction heads, this method is justified. For each soil layer the volumetric moisture content at pF4.2 was determined twice and values obtained were averaged. The volumetric moisture content at pF7 is taken zero by definition.

# 5 IMPORTANCE OF THE SOIL PHYSICAL PROPERTIES

## 5.1 Introduction

This chapter contains a discussion on the importance of the soil physical properties studied. Although most information given may be known by soil scientists, it was decided to deal with it to serve the interdiciplinar context of the research. It may contribute, especially for researchers of other disciplines, to a better understanding of the research and its importance. Some of the information stresses subjects especially important for soil research in the Kaya area.

## 5.2 Importance of texture

Texture can be seen as the most fundamental soil physical property. The character of most if not all other soil physical properties mainly depends on the soil texture. However, the contribution of soil texture to soil characteristics, such as soil structure and porosity, amount and type of organic matter and the type of clay minerals present, is difficult to establish exactly. The rate and extent of many physical and chemical reactions in soils are governed by texture, because it determines the amount of surface area on which the reactions occur. Texture therefore can be helpful in estimating other soil physical and soil chemical properties, which are related to it. For example the cation exchange capacity (CEC) of the soil, the transport of air, water and heat in the soil, the erodibility of the soil, the

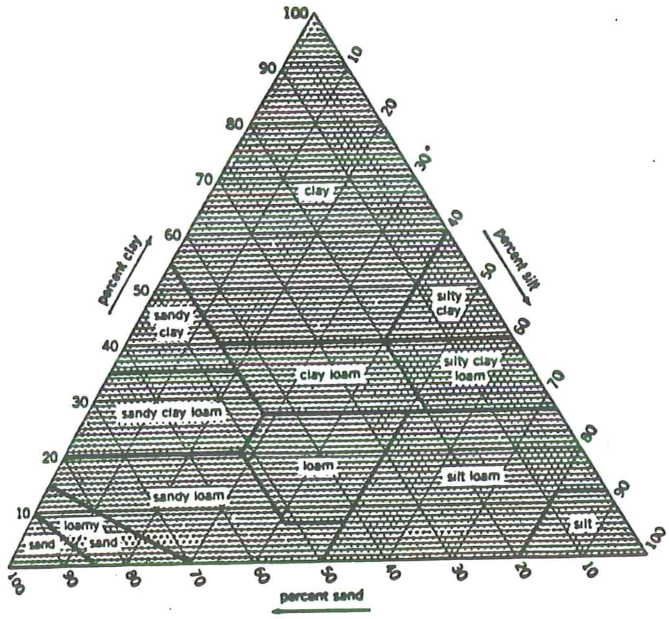


Figure 5.1: The USDA texture triangle (Source: Soil Survey Staff, 1951).
*Figure 5.1: Le triangle de la texture d'USDA (Source: Soil Survey Staff, 1951).*

workability of the soil, the water holding capacity of the soil and capillary rise in the soil are all texture related soil properties (Pape and Legger, 1991).

The accuracy with which texture is determined often depends on the purpose of the analysis. Texture analysis as carried out for this research did not give very detailed results; only major texture fractions, sand ,silt and clay (lutum), were distinguished. The proportions of sand, silt and clay determine the texture class of the texture triangle according to the Soil Survey Staff (1951). Figure 5.1 is a representation of this texture triangle in which 12 texture classes are distinguished. Along the three sides of the texture triangle respectively the clay-, silt- and sand-fraction are represented. Samples are allocated to one of the texture classes depending on the weight percentages of sand, silt and clay present within a sample.

The best texture is usually the one with about equal proportions of sand, silt and clay. If one of the fractions dominates too much certain problems may arise. If sand dominates, as in most soils in the research area, this will have the negative following effects: low water availability, low CEC (poor nutrient retaining capacity), risk of wind erosion, risk of poor root penetration due to mechanical compaction, too fast drainage and fast but low capillary rise. The more loam soils contain the more they are liable to surface crusting and water erosion. The LS- but more so the SL-textured top-soils in the area are therefore liable to surface crusting and water erosion.

## 5.3 Importance of the bulk density

Bulk Density (BD) measurement is often made during soil surveys as a guide to soil compaction and porosity. BD-measurements can be of importance for indicating problems of root penetration and soil aeration. BD-values tend to rise if texture is getting coarser. BD-values above values varying between 1.60-1.75 g/cm3 are quoted as causing hindrance to root penetration (Landon, 1984).

Increases in bulk density impose the following stresses on a plant's root system. The mechanical resistance to root penetration increases, so reducing the plant's ability to exploit its environment. The air-filled porosity of the soil decreases, restricting the air supply to plant roots and facilitating the build-up of toxic products. The proportion of porosity occupied by water at any given suction increases, which may have a negative influence, especially for fine-textured soils, on the amount of water available for plants, the available water capacity (AWC) (see section 5.5). Because in general permeability decreases with increasing bulk densities, field crops are more susceptible to the adverse effects of waterlogging.

However, BD-values have to be interpreted with care, since high BD-values also may be caused by a high particle density. Especially in tropical soils containing high amounts of iron having high particle densities, high BD-values occur although the pore volume is not too low. In this case no hindrance to root penetration, low AWC-values and drainage problems occur in spite of high BD-values. For this reason it would be better if BD-values are only related to pore volume related characteristics if the particle density is known.

## 5.4 Importance of the saturated hydraulic conductivity

The saturated hydraulic conductivity (Ksat) of the soil is of importance for the soil-water balance. It gives insight into the characteristic of water movement in the soil and into possible drainage problems. Ksat-values are strongly related to textural and structural characteristics of the soil. Obtaining genuinely undisturbed cores for laboratory tests is extremely difficult. If exact Ksat-values are needed laboratory results are of no value. However, such Ksat-results may give a rough idea about field Ksat-values of the soils studied.

## 5.5 Importance of the soil moisture characteristic

The soil moisture characteristic (SMC) is of importance for the soil-water balance. The SMC gives an good insight into soil-water relations in the unsaturated zone of the soil. Water in an unsaturated soil is held as thin films on soil particle or pore surfaces. The forces retaining soil-water against the pull of gravity are essentially short-distance electrical forces which vary as the reciprocal of some power of the distance from the attracting surface. For this reason water is retained to the soil particles with different forces. The more water a soil contains the more water retained with low forces is present. The SMC is especially important, because it gives information about the amount of available water for plants by means of the available water capacity (AWC).

The AWC, which easily can be determined out of a pF-curve, is defined as the volume of water which is held in the soil between pF2, 'field capacity' and pF4.2, the 'permanent wilting point'. 'Field capacity' is the lowest force (around pF2), at which part of the soil-water is retained in the soil after free drainage of a saturated soil. Water held with lower forces is drained too quickly to be of importance for plants. 'Permanent wilting point' is the highest force (around pF4.2) at which water is retained in soil which is still available for plants. Soil moisture present in the soil at higher pF-values, is retained by such high forces that plant roots are not able to absorb it. However, it must be stressed that the pF-value of the 'permanent wilting point' differs per plant and pF4.2 is just an average value. especially natural vegetation in relatively arid environments, like the research area, is able to absorb water retained with higher forces. This characteristic for example is known for Acacia species. For millet it is known that the 'permanent wilting point is a higher pF-value than that for Maize. Millet for this reason is a more 'drought resistant' crop than Maize.

It must be remarked that not all water held between 'field capacity' and 'permanent wilting point' can be considered as equally available for plants. Water retained with forces between pF2 and pF3.2 is easily available for plants. However, water retained with forces between pF3.2 and pF4.2 is less easily available for plants.

The AWC is strongly related to texture. A large AWC is often found in medium-textured soils. If texture is very fine most soil-water will be retained with suction values above pF4.2 and the AWC will be low. If texture is very coarse most soil-water is retained with suction values lower than pF2, and the AWC will also be low. Other soil characteristics like soil structure, bulk density, organic matter content and the presence or absence of gravel and stones also determine the AWC.

# 6 RESULTS OF MEASUREMENT OF THE SOIL PHYSICAL PROPERTIES

## 6.1 Introduction

This chapter gives the results of the different soil physical analyses which will be discussed and elucidated. Successively there will be dealt with texture, bulk density (BD), saturated hydraulic conductivity (Ksat) and the soil moisture characteristic (SMC).

## 6.2 Results of measurement of texture

In the tables C1.1 to C1.10 of annex C1 the results of the measurement of texture for the different clusters are given. These tables contain rough data of the weight percentages of the 5 texture fractions and the texture class according to the Soil Survey Staff (1951) for each soil layer. The data in the tables C1.1 to C1.10 of annex C1 were analyzed statistically by calculation of means of the percentages of clay, silt and sand and standard deviations from these values. The means and standard deviations were calculated for each sub-unit per soil depth. The results of these calculations are given in table 6.1, which gives also the number of samples used. For the sub-unit GRvb means and standard deviations were calculated separately for the non-degraded phase (represented by GRvb1-6,10,11) and the degraded phase (represented by GRvb7-9). Remarkable is that high standard deviations were calculated which implies that variation in texture for a certain soil depth within a sub-unit is high.

The non-degraded phase of sub-unit GRvb (GRvb1-6,10,11) is characterized by coarse- and moderately coarse textured soils having loamy sand (LS) and sandy loam (SL) textures, which occur rather random. As exception for soil layer GRvb3C a moderately fine texture of sandy clay loam (SCL) was measured.
Table 6.1 shows that at all soil depths the soil contains more than 70 % sand. During field survey and by manual estimating the texture, it appeared that almost all sand could be quoted as fine sand. Table 6.1 shows that the percentage of clay increases with depth. Clay percentages of 6.5 % in the A-layer, 9.1 % in the B-layer and 12.2 % in the C-layer were measured. For the B- and C-layer relatively high standard deviations of over 5 % were measured.

The degraded phase (GRvb7-9) is characterized by textures of LS in the top-soil and SCL in the sub-soil. The soil of this degraded phase, which is strongly cemented, is characterized by a sub-soil illuviated with clay. Table 6.1 indicates that the soil contains 21.8 % clay in the C-layer, but only 5.1 % in the A-layer.

Sub-unit GSvb is characterized by coarse- and moderately coarse textured soils having loamy sand (LS) and sandy loam (SL) textures. A SL-texture however is dominant within this sub-unit For cluster GSvb1-3 only SL-textures were measured, which may be caused by the fact that the cluster is located close to bedrock of greenschist so that colluvium of the greenschist-hills is present. For the clusters GSvb4-6 and GSvb7-9 in most profiles also LS-textures were measured for some soil layers. Table 6.1 shows that higher clay percentages in the A- and B-layer, a lower clay percentage in the C-layer and higher silt percentages and lower sand percentages in all layers were measured than for sub-unit GRvb (non-degraded phase).

Table 6.1: Number of samples (N), mean percentages of clay, silt and sand and the standard deviations (s) from these means per geological-soil sub-unit and per soil depth. For the sub-unit GRvb results are given for the non-degraded phase (GRvb1-6,10-11) and the degraded phase (GRvb7-9).
*Tableau 6.1: Nombre des échantillons (N); les teneurs moyennes en argile, en limon et en sable; et les écarts types (s) pour ces moyennes par sub-unité géologique du sol et par profondeur du sol (soil layer). Pour le sub-unité GRvb, les resultats ont été donnés pour la phase non-dégradée (GRvb1-6, 10-11) et dégradée (GRvb7-9).*

| sub-unit soil layer | N | mean % clay | s % clay | mean % silt | s % silt | mean % sand | s %sand |
|---|---|---|---|---|---|---|---|
| GRvb*A | 8 | 6.5 | 3.8 | 15.5 | 3.1 | 79.0 | 5.8 |
| GRvb*B | 7 | 9.1 | 5.5 | 14.7 | 3.9 | 76.6 | 5.3 |
| GRvb*C | 6 | 12.2 | 5.6 | 14.7 | 1.8 | 73.2 | 6.2 |
| GRvb7-9A | 3 | 5.1 | 2.1 | 13.7 | 0.6 | 81.3 | 2.7 |
| GRvb7-9B | 3 | 21.0 | 0.8 | 16.3 | 8.7 | 62.7 | 9.5 |
| GRvb7-9C | 1 | 21.8 | - | 10.9 | - | 67.5 | - |
| GSvbA | 9 | 9.9 | 3.3 | 17.2 | 4.7 | 72.4 | 4.3 |
| GSvbB | 9 | 10.9 | 3.5 | 18.0 | 2.7 | 71.3 | 4.9 |
| GSvbC | 9 | 10.6 | 4.4 | 17.3 | 3.0 | 72.1 | 5.2 |
| GSvsA | 4 | 17.8 | 7.3 | 26.0 | 4.1 | 56.3 | 11.1 |
| GSvsB | 2 | 32.6 | 2.7 | 28.8 | 5.8 | 38.9 | 3.2 |
| GSvsC | 2 | 34.2 | 0.7 | 27.1 | 0.9 | 38.9 | 1.6 |
| RSvbA | 3 | 2.8 | 2.8 | 20.5 | 0.7 | 76.9 | 3.6 |
| RSvbB | 3 | 12.9 | 4.4 | 18.1 | 2.3 | 69.2 | 4.6 |
| RSvbC | 3 | 6.2 | 5.6 | 24.0 | 6.3 | 69.8 | 4.3 |

GRvb* indicates GRvb1-6,10-11 (non-degraded phase).
soil layer A = soil depth 5-10 cm
soil layer B = soil depth 30-35 cm
soil layer C = soil depth 55-60 cm

For sub-unit GSvs, especially for the sub-soil, finer textures were measured than for the other sub-units. For this sub-unit in the top-soil loamy sand (LS) to sandy clay loam (SCL) textures and in the sub-soil clay loam (CL) textures were measured. The sample pits of this cluster are characterized by relatively shallow bedrock of greenschists. The weathering material of these greenschists in which the soils of this sub-unit are formed consists of relatively fine textured material. The texture of SCL for soil layer GSvs2A, which is a relatively fine texture for an A-layer, may be due to the presence of very shallow bedrock in the sample pit. Table 6.1 shows that clay percentages of 17.8 % in the A-layer, 32.6 % in the B-layer and 34.2 % in the C-layer were found. A high standard deviation 7.3% from the mean clay percentage was measured for the A-layer. Silt percentages for this sub-unit are higher than for the other sub-units.

For sub-unit RSvb SL-textures and LS-textures were measured. Table 6.1 shows that clay percentages in the A- and C-layer are low, although a remarkable high percentage of over 12 % was measured for the B-layer. Silt percentages measured are higher than for sub-unit GSvb.

Table 6.1 indicates that texture usually becomes finer with depth In most sample pits the highest clay percentages are found within the C-layer (55-60 cm), caused by the illuviation of clay eluviated from the soil layers located on top of this soil layer. However, for sample pits GRvb1 and GRvb4 and some other sample pits, highest clay percentages are found within the top soil (A-layer), which is rather remarkable.

It can be concluded that most soils in the area are characterized by relatively coarse textured soils. Only for the degraded phase of sub-unit GRvb and for sub-unit GSvs especially in the sub-soil, moderately fine textures were measured. It must be remarked that the sand fraction for the soils of all sub-units consists mainly of fine sand. Soils can be classified as coarse or moderately coarse textured, but because of the presence of fine instead of coarse sand, soil-textures are not unfavourable.

## 6.3 Results of measurement of the bulk density

In the tables C2.1 to C2.10 of annex C2 the results of measurement of the BD for the different clusters are given. These tables contain rough data of the BD for each soil layer. Most BD-values measured for the research area vary between 1.40 and 1.75 g/cm3. The BD-data in the tables C2.1 to C2.10 of annex C2 were analyzed statistically by calculation of the mean BD and the standard deviation from this mean for each sub-unit per soil depth. The calculated data can be found in table 6.2, which gives also the number of samples used. For the sub-unit GRvb means and standard deviations were calculated separately for the non-degraded phase (represented by GRvb1-6,10,11) and the degraded phase (represented by GRvb7-9). Moderately high standard deviations of sometimes 0.09 g/cm3 were calculated which means that variation in BD-values for a certain soil depth within a sub-unit is relatively high.

Table 6.2: Number of samples of BD-measurements (N(BD), mean BD (g/cm3), standard deviation from the mean BD (s BD) (g/cm3), sample size of Ksat-measurements (N(Ksat), mean Ksat (cm/h) and standard deviation from the mean Ksat (s Ksat) (cm/h) per geological-soil sub-unit and per soil depth (soil layer). For the sub-unit GRvb results are given for the non-degraded phase (GRvb1-6,10-11) and the degraded phase (GRvb7-9).
*Tableau 6.2: Nombre des échantillons des données de la densité apparente (N (BD)), la densité apparente moyenne (BD) (g/cm³), les écarts types pour la densité apparente moyenne (s BD), nombre des échantillons des données du Ksat (s Ksat) (cm/h) par sub-unité géologique du sol et par profondeur du sol (soil layer). Pour la sub-unité GRvb, les resultats ont été donnés pour la phase non-dégradée (GRvb1-6, 10-11) et dégradée (GRvb7-9).*

| sub-unit soil layer | N (BD) | mean BD | s BD | N (Ksat) | mean Ksat | s Ksat |
|---|---|---|---|---|---|---|
| GRvb1-6,10-11A | 24 | 1.60 | 0.09 | 16 | 7.15 | 5.65 |
| GRvb1-6,10-11B | 21 | 1.59 | 0.07 | 14 | 5.09 | 2.67 |
| GRvb1-6,10-11C | 18 | 1.62 | 0.07 | 12 | 2.49 | 1.91 |
| GRvb7-9A | 9 | 1.61 | 0.05 | 6 | 0.40 | 0.22 |
| GRvb7-9B | 9 | 1.64 | 0.03 | 6 | 1.80 | 0.71 |
| GRvb7-9C | 3 | 1.67 | 0.01 | 2 | 0.54 | 0.14 |
| GSvbA | 27 | 1.44 | 0.06 | 18 | 8.10 | 2.58 |
| GSvbB | 27 | 1.48 | 0.06 | 18 | 6.92 | 3.14 |
| GSvbC | 27 | 1.54 | 0.07 | 18 | 4.34 | 3.02 |
| GSvsA | 12 | 1.62 | 0.06 | 8 | 2.29 | 1.26 |
| GSvsB | 6 | 1.62 | 0.04 | 4 | 2.09 | 4.19 |
| GSvsC | 6 | 1.71 | 0.06 | 4 | 0.08 | 0.15 |
| RSvbA | 9 | 1.51 | 0.05 | 6 | 9.38 | 5.51 |
| RSvbB | 9 | 1.43 | 0.05 | 6 | 11.55 | 7.00 |
| RSvbC | 9 | 1.45 | 0.09 | 6 | 7.00 | 4.02 |

soil layer A = soil depth 5-10 cm
soil layer B = soil depth 30-35 cm
soil layer C = soil depth 55-60 cm

Given the textures present, the BD-values are medium to high. For tropical soils high BD-values are common. High percentages of iron are often present causing high particle densities and high BD-values. Next to high particle densities high BD-values may also be due to relatively low concentrations of organic matter present in the soils. According to Tammes (1993) the percentage of organic matter in the top-soils of loamy sand soils in the area are lower than 1.25 % and often even lower than 0.30 %. Also Van Dam (1993) measured very low percentages of organic matter in different soils in the area. Differences in BD-values may also be caused by measuring-errors (see section 7.4) and differences in root penetration, soil structure and the presence of gravel and stones. Possibly, measuring-errors and differences in particle density, soil structure and the presence of gravel and stones cause most variability.

Table 6.2 shows that BD-values for the sub-unit GRvb (non-degraded phase) tend to be higher than those for the sub-unit GSvb. For sub-unit GRvb (non-degraded phase) BD-values of 1.60 g/cm3 for the A-layer, 1.59 g/cm3 for the B-layer and 1.62 g/cm3 for the C-layer were found. For sub-unit GSvb BD-values of 1.44 g/cm3 for the A-layer, 1.48 g/cm3 for the B-layer and 1.54 g/cm3 for the C-layer were found. The difference in BD-values partly may be due to differences in organic matter levels, although it is thought that differences in particle density and soil structure are more important. In the sub-unit GSvb no cuirasses are present and percentages of iron and particle density possibly are higher here than in sub-unit GRvb. Table 6.1 indicates that the differences can not be attributed to differences in texture.

For the sub-units GRvb (non-degraded phase) and GSvb no big differences in BD-values between the clusters of one sub-unit or between the sample pits of one cluster are present (see annex C2). Table 6.2 shows that the degraded phase of sub-unit GRvb in the sub-soil is characterized by a higher BD-value of 1.67 g/cm3 than the non-degraded phase.

Table 6.2 indicates that sub-unit GSvs is characterized by BD-values of 1.62 g/cm3 in the A- and B-layer and a value of 1.71 g/cm3 in the C-layer, which are high values for fine-textured soils (see table 6.1) of this cluster. This may indicate that the soils of this cluster are rather compact or have high particle densities, although higher particle densities than for the sub-unit GSvb cannot easily be explained. The high BD-values may partly be due to presence of gravel and stones in the samples, especially in the soil layer just above the bedrock.

Table 6.2 indicates that BD-values for sub-unit RSvb are almost the same as for sub-unit GSvb. During sample pit survey it turned out that profiles in the sub-units GSvb and RSvb often were characterized by better soil structures than those in sub-unit GRvb. This may explain why BD-values are higher for sub-unit GRvb than for the sub-units GSvb and RSvb. Taking into account that in sub-unit RSvb, unlike sub-unit GSvb, cuirasses are present and percentages of iron and particle densities may be higher than for GSvb, equal BD-values for both sub-units can not easily be explained.

In general BD-values tend to increase with depth, as the effects of cultivation decrease. Also the pressure of above laying soil material increases with depth. This tendency of rising BD-values with depth is also found for BD-values measured in the research area, however not very clearly and not for the sub-unit RSvb (see table 6.2). Sample pit RSvb2 for example is characterized by dropping BD-values with depth (see annex C2).

## 6.4 Results of measurement of the saturated hydraulic conductivity

In the tables C2.1 to C2.10 of annex C2 the results of measurement of the Ksat for the different clusters are given. These tables contain rough data of the Ksat for each soil layer. Ksat-values measured vary from 0.00 to 21.26 cm /hour, but most values lay between 0.5 and 15 cm/hour. The Ksat-data in the tables C2.1 to C2.10 of annex C2 were analyzed statistically by calculation of the mean Ksat and the standard deviation from this mean for each sub-unit per soil depth. The calculated data can be found in table 6.2, which gives also the number of samples used. For the sub-unit GRvb means and standard deviations were calculated separately for the non-degraded phase (represented by GRvb1-6,10,11) and the degraded phase (represented by GRvb7-9). Table 6.2 shows that often high standard deviations of more than 5cm/h are present. It is very possible that these may be due to measuring-errors (see section 7.5).

Ksat-values of 12-25 cm/hour for loamy sand and fine sand, 6-12 cm/hour for fine sandy loam and sandy loam, 2-6 cm/hour for loam and 0.25-2 cm/hour for sandy clay loam and clay loam according to Landon (1984) are indicative Ksat-values. It must however be stressed that indicative values depend also on other soil properties like soil structure, amount of gravel and stones, bulk density, organic matter level and root penetration. Especially soil-structure is next to soil-texture important for the Ksat. Table 6.2 shows that lower values were measured in the research area, taking into account soil-texture, than the indicative values of Landon (1984). This may be explained by the poorly developed soil structure of the soils, but may be also high bulk densities are responsible for it (see section 6.3). Table 6.2 shows that for all sub-units for each soil layer K-sat-values are lower than 12 cm/h. Except for the A-layer of sub-unit GRvb (degraded phase), the A- and B-layers of sub-unit GSvb and for all layers of sub-unit RSvb Ksat-values higher than 6 cm/h were found.

Table 6.2 shows that Ksat-values for sub-unit GRvb (non-degraded phase) tend to be lower than for the sub-unit GSvb. Since this difference can not well be attributed to texture differences, it is quite possible that it is due to differences in soil structure and BD-values (see section 6.3). The relatively high Ksat values of sub-unit RSvb cannot easily be explained. Possibly, soils have better developed soil structures than those of sub-unit GSvb.

Table 6.2 indicates that the degraded phase of sub-unit GRvb (GRvb7-9), especially in the top-soil, is characterized by lower Ksat-values than those measured for the non-degraded phase of the sub-unit GRvb (GRvb1-6,10,11). The very low Ksat-values in the A-layer of sub-unit GRvb (degraded phase) of 0.40 cm/h can be explained by the presence of a surface crust here which also was partly present in the samples. Soils of this sub-unit are cemented in the whole profile which explains the relatively low Ksat-values for all soil layers.

No large differences in Ksat-values were measured between the clusters and between the sample pits within each cluster for the sub-units GRvb (non-degraded phase) and GSvb.

Table 6.2 shows that the Ksat-value of especially the C-layer of sub-unit GSvs is low, which possibly can be explained by the high BD-value present. For this sub-unit in the B- and C-layer Ksat-values of 0.00 cm/hour were measured. A low Ksat-value here can be explained by the high bulk density, although a Ksat-value of 0.00 cm/h seems to be unrealistic. Possibly the samples in question were sealed when they were cut, although there was taken care to avoid this (see section 7.2). Especially fine- and medium-textured soils are sensitive to sealing. The mean Ksat value of 2.09 cm/h for the B-layer of sub-unit GSvs is not representative for this layer of the sub-unit. This is also indicated by the high standard deviation of 4.19 cm/h calculated for this soil layer. The value is too much influenced by the strongly deviating value for GSvs3B of 8.37 cm/h. This high value was possibly due to the presence of a crack or large root-corridor in the sample. Especially in fine-textured soils megapores, such as cracks and root-corridors, may play an important role for the transport of water in the soil.

In general there is a tendency for the Ksat-values to decrease with depth. Possibly this is due to the fact that BD-values tend to increase with depth (see section 6.3) and soil structure is less developed in the sub-soil than in the top-soil. As a rule of thumb, a horizon with a Ksat-value less than 10 % that of the overlying horizon should be regarded as effectively impermeable (Landon, 1984). For this reason abrupt change in Ksat-values with depth can have serious effects on the drainage within a profile. Except for sub-unit GSvb, in which the very low Ksat-values of the sub-soil may lead to drainage problems, no abrupt changes in Ksat-values were measured. For this sub-unit waterlogging in the top-soil may be caused, on the other hand lateral sub-surface flow caused by the presence of a slope possibly will avoid this. Low Ksat-values in the sub-soil may result in shortages of water here.

It can be concluded that the Ksat for the soils studied is not everywhere favourable. Especially unfavourable values were measured for the degraded phase of sub-unit GRvb (GRvb7-9) and for sub-unit GSvs. For sub-unit RSvb and to a lesser degree for sub-unit GSvb high Ksat-values may cause that too much water get lost by too quick drainage if high amounts of rainfall occur. However it must however be stressed that in a semi-arid area, like the research area, soils, except for some soils located in depressions, almost never are saturated with water. Unsaturated hydraulic conductivity (Kunsat) rates are much lower than Ksat-rates. For this reason the rates of downward water-movement into the soil often are slower than the Ksat-rates and not much water will get lost by quick drainage. Because the degraded phase of sub-unit GRvb is characterized by a low permeability of the top-soil, after showers a lot of water may get lost by evaporation here. Since rainfall can not infiltrate well overland flow may cause water erosion here.

## 6.5 Results of measurement of the soil moisture characteristic

In the tables C3.1 to C3.10 of annex C3 the results of measurement of the SMC for the different clusters are given. These tables contain rough data of the SMC for each soil layer. The measured values of the available water capacity (AWC) vary between the low value of 10 % and the high value of 20 %. The AWC-values are low for the moderately coarse textures present. This may be due to the poorly developed soil structure, low percentage of organic matter and high BD-values in the soils. The SMC-data in the tables C2.1 to C2.10 of annex C2 were analyzed statistically by calculation of the means of the VMC at pF2, the VMC at pF4.2, the AWC and the standard deviations from these means for each sub-unit per soil depth. The calculated data can be found in table 6.2, which gives also the number of samples used. For the sub-unit GRvb means and standard deviations were calculated separately for the non-degraded phase (represented by GRvb1-6,10,11) and the degraded phase (represented by GRvb7-9). Table 6.3 shows that often standard deviations of more than 3% are present for the VMC's at pF2 and pF4.2 and the AWC within a certain soil layer of a sub-unit. This variation may have many causes, although measuring-errors are thought to be a major cause (see section 7.6).

Table 6.3 shows that the SMC for sub-unit GRvb (non-degraded phase), having low AWC's of 15 % for the A-layer, 14% for the B-layer and 13 % for the C-layer, tends to be more unfavourable, than SMC's for the sub-units GSvb and RSvb. This cannot well be attributed to differences in texture (see section 6.2). Possibly it may be due to differences in soil structure, BD-values (see section 6.3) and organic matter levels.

For sub-unit GSvs unfavourable SMC's, characterized by low AWC's of 14 % for the A-layer, 13% for the B-layer and 14 % for the C-layer, were measured. This may be due to the high bulk density found for this sub-unit (see table 6.2). For the sub-soil of this sub-unit a high VMC of 25 % was measured at pF4.2 due to a higher clay percentage present here.

The SMC of soil layer GRvb5A characterized by an AWC of 13 % (see annex C3), can be seen as representative for soil layers of the sub-unit GRvb (non-degraded phase). In figure 6.1a the pF-curve of soil layer GRvb5A is represented. The SMC of soil layer

GSvb6A, characterized by an AWC of 19 %, can be seen as representative for soil layers of the sub-unit GSvb, although the VMC of 24 % at pF2 is relatively low for this sub-unit (see table 6.3). In figure 6.1b the pF-curve of soil layer GSvb6A is

Table 6.3: Number of samples (N), mean volumetric moisture content (VMC) at pF2 (%), standard deviation from the mean VMC at pF2 (s VMC pF2) (%), mean VMC at pF4.2 (%), standard deviation from the mean VMC at pF4.2 (s VMC pF4.2) (%), mean available water capacity (AWC) (%) and standard deviation from the mean AWC (s AWC) (%) per geological-soil sub-unit and per soil depth (soil layer). For sub-unit GRvb results are given for the non-degraded phase (GRvb1-6,10-11) and the degraded phase (GRvb7-9).
*Tableau 6.3: Nombre des échantillons (N), le taux d'humidité volumique moyen (VMC) à pF2 (%), les écarts types pour le taux d'humidité volumique moyen à pF2 (s VMC pF2) (%), le taux d'humidité volumique moyen à pF4.2 (s VMC pF4.2) (%), les écarts types pour le taux d'humidité volumique moyen à pF4.2 (s (VMC pF4.2)) (%), la réserve utile moyenne (AWC) (%), et les écarts types pour la réserve utile moyenne (s AWC) (%), par sub-unité géologique du sol et par profondeur du sol (soil layer). Pour la sub-unité GRvb, les resultats ont été donnés pour la phase non-dégradée (GRvb1-6, 10-11) et dégradée (GRvb7-9).*

| sub-unit soil layer | N | mean VMC pF2 | s VMC pF2 | mean VMC pF4.2 | s VMC pF4.2 | mean AWC | s AWC |
|---|---|---|---|---|---|---|---|
| GRvb1-6,10-11A | 8 | 20 | 3.7 | 5 | 1.5 | 15 | 3.2 |
| GRvb1-6,10-11B | 7 | 21 | 2.4 | 7 | 2.2 | 14 | 2.9 |
| GRvb1-6,10-11C | 6 | 21 | 4.1 | 9 | 1.9 | 13 | 2.3 |
| GRvb7-9A | 3 | 21 | 4.4 | 5 | 1.7 | 16 | 2.6 |
| GRvb7-9B | 3 | 24 | 1.2 | 14 | 1.5 | 11 | 0.6 |
| GRvb7-9C | 1 | 27 | - | 15 | - | 12 | - |
| GSvbA | 9 | 27 | 2.7 | 6 | 1.4 | 21 | 2.3 |
| GSvbB | 9 | 27 | 3.1 | 8 | 2.0 | 19 | 1.6 |
| GSvbC | 9 | 29 | 3.2 | 8 | 2.7 | 21 | 4.0 |
| GSvsA | 4 | 26 | 4.9 | 13 | 2.1 | 14 | 2.9 |
| GSvsB | 2 | 35 | 2.1 | 22 | 2.1 | 13 | 4.2 |
| GSvsC | 2 | 38 | 0.0 | 25 | 0.7 | 14 | 0.7 |
| RSvbA | 3 | 22 | 2.6 | 4 | 0.6 | 18 | 2.5 |
| RSvbB | 3 | 23 | 2.1 | 8 | 1.2 | 16 | 1.5 |
| RSvbC | 3 | 28 | 6.5 | 9 | 0.6 | 19 | 6.0 |

soil layer A = soil depth 5-10 cm
soil layer B = soil depth 30-35 cm
soil layer C = soil depth 55-60 cm

represented. Comparing the two pF-curves of GRvb5A and GSvb6A it can be seen that the difference in AWC is caused by the higher VMC of GSvb6A at pF4.2. The SMC in the sub-soil of the degraded phase of sub-unit GRvb (GRvb7-9) is very unfavourable for the sandy clay loam texture present. This may be explained by the high bulk density of the soil here (see table 6.2).

In the figures 6.1c and 6.1d two contrasting pF-curves are given, representing each a SMC with a low AWC. The pF-curve for soil layer GRvb2A with a low VMC of 3% at pF4.2 is given in figure 6.1c. Since the VMC at pF2 is also low, this soil layer is not characterized by a higher AWC than most other soil layers within the sub-unit GRvb (non-degraded phase). Figure 6.1d gives the pF-curve for soil layer GSvs1C which is characterized by a high VMC of 25 % at pF4.2. Since the VMC at pF2 is rather high the AWC does not deviate much from that of other soil layers.

The SMC varies with depth. Table 6.3 shows that there is a slight tendency of measured AWC-values to decrease with depth. Possibly this may be due to the fact that BD-values tend to increase with depth (see section 6.3) and percentages of organic matter tend

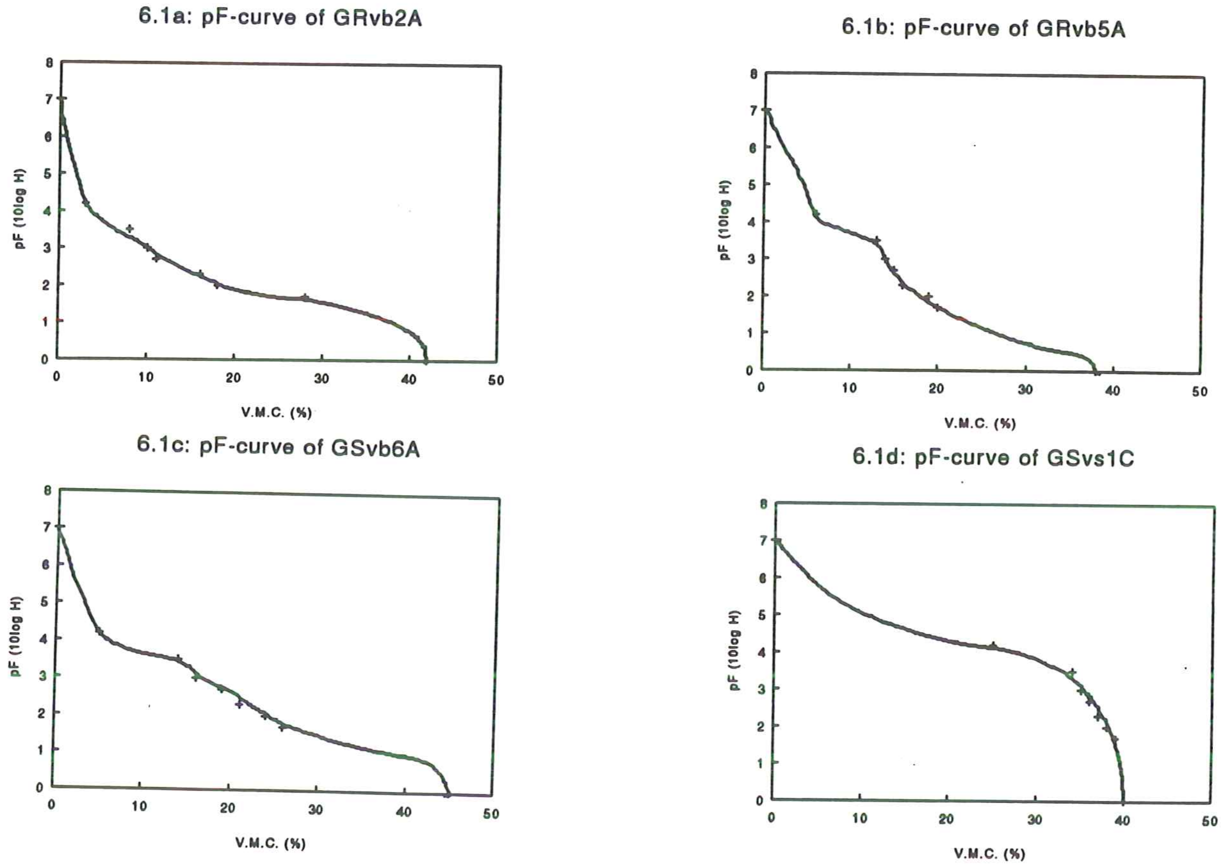


Figure 6.1: pF-curve of GRvb5A (figure 6.1a), pF-curve of GSvb6A (figure 6.1b), pF-curve of GRvb2A (figure 6.1c) and pF-curve of GSvs1C (figure 6.1d).

*Figure 6.1: Courbe-pF de GRvb5A (figure 6.1a), courbe-pF de GSvb6A (figure 6.1b), courbe-pF de GRvb2A (figure 6.1c) et courbe-pF de GSvs1C (figure 6.1d).*

to decrease with depth. On the other hand percentages of clay in the average tend to increase with depth, which may have a favourable influence on the AWC if soil textures are relatively coarse.

It can be concluded that the SMC's of the soils studied is not favourable, especially if the textures present are taken into account. Most favourable SMC's were measured for the sub-units GSvb and RSvb. Interpretations of the measurement-results however must be made with care. In practice, water uptake by roots is affected by the depth and density of rooting, by gradients in water potential and by hydraulic conductivity of both soils and roots. It must also be marked that rainfall is relatively low in the research area. For this reason in a large part of the soil 'field capacity' is only sometimes reached and the available water for plants will even be lower as expected by seeing the pF-curves, since the AWC-percentage is not totally occupied with water. The importance of the AWC depends on the frequency of wetting expected, the duration of dry periods between rainfall and the VMC-values at 'field capacity' (FC) and 'permanent wilting point' (PWP). If large showers occur, as is often the case in the area, it is important that the VMC at FC is high so that not too much water drains. If small showers occur it is important that the VMC at PWP is low so that not all the new water which enters the soil is retained with too high forces. It must be remarked that in this context not only rainfall but also sub-surface seepage plays a role in the research area, since during the survey of sample pits sometimes wet layers were found, e.g. in sample pit RSvb3 (see annex B), which cannot be explained by rainfall.

# 7 DISCUSSION OF ACCURACY AND ERRORS

## 7.1 Introduction

Variation in data results consist of spatial variation and 'error variation'. The variation due to inaccuracy and errors made during sampling and analysis is called 'error variation'. If a horizon is homogeneous, type 5 of variations mentioned in section 3.3 will mainly be 'error variation'. However, in the research area horizons often are not homogeneous, especially where randomly gravel is present and spatial 'natural' variation may be large. The bigger the share of 'error variation' the more the results become questionable. By analyses of variance it is often very difficult or even impossible to give an exact estimation about the percentages of total variation which consist of 'error variation' and spatial variation.

This chapter deals with the inaccuracy and errors made during the processes of sampling, sample management and application of methods used for measuring soil physical properties. This subject is very important, since it tells something about the quality and usefulness of the results.

Consider a situation where at different places soil samples are taken for measuring a certain soil physical property from a homogeneous soil layer. The value of this soil property for all samples will be exactly the same for each sample if no errors are made. This however is a hypothetical case. In reality samples will never be identical, even if they are taken from a completely homogeneous horizon. Sampling and sample management always involve some inaccuracy and small differences between samples may arise. Further inaccuracy and errors related to the analysis methods will be responsible for a part of the variation in results.

Standard deviations given in the tables 6.1, 6.2 and 6.3 show that variability for a certain soil depth within a sub-unit is high for all soil physical properties measured. However, no conclusion can be given about the percentage of 'error variation' present. Surely a large parts of the standard deviations are not caused by 'error variation', since no completely homogeneous soil layers are present within a 'sub-unit'. Field survey and study of sample pits revealed that within a cluster of sample pits and even at a certain soil depth within one sample pit, variability in soil characteristics may be high.

## 7.2 Inaccuracy and errors made during the process of sampling and associated with sample management

During sampling it may occur that the sample taken is not a representative. For example if a sample taken from a soil layer which contains almost no stones, is containing a large stone. In this case the soil physical properties will also not be representative. Variation from the mean value of a soil physical property for a certain soil layer, found by taking a 'non-representative' sample is not part of the 'error variation', but indicates real variation. Especially if only 1 sample is taken, as for the soil moisture characteristic (SMC), it cannot easily be traced if a 'non-representative' sample is taken. Therefore it is dangerous to predict the value of a soil physical property by taking only one sample. For the determination of the SMC of a certain soil layer only one sample was used, since analysis is time consuming. The risk of taking 'non-representative' samples increases if more gravel and stones are present. In the case of very stony soil layers, determination of BD, Ksat and SMC of these layers by ring samples is useless.

Taking undisturbed ring samples must be done accurately. However, the sample will never be an ideal representation of the soil layer from which it is taken. The sample will always be disturbed to a certain degree. Disturbances can arise when the sample rings are driven in the soil, when they are taken out and when they are cut in the right size. A rather large error can be made by measuring the Ksat of a core sealed during sampling. Samples often will be sealed to a certain degree when they are cut in the right size. For this reason the Ksat may be structurally underestimated. Sample disturbances can also arise by improper management of them. Samples may be disturbed during transport by car or motorbike and the original soil structure may be affected.

## 7.3 Inaccuracy and errors made by measurement of texture

Because of the high concentrations of iron-oxides, the soils in the research area often contain high amounts of aggregates like 'pseudo-sand' and 'pseudo-silt'. 'Pseudo-sand' and 'pseudo-silt' are particles with the size of respectively sand and silt, but which are all combinations of smaller particles. These aggregates may be very stable, even after repeated wetting and drying. In this case they will behave like sand- or silt-particles, instead of the composing smaller particles, if texture-related soil-physical properties are concerned. Less stable aggregates will disintegrate under wetting. So it is important in texture analysis to know the degree of dispersion of the original samples.

The soil physical properties BD, Ksat and SMC are all partly texture related. During the texture analysis stable 'pseudo-sand' and 'pseudo-silt' may be destructed. However it is difficult to estimate to what degree stable aggregates were destructed. So it was decided to pulverize dry sample material in a mortar. For the hydrometer method dispersing agent was added to the sample material (see section 4.2). It must be remarked that for searching relations between texture and soil physical properties in gravelly soils a texture analysis of the 'fine-earth' is not sufficient, since the presence of gravel may not be neglected.

During sieving in the laboratory small amounts of very fine dust escaped. For this reason the fraction < 2 $\mu$m may be slightly underestimated.

Soil mixtures for the hydrometer method may not have been completely homogeneous. So small errors may have been made.

The sand-fraction was divided in only two sub-fractions, because no sieves were available for more separation. The Soil Survey Staff (1951) of the United States Department of Agriculture (USDA) and the FAO (1977,1990) distinguish 5 sub-fractions within the sand fraction. The FAO (1977 and 1990) uses 63 $\mu$m instead of 50 $\mu$m, as particle-size boundary between silt and sand.

It appeared that using the 53 $\mu$m resulted in inaccurate results. In first instance the aim was to compare the weight percentage of the fraction 53$\mu$m-1mm determined by sieving with the weight percentage of this fraction determined with the hydrometer method. The differences in results may give an idea about the amount of pseudo-sand. However the periods of sieving due to limited time were thought to be too short sieving out all the particles < 53 $\mu$m, although they were long enough for separating the fraction 1-2 mm from the rest of the 'fine earth'. Also the size of the meshes of the sieve does not correspond with the critical value of 50 $\mu$m used for the hydrometer method. So it was decided not to carry out the comparison mentioned.

## 7.4 Inaccuracy and errors made by measurement of the bulk density

Next to taking 'non-representative' and disturbed samples errors may be made by determining the BD.

The rings sometimes were not filled completely. In the calculations of the BD-values, however not the volume of the rings was used but also the missing volume was taken into account. Small errors were made by estimation of the sample volume.

The ring samples were not all taken at the same soil-moisture content. This influences especially BD-determinations of swelling and shrinking soils. These more finely textured soils will decrease in volume upon drying. No error was made, since the stove dry volume estimated was used in the calculations. However, for swelling and shrinking soils, like that of sub-unit GRvs, BD-determinations at different soil-moisture contents would have been more useful. Carrying out accurately such BD-determinations is difficult since the process of swelling of soil material in the soil is different from that of soil material in ring samples.

## 7.5 Inaccuracy and errors made by measurement of the saturated hydraulic conductivity

Next to taking 'non-representative' and disturbed samples errors may be made by determining Ksat. Most important in this context is that laboratory-measurements of the Ksat are inaccurate. Other errors maybe can be neglected with regard to this, but for completeness will be shortly discussed.

# 8 STATISTICAL TESTS

## 8.1 Introduction

This chapter deals with the application of some statistical test on the rough data of annex C, in order to test if samples are taken from different or identical populations. It is tested if different populations can distinguished on account of data-results of a soil physical property. Common statistical tests are used to test if spatial units can be distinguished. In this way it may e.g. be tested if the sub-unit GRvb (non-degraded phase) differs from sub-unit GSvb on account of measured soil-physical data. The analysis of variance (ANOVA) was used if many samples were taken and the Mann-Whitney test if not much samples were taken (Blalock, 1985). No geostatistical tests can be used, since not enough sampling took place and the sampling method used was executed incompletely.

## 8.2 Testing the difference between sub-units with the analysis of variance.

By applying the ANOVA it was tested if sub-unit GRvb (non-degraded phase) can be distinguished from sub-unit GSvb on account of soil physical properties measured. The ANOVA only can be applied for testing if these two sub-units can be distinguished on account of BD- and Ksat-values. For other sub-units and for other soil physical properties the amount of samples taken was too low. Too have equal amounts of data in both sub-units for sub-unit GSvb only data of the clusters GSvb4-6 and GSvb7-9 and for sub-unit GRvb (non-degraded phase) only data of the clusters GRvb1-3 and GRvb4-6 were used. The ANOVA was carried out for the three soil layers separately, since in this way the effect of changing values with depth was avoided. So it was tested if sub-unit GRvb (non-degraded phase) differs from sub-unit GSvb on account of BD values of the A-, B- and/or C-layer and/or Ksat-values of the A-, B- and/or C-layer. The next procedure was followed:

1. Assumptions

Level of measurement: -BD- and Ksat-values on ratio scale
-sub-unit on nominal scale

Model: -independent random sampling
-normal populations for each sub-unit
-population variances are equal (in this case almost equal, since the amount of samples is not large)

Hypothesis: -H0:identical populations ($\mu1=\mu2$)
-Ha:not H0 (different populations)

2. Significance level: -$\alpha$=0.05 (95 %)

3. Sampling distribution: -F distribution (see e.g. table J of Blalock, 1985)

4. Critical F-value: -Fcr. for (k-1),(N-k);in this case 2 sub-units and k=2;Fcr for 1,N-2 (for BD N=36, for Ksat N=24)
-Values of Fcr. are given in table 8.1

5. Computation of F: -F = between variance/within variance
-F values calculated are given in table 8.1

6. Decision; -H0 is rejected if F > Fcr.

Table 8.1 gives for the test with the BD and Ksat per soil layer a Fcr.-value , a calculated F-value and the result of the ANOVA. It can be concluded that according to the ANOVA the two sub-units may be distinguished on account of BD values of the A-, B- and C-layer and Ksat-values the B-layer, but not on account of Ksat-values of the A- and C-layer. With this ANOVA it is proved that sub-units can be distinguished on account of soil physical properties.

Table 8.1: Data and results of the ANOVA for testing if sub-unit GRvb (non-degraded phase) can be distinguished from sub-unit GSvb on account of BD- and/or Ksat-values for the A-, B- and/or C-layer.
*Tableau 8.1: Les données et les resultats de l'analyse ANOVA démontrent que sub-unité GRvb (phase non-dégradée) se distingue de la sub-unité GSvb, sur la base des valeurs de la densité apparente (BD) et/ou des valeurs du Ksat des couches A, B et/ou C.*

| soil property soil layer | Fcr. | F | reject H0 |
|---|---|---|---|
| BD, A | 4,13 | 44,7 | yes |
| BD, B | 4,13 | 25,9 | yes |
| BD, C | 4,13 | 12,1 | yes |
| Ksat, A | 4,30 | 0,9 | no |
| Ksat, B | 4,30 | 5,5 | yes |
| Ksat, C | 4,30 | 0,2 | no |

## 8.3 Testing the difference between sub-units with the Mann-Whitney test

For other soil physical properties than BD and Ksat the amount of samples taken was too low for applying the ANOVA. The Mann-Whitney test is used for testing if sub-unit GRvb (non-degraded phase) can be distinguished from sub-unit GSvb on account of percentage of clay, VMC at pF4.2, VMC at pF2 and/or the AWC of the A-, B- and/or C-layer. To have equal amounts of data in both

Table 8.2: Data and results of the Mann-Whitney test for testing if sub-unit GRvb (non-degraded phase) can be distinguished from sub-unit GSvb on account of values of the % of clay, the VMC at pF4.2, the VMC at pF2 and/or the AWC for the A-, B- and/or C-layer.

*Tableau 8.2: Les données et les resultats du test Mann-Whitney démontrent que sub-unité GRvb (phase non-dégradée) se distingue de la sub-unité GSvb, sur la base des valeurs de la teneur en argile (%), le taux d'humidité volumique à pF4.2 (VMC pF4.2), le taux d'humidité volumique à pF2 (VMC pF2) et/ou la réserve utile (AWC) des couches A, B et/ou C.*

| soil property soil layer | Ucr. | U | reject H0 |
|---|---|---|---|
| % clay, A | 5 | 14.0 | no |
| % clay, B | 5 | 10.0 | no |
| % clay, C | 5 | 12.0 | no |
| VMC pF4.2 A | 5 | 17.5 | no |
| VMC pF4.2 B | 5 | 12.0 | no |
| VMC pF4.2 C | 5 | 7.5 | no |
| VMC pF2 A | 5 | 4.5 | yes |
| VMC pF2 B | 5 | 5.0 | yes |
| VMC pF2 C | 5 | 3.5 | yes |
| AWC A | 5 | 4.0 | yes |
| AWC B | 5 | 4.0 | yes |
| AWC C | 5 | 0.0 | yes |

sub-units the same clusters of both sub-units were used as for the ANOVA. The Mann-Whitney test was carried out for the three soil layers separately, since in this way the effect of changing values with depth was avoided. The next procedure was followed:

1. Assumptions

Level of measurement: -values on ratio scale
-sub-unit on nominal scale

Model: -independent random samples

Hypothesis: -H0:identical populations (mixed values)
-Ha:not H0 (different populations)

2. Significance level: -$\alpha$=0.05 (95 %)

3. Sampling distribution: -U distribution (see e.g. tables F and G of Blalock, 1985)

4. Critical U-value: -Ucr. for N1 and N2;in this case N1=N2=6
-Values of Ucr. are given in table 8.2

5. Computation of U: -U is calculated by ranking values (see e.g. Blalock, 1985)
-U values calculated are given in table 8.2

6. Decision: -H0 is rejected if U =< Ucr.

Table 8.2 gives for the test with the percentage of clay, the VMC at pF4.2, the VMC at pF2 and the AWC per soil layer an Ucr.-value , a calculated U-value and the result of the Mann-Whitney test. It can be concluded that according to the Mann-Whitney test the two sub-units may be distinguished on account of values of the VMC at pF2 and values of the AWC for the A-, B- and C-layer, but not on account of values of the percentage of clay and the VMC at pF4.2 for the A-, B- and C-layer. The characteristic of not all soil physical properties do have to differ for two different soil units. With this Mann-Whitney test it is proved that sub-units can be distinguished on account of soil physical properties.

## 8.4 Testing the difference between clusters within the sub-unit 'granitic area, valley bare' with the Mann-Whitney test

The Mann-Whitney test was also used for testing if, on account of soil physical properties, the different clusters of sub-unit GRvb can be distinguished. In other words it is tested if the variability within the sub-unit is high.

Firstly, it was tested if cluster GRvb1-3 can be distinguished from cluster GRvb4-6 on account of BD-values, Ksat-values, values of the clay percentage, VMC at pF4.2, VMC at pF2 and/or the AWC of the A- and/or C-layer. The procedure is the same as described for the Mann-Whitney test in section 8.3. Only lower values for N1 and N2 are present. N1 and N2 are both 9 in tests with BD-values, both 6 in tests with Ksat-values and both 3 in tests with values of the other soil-physical properties.

Table 8.3 gives for the test, between the clusters GRvb1-3 and GRvb4-6, with the BD, the Ksat, the percentage of clay, the VMC at pF4.2, the VMC at pF2 and the AWC per soil layer an Ucr.-value ,a calculated U-value and the result of the Mann-Whitney test. It can be concluded that according to the Mann-Whitney test the two clusters only may be distinguished on account of Ksat-values for both soil layers, but not on account of values of the percentage of clay, the VMC at pF4.2, the VMC at pF2 and the AWC for both soil layers. It can be concluded that on account of most soil-physical properties both clusters belong to the same population, in this case the same sub-unit. The fact that U equals Ucr. in the tests with Ksat-values may be due to the fact that the Ksat-data are inaccurate (see section 7.5).

proved that the degraded phase of sub-unit GRvb (cluster GRvb7-9) on account of soil physical properties differs from the non-degraded phase (cluster GRvb1-3).

Table 8.4: Data and results of the Mann-Whitney test for testing if cluster GRvb1-3 can be distinguished from cluster GRvb7-9, located in the degraded phase of the sub-unit, on account of BD-values, Ksat values, values of the % of clay, the VMC at pF4.2, the VMC at pF2 and/or the AWC for the A- and/or B-layer.
*Tableau 8.4: Les données et les resultats du test Mann-Whitney démontrent que groupe GRvb1-3 se distingue de la groupe GRvb7-9 (phase dégradée), sur la base des valeurs de densité apparente (BD), du Ksat, de la teneur en argile (%), du taux d'humidité volumique à pF4.2 (VMC pF4.2), du taux d'humidité volumique à pF2 (VMC pF2) et/ou de la réserve utile (AWC) des couches A et/ou B.*

| soil property soil layer | Ucr. | U | reject H0 |
|---|---|---|---|
| BD, A | 17 | 13.5 | yes |
| BD, B | 17 | 10.0 | yes |
| Ksat, A | 5 | 0.0 | yes |
| Ksat, B | 5 | 0.0 | yes |
| % clay, A | 2 | 3.0 | no |
| % clay, B | 2 | 0.0 | yes |
| VMC pF4.2 A | 2 | 3.5 | no |
| VMC pF4.2 B | 2 | 2.0 | yes |
| VMC pF2 A | 2 | 4.5 | no |
| VMC pF2 B | 2 | 1.0 | yes |
| AWC B | 2 | 2.5 | no |
| AWC B | 2 | 1.0 | yes |

# 9 REGRESSION ANALYSIS

## 9.1 Introduction

In this chapter relations between the different soil physical properties will be studied by means of regression analysis (Webster and Oliver, 1990). Soil physical properties may be the cause of others. Sometimes they might be of little interest in themselves but are recorded in order to predict the values of others that are difficult or expensive to measure. For this reason correlation between soil physical properties is an advantage and the field of regression may point out statistical relations between soil physical properties. In this chapter linear regression was applied and R2-factors were calculated. R2 gives the explained sum of squares (SSe) divided by the total sum of squares (SSt). Therefore R2 is a measure which indicates which amount of the variation can be explained by the linear regression line. If R2 is equal to 1, an optimum linear correlation between two properties is present and all points lay on the curve. In this case SSe is equal to SSt. If R2 is equal to 0, no linear correlation at all between two properties exists. In this case SSe is equal to 0. Only linear regression is dealt with, since relations are expected to be linear. Non-linear regression was tried, but seldom yielded a higher R2-value than linear regression.

Regression analyses was carried for data of all sub-units together and for some combinations of soil physical properties for the data of sub-unit GRvb (non-degraded phase, GRvb1-6 (exclusive GRvb10-11 !)) and sub-unit GSvb separately. Within a certain sub-unit a stronger or weaker correlation between soil physical properties may exist than for an other sub-unit or for the overall data.

Regression analysis was carried out between BD and Ksat; between the percentage of clay and the percentage sand on one hand and Ksat on the other hand; between the percentage clay and the VMC at pF4.2;between the percentage of sand and the VMC at pF2;between the percentage of clay and the percentage of sand on one hand and the AWC on the other hand.

Since data quality is far from optimum (see chapters 6 and 7), it was decided not to search by means of multiple regression for so called 'pedotransfer functions'. Unreliable values for the VMC at pF2.3, pF2.7, pF3 and pF3.5 may have been measured which makes searching for the relation between texture and the SMC, the relation of interest, by means of multiple regression impossible.

## 9.2 Linear regression between the bulk density and the saturated hydraulic conductivity

Figure 9.1 shows the linear regression-curve between all BD and Ksat-values. Sample points in the curve consist of combinations of the BD1-value with the Ksat1-value and the BD2-value with

Ksat2-value as given in annex C2. A negative linear correlation is present between BD and Ksat characterized by a R2 of 0.34. This negative linear correlation can be explained by the fact that often a lower porosity and related permeability is present if higher BD-values are measured. R2 is not high which is explained by the fact that the BD is not the only soil physical characteristic which influences the Ksat and also measuring-errors, especially large for the Ksat-values, may decrease R2.

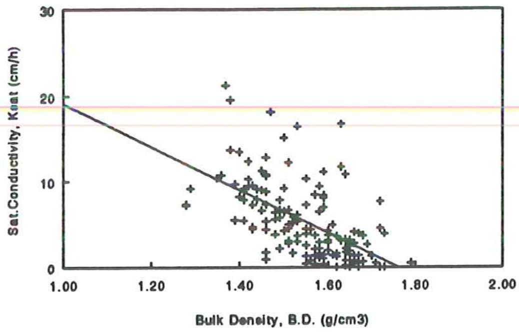


Figure 9.1: Linear regression-curve for BD and Ksat (R2=0.342648).
*Figure 9.1: Courbe de la régression linéaire entre la densité apparente et le Ksat (R2=0.342648).*

## 9.3 Linear regression between the percentage of clay and the percentage of sand and the saturated hydraulic conductivity

Figure 9.2 shows the linear regression-curves for percentages clay and Ksat-values and percentages sand and Ksat-values. Sample points in the curves consists of combinations of the percentage of clay or sand for a certain soil layer and the Ksat-value of that soil layer.

Figure 9.2 shows that a negative linear correlation is present between the percentage clay and Ksat characterized by a R2 of 0.16. This negative linear correlation can be explained by the

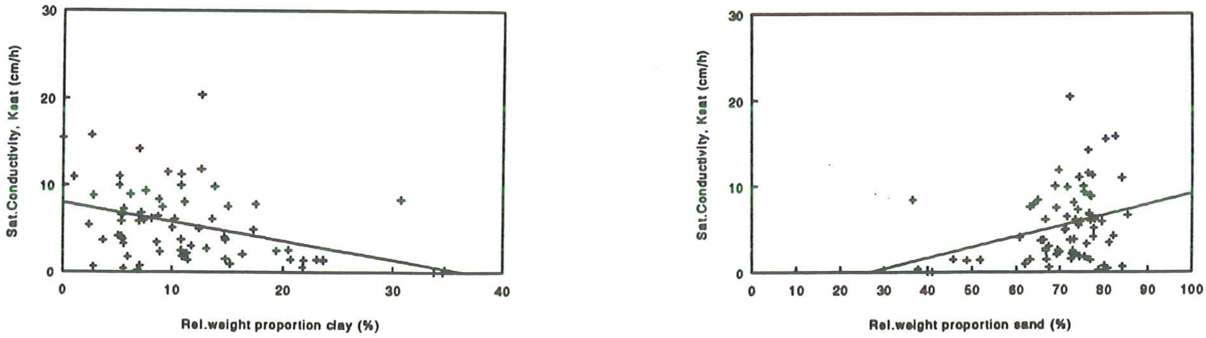


Figure 9.2: Linear regression-curves for the % clay and Ksat (R2=0.158245) and the % sand and Ksat (R2=0.096837).
*Figure 9.2: Courbe de la régression linéaire entre le taux d'argile et le Ksat (R2=0.158245) et entre le taux de sable et le Ksat (R2=0.096837).*

fact that often a lower porosity and related permeability is present if higher amounts of clay are present. The low R2 can be explained by the fact that in coarse textured soils percentages of clay do not influence permeability that much. Since the percentage of clay is not the only soil physical characteristic which influences the Ksat together with the fact that measuring-errors, especially for the Ksat-values, were made, may decrease R2.

Figure 9.2 shows that a positive linear correlation is present between the percentage of sand and Ksat characterized by a R2 of 0.10. This positive linear correlation can be explained by the fact that often a higher porosity and related permeability is present if higher amounts of sand are present, since the amount of large pores increases. The low R2 can be explained by the fact that percentages of sand do not fluctuate much in the research area and the percentage of sand is not the only soil physical characteristic which influences the Ksat. Measuring-errors, especially for the Ksat-values, were made, which also may decrease R2.

## 9.4 Linear regression between the percentage of clay and the volumetric moisture content at pF4.2

Figure 9.3 shows the linear regression-curve for values of the percentage clay and VMC-values at pF4.2. Sample points in the curve consists of combinations of the percentage of clay of a soil layer and the VMC-values at pF4.2 for that soil layer. Figure 9.3 shows that a positive linear correlation is present characterized by a high R2 of 0.84. This strong positive correlation explains that clay particles are responsible for the retention of soil-water with high suction-values. The VMC at pF4.2 is mainly determined by the clay percentage and related soil properties. Measuring-errors appearently do not much influence the correlation.

Figure 9.4 shows the linear regression-curves for percentages clay and VMC-values at pF4.2 for sub-unit GRvb (GRvb1-6, non-degraded phase) and sub-unit GSvb (GSvb1-9). The figure shows

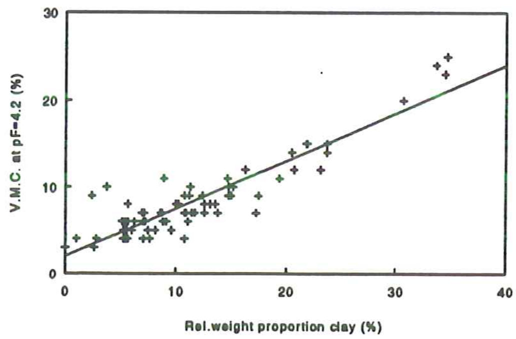


Figure 9.3: Linear regression-curve for the % clay and the VMC at pF4.2 (R2=0.835538).

*Figure 9.3: Coubre de la régression linéaire entre le teneur en argile et le taux d'humidité volumique à pF4.2 (R2=0.835538).*

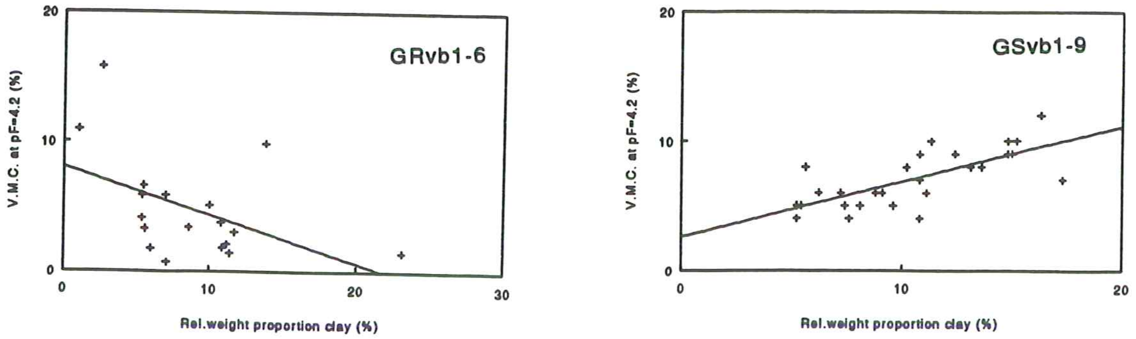


Figure 9.4: Linear regression-curves for the % clay and the VMC at pF4.2 for sub-unit GRvb (GRvb1-6, non-degraded phase) (R2=0.218777) and sub-unit GSvb (GSvb1-9) (R2=0.514202).

*Figure 9.4: Courbe des régressions linéaires entre teneur en argile (%) et les taux d'humidité volumique à pF4.2 pour la sub-unité GRvb, phase non-dégradée (GRvb1-6) (R2=0.218777) et la sub-unité GSvb (GSvb1-9) (R2=0.514202).*

that a negative linear correlation is present for sub-unit GRvb (GRvb1-6, non-degraded phase) characterized by a relatively low R2 of 0.22, which is remarkable. A small range in values for the clay percentage may explain part of this remarkable result. The figure shows that a positive linear correlation is present for sub-unit GSvb (GSvb1-9) characterized by a moderate R2 of 0.51. The correlation between percentage of clay and the VMC at pF4.2 appears to be weaker for the values of this sub-unit than for all values together. Explanations may be that the range in values is larger in the overall data, the correlation may be stronger for other sub-units than sub-unit GRvb (non-degraded phase) and sub-unit GSvb and deviating values have more influence if the amount of data is low.

## 9.5 Linear regression between the percentage of sand and sand and the volumetric moisture content at pF2

Figure 9.5 shows the linear regression-curve for all values of the percentage of sand and the VMC-values at pF2. Sample points in the curve consist of combinations of the percentage of sand of a soil layer and the VMC at pF2 for that soil layer. Figure 9.5 shows that a negative linear correlation is present characterized by a medium R2 of 0.46. The negative correlation explains that a higher sand percentage causes a lower water content at pF2. The VMC at pF2 is partly determined by the sand percentage and related soil properties. The percentage of sand is not the only soil physical property which determines the VMC at pF2 which may explain that no stronger correlation was found. Measuring-errors also may have caused a lower R2.

Figure 9.6 shows the linear regression-curves for percentages sand and the VMC-values at pF2 for sub-unit GRvb (GRvb1-6, non-degraded phase) and sub-unit GSvb (GSvb1-9). The figure shows that a negative linear correlation is present for sub-unit GRvb (GRvb1-6, non-degraded phase) characterized by a relatively high R2 of 0.61. A negative linear correlation is also present for sub-unit GSvb (GSvb1-9), however with a low R2 of 0.09. The difference in R2 may be explained by the fact that the VMC at pF2 is more influenced by the percentage of sand if higher percentages of sand (see table 6.1) are present.

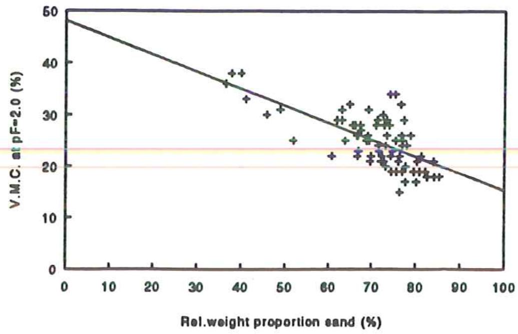


Figure 9.5: Linear regression-curve for the % sand and the VMC at pF2 (R2=0.457218).

*Figure 9.5: Courbe de la régression linéaire entre teneur en sable (%) et le taux d'humidité volumique à pF=2.0 (R2=0.457218).*

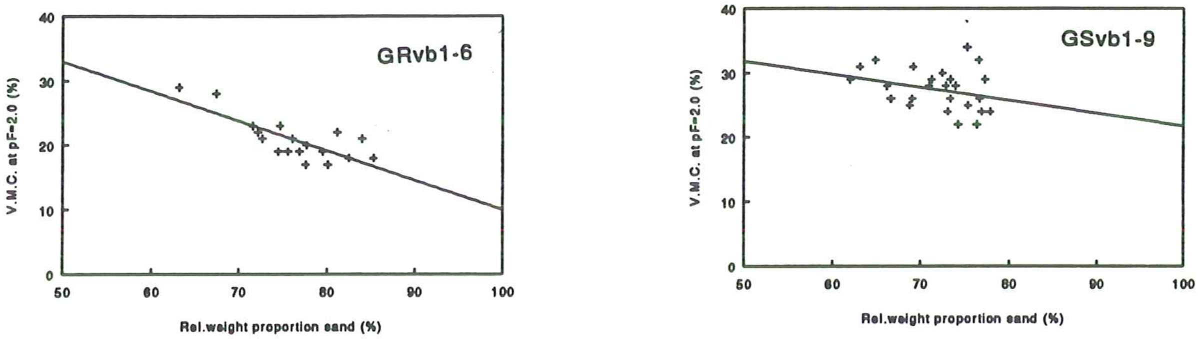


Figure 9.6: Linear regression-curves the % sand and the VMC at pF2 for sub-unit GRvb (GRvb1-6, non-degraded phase) (R2=0.60538) and sub-unit GSvb (GSvb1-9) (R2=0.091974).

*Figure 9.6: Courbes des régressions linéaires entre teneur en sable (%) et les taux d'humidité volumique à pF2.0 pour la sub-unité GRvb, phase non-dégradée (GRvb1-6) (R2=0.60538) et la sub-unité GSvb (GSvb1-9) (R2=0.091974).*

## 9.6 Linear regression between the percentage of clay and the percentage of sand and the available water capacity

Figure 9.7 shows the linear regression-curves for all values of the percentage of clay and AWC-values and all values of the percentage of sand and AWC-values.

A negative linear correlation is present between the percentage of clay and the AWC characterized by a low R2 of 0.09. This negative linear correlation, although very weak, is remarkable for coarse and moderately coarse textured soils as present in the research area. It may be the result of the fact that a higher clay percentages causes a higher VMC at pF4.2 (see section 6.4) which is not available for plants. An almost negligible positive linear correlation is present between the percentage of sand and the AWC characterized by a very low R2 of 0.02. A positive correlation may be the result of the fact that a higher percentage of sand causes a lower VMC at pF2 (see section 6.5)

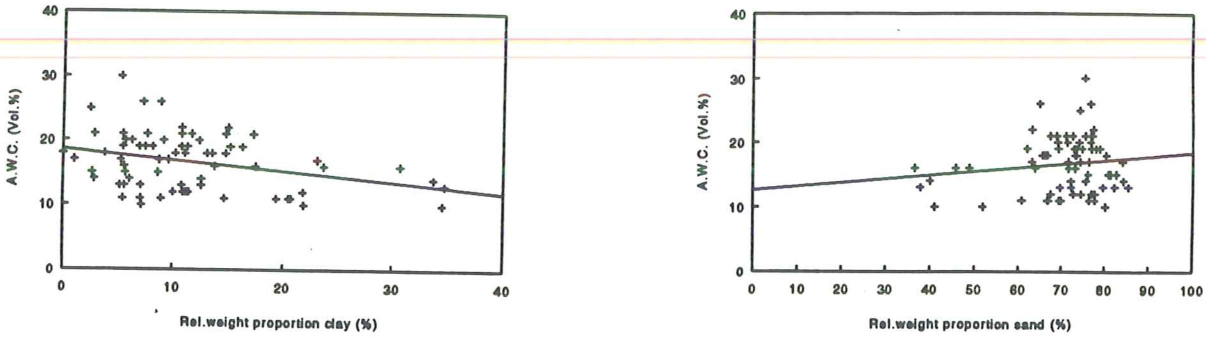


Figure 9.7: Linear regression-curves for the % clay and the AWC (R2=0.08981) and the % sand and the AWC (R2=0.020404).

*Figure 9.7: Courbes des régressions linéaires entre le taux d'argile (%) et la réserve utile (R2=0.08981) et entre le taux de sable et la réserve utile (R2=0.020404).*

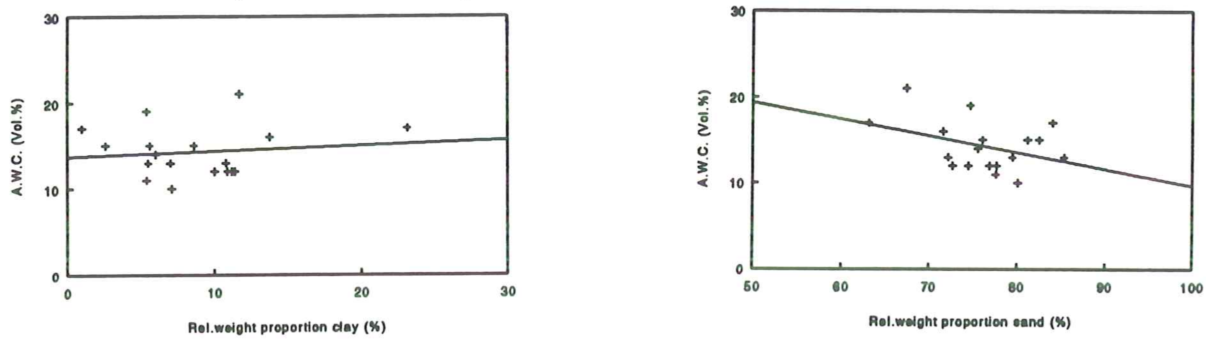


Figure 9.8: Linear regression-curves for the % clay and the AWC (R2=0.01238) and the % sand and the AWC (R=0.14475) for sub-unit GRvb (GRvb1-6, non-degraded phase).

*Figure 9.8: Courbes des régressions linéaires entre le taux d'argile (%) et la réserve utile (R2= 0.01238) et entre le taux de sable et la réserve utile (R2=0.14475) pour la sub-unité GRvb, phase non-dégradée (GRvb1-6).*

which is not available for plants. It can be concluded that the AWC for the research area may not be estimated from the percentages of clay and sand present, but must be related to the 'overall' texture.

Figure 9.8 shows linear regression-curves for percentage of clay and the AWC and percentage of sand and the AWC for sub-unit GRvb (GRvb1-6, non-degraded phase). The figure shows that a negligible positive linear correlation is present for the percentage of clay and the AWC with a very small R2 of 0.02. The figure also shows that a negative linear correlation is present for the percentage of sand and the AWC with a small R2 of 0.14. By comparing these R2-values with the R2-values of the overall data it may be concluded that for soils relatively rich in sand (see table 6.1) a higher percentage of sand causes a smaller AWC and a higher percentage of clay causes a larger AWC.

# 10 CONCLUSIONS

The late availability of the soil map used as basis for sampling, together with a lack of time are responsible for the fact that the sampling strategy was carried out incomplete. Inaccuracy and errors made during the processes of sampling, sample management and application of methods used for measuring soil physical properties have reduced data quality much more than it would have been the case if circumstances were optimum. For these reasons not all aims of the research were reached.

Results of the research do not give reason to conclude that a wrong sampling method was used. It is however difficult to judge if the method is optimum and it is a pity the sampling method was carried out incomplete.

Especially the Ksat- and SMC-data were expected to contain high 'error variations'. For this reason no effort was made for finding a 'transfer-function' between texture and the SMC.

In spite of these disappointments the research yielded a lot of useful data and information and gives insight into physical properties of some soils, which are better characterized now. It appeared that the soil physical properties of the sub-units GSvb and RSvb are slightly more favourable than that of sub-units GRvb (non-degraded phase) and GSvs. This may explain why the sub-units GSvb and RSvb are characterized by higher AWC-values than the other two. Especially the degraded phase of sub-unit GRvb has unfavourable soil physical properties and is characterized by low AWC-values.

The ANOVA and Mann-Whitney test proved that sub-unit GRvb (non-degraded phase) can be distinguished on account of some soil physical properties from sub-unit GSvb. The Mann-Whitney test proved that for the non-degraded phase 2 clusters can not be distinguished on account of soil physical properties. It can be concluded that variation within the sub-unit (only the non-degraded phase) is less than the variation between sub-unit GRvb (non-degraded phase) and sub-unit GSvb. The Mann-Whitney test further proved that a cluster of the degraded phase of sub-unit GRvb can be distinguished from a cluster of the non-degraded phase.

A medium to low negative linear correlation is present between all BD- and Ksat-data ($R2=0.34$). A high positive linear correlation is present between the overall data of the clay percentage and the VMC at pF4.2 ($R2=0.84$). Linear correlations may differ considerably per sub-unit. Regression analysis showed that for soils containing a relatively high percentage of sand, like the soils of sub-unit GRvb (non-degraded phase), a higher percentage of sand causes a lower AWC and a higher percentage of clay causes a higher AWC, which is not the case for other soils.

Although 'error variation' is present in the data-results, most variation is also caused by the 'natural' spatial variability of soil physical properties. Spatial variability of soil physical properties often may be high within small distances. This makes research of them difficult. Supplementary geostatistical research need to be carried out for getting a better insight in the spatial variability of soil physical properties in the area.

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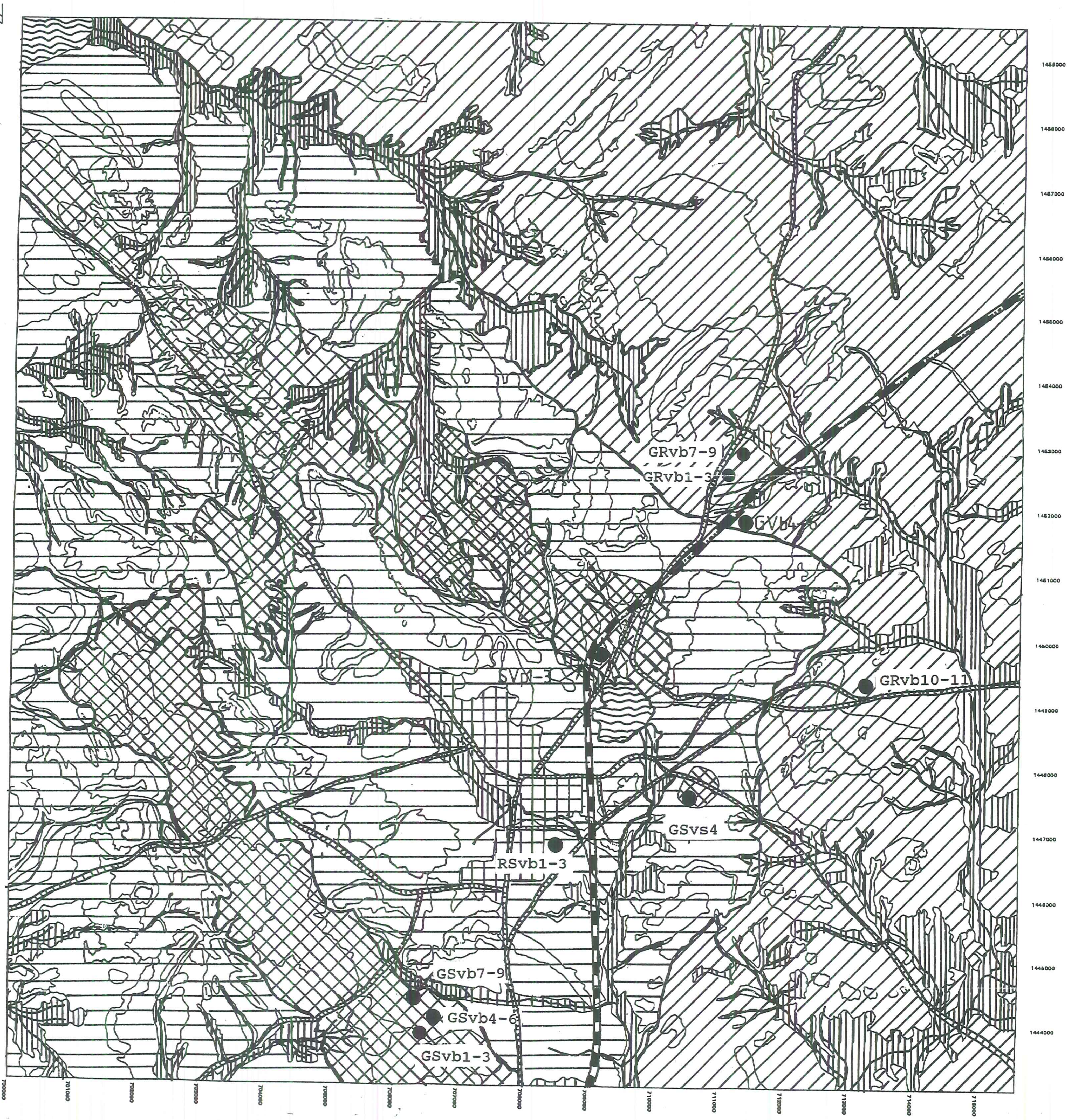
ANNEX A

# GEOLOGICAL - SOIL MAP OF THE AREA AROUND KAYA
## BURKINA FASO




LEGENDA

Granitic Area

Red Schist Area (Incl. Manganese Area)

Green Schist Area

Alluvium / Valley Bottom

Lake

Kaya Town

Road

Railway

Cluster with code Geological-Soil Subunit

0 1000 2000 3000 m

source: Legger et al., 1994.

ANNEX B: DESCRIPTIONS OF THE CLUSTERS OF SAMPLE PITS AND INDIVIDUAL SAMPLE PITS

A) SAMPLING IN THE GRANITIC AREA

A) Clusters in the geological-soil sub-unit 'granitic area, valley bare' (GRvb)

Cluster GRvb1-3 with the sample pits GRvb1, GRvb2 and GRvb3:

COORDINATES:UTM 710867 DMS 13-07-20 N.
1452441 DMS 1-03-31 W.
LAND ELEMENT:Valley (bas-fond)
LAND USE:Traditional dryland farming
CROP(S):Sorghum
REMARK(S):Around and within the field where the cluster is located at many places small dikes of stones or soil material are present to protect the soil against water erosion.

Sample pit GRvb1:

SLOPE:0-2 %
SURF.STONES:Less than 2 % very fine gravel
SEALING:Slight sealing (slightly hard crust less than 0.5cm thick)
EROSION:Slight water erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb1A1, GRvb1A2 and GRvb1A3
30-35 cm, 1 bag and rings GRvb1B1, GRvb1B2 and GRvb1B3
55-60 cm, 1 bag and rings GRvb1C1, GRvb1C2 and GRvb1C3
REMARK(S):-Till 25 cm relatively compact loamy material, deeper less compact more sandy material is present.
-soil material is from a depth of 30 cm to a at least 70 cm slightly moist.
-no stones and gravel present in the soil profile.
-In the upper 20 cm a very slight stratification is visible

Sample pit GRvb2:

SLOPE:0-2 %
SURF.STONES:Less than 2 % very fine gravel
SEALING:Slight sealing (slightly hard crust less than 0.5cm thick)
EROSION:Slight water erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb2A1, GRvb2A2 and GRvb2A3
30-35 cm, 1 bag and rings GRvb2B1, GRvb2B2 and GRvb2B3
55-60 cm, 1 bag and rings GRvb2C1, GRvb2C2 and GRvb2C3
REMARK(S):-Till 70cm a loamy sand profile.
-no stones and gravel present in the soil profile
-In the upper 20 cm a very slight stratification is visible where very thin more sandy and more loamy layers alternate each other.

Sample pit GRvb3:

SLOPE:0-2 %
SURF.STONES:Less than 2 % very fine gravel
SEALING:Almost no sealing
EROSION:Slight water erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb3A1, GRvb3A2 and GRvb3A3
30-35 cm, 1 bag and rings GRvb3B1, GRvb3B2 and GRvb3B3
55-60 cm, 1 bag and rings GRvb3C1, GRvb3C2 and GRvb3C3
REMARK(S):-Till 20 cm a relative sandy profile, till at least 70 cm a relative loamy profile.
-no stones and gravel present in the soil profile.

Cluster GRvb4-6 with the sample pits GRvb4, GRvb5 and GRvb6:

COORDINATES:UTM 710897 DMS 13-07-18 N.
1451381 DMS 1-03-18 W.
LAND ELEMENT:Valley (bas-fond)
LAND USE:Traditional dryland farming
CROP(S):Sorghum just harvested
REMARK(S):-Around the small fields in which the cluster is located small dikes of soil material on which herbs are growing are present to protect the soil against water erosion.
-Not far from the pits at many places big outcrops of granitic rock are present.
-Some harvest remainders are present on the small fields

Sample pit GRvb4:

SLOPE:0-2 %
SURF.STONES:Less than 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion, slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb4A1, GRvb4A2 and GRvb4A3
30-35 cm, 1 bag and rings GRvb4B1, GRvb4B2 and GRvb4B3
55-60 cm, 1 bag and rings GRvb4C1, GRvb4C2 and GRvb4C3
REMARK(S):-loamy sand profile,deeper in the profile more loamy.
-some fine gravel present in the soil profile.
-At depths of around 10 cm and around 25 cm very thin layers of very coarse sand and very fine gravel are present.

Sample pit GRvb5:

SLOPE:0-2 %
SURF.STONES:Less than 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion, very slight wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb5A1, GRvb5A2 and GRvb5A3
30-35 cm, 1 bag and rings GRvb5B1, GRvb5B2 and GRvb5B3
55-60 cm, 1 bag and rings GRvb5C1, GRvb5C2 and GRvb5C3
REMARK(S):-loamy sand profile.
-some percents of fine gravel present in the whole soil profile.

-At a depth of around 8 cm a very thin layer of very coarse sand and very fine gravel is present.

Sample pit GRvb6:

SLOPE:0-2 %
SURF.STONES:Less than 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion, very slight wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GRvb6A1, GRvb6A2 and GRvb6A3
30-35 cm, 1 bag and rings GRvb6B1, GRvb6B2 and GRvb6B3
55-60 cm, 1 bag and rings GRvb6C1, GRvb6C2 and GRvb6C3
REMARK(S):-loamy sand profile.
-some percents of fine gravel present in the whole soil profile.
-In the whole profile, but more especially till a depth of 20 cm some very thin layers of very coarse sand and very fine gravel are present.

Cluster GRvb7-9 with the sample pits GRvb7, GRvb8 and GRvb9:

COORDINATES:UTM 710892 DMS 13-07-57 N.
1452609 DMS 1-03-19 W.
LAND ELEMENT:Valley (bas-fond)
LAND USE:Degraded spot on field with traditional dryland farming
CROP(S):Around degraded spot sorghum is growing
REMARK(S):-The 3 pits are all located near the edges but still inside a degraded spot. The farmer told that crop growing was almost impossible here because of the compact cemented soil.
-some hundred metres south of the pits at many places big outcrops of granitic rock are present.

Sample pit GRvb7:

SLOPE:0-2 %
SURF.STONES:some 2-5 % gravel (partly pieces of granitic rock)
SEALING:Strong sealing (hard crust more than 0,5 cm thick)
EROSION:Moderate water erosion, slight wind erosion
SOIL DEPTH:At a depth of 50 cm an indurated layer of silcrete and iron stone concretions is present.
SAMPLES:5-10 cm, 1 bag and rings GRvb7A1, GRvb7A2 and GRvb7A3
30-35 cm, 1 bag and rings GRvb7B1, GRvb7B2 and GRvb7B3
55-60 cm, no samples;indurated layer
REMARK(S):-loamy sand profile very compact and cemented, which made digging of the pit a difficult job.
-almost no gravel present till a depth of 50 cm.
-soil profile has a relative red colour compared with the profiles of the clusters GRvb1-3 and GRvb4-6.

Sample pit GRvb8:

SLOPE:0-2 %
SURF.STONES:some 2-5 % gravel (partly pieces of granitic rock)
SEALING:Strong sealing (hard crust more than 0,5 cm thick)
EROSION:Moderate water erosion, slight wind erosion

SOIL DEPTH:At a depth of 60 cm an indurated layer of silcrete and iron stone concretions is present.
SAMPLES:5-10 cm, 1 bag and rings GRvb8A1, GRvb8A2 and GRvb8A3
30-35 cm, 1 bag and rings GRvb8B1, GRvb8B2 and GRvb8B3
55-60 cm, 1 bag and rings GRvb8C1, GRvb8C2 and GRvb8C3
REMARK(S):-loamy sand profile very compact and cemented, which made digging of the pit a difficult job.
-sporadic granitic gravel present till a depth of 60 cm.
-soil profile has a relative red colour compared with the profiles of the clusters GRvb1-3 and GRvb4-6.

Sample pit GRvb9:

SLOPE:0-2 %
SURF.STONES:some 2-5 % gravel (partly pieces of granitic rock)
SEALING:Strong sealing (hard crust more than 0,5 cm thick)
EROSION:Moderate water erosion, slight wind erosion
SOIL DEPTH:At a depth of 50 cm an indurated layer of silcrete and iron stone concretions is present.
SAMPLES:5-10 cm, 1 bag and rings GRvb9A1, GRvb9A2 and GRvb9A3
30-35 cm, 1 bag and rings GRvb9B1, GRvb9B2 and GRvb9B3
55-60 cm, no samples; indurated layer
REMARK(S):-loamy sand profile very compact and cemented, which made digging of the pit a difficult job.
-Almost no gravel present till a depth of 50 cm.
-soil profile has a relative red colour compared with the profiles of the clusters GRvb1-3 and GRvb4-6.

Cluster GRvb10-11 with the sample pits GRvb10 and GRvb11:

COORDINATES:UTM 713106 DMS 13-05-55 N.
1448889 DMS 1-02-03 W.
LAND ELEMENT:gentle slope of cuirasse (shallow iron crust)
LAND USE:Traditional (communal) grazing
REMARK(S):-

Sample pit GRvb10:

SLOPE:1-3 %
SURF.STONES:some 2-5 % small iron stone concretions
GRASS COVER:> 50 %
SEALING:slight sealing (slightly hard crust less than 0,5 cm thick)
EROSION:Slight water erosion
SOIL DEPTH:At a depth of 35 cm an indurated layer of iron stone concretions is present.
SAMPLES:5-10 cm, 1 bag and rings GRvb10A1, GRvb10A2 and GRvb10A3
30-35 cm, 1 bag and rings GRvb10B1, GRvb10B2 and GRvb10B3
55-60 cm, no samples; indurated layer
REMARK(S):-Upper 5 cm loamy sand texture, 5-35 cm a more loamy texture is present.
-Almost no gravel present till a depth of 30 cm; from 30-35 cm iron stone concretions are present.

Sample pit GRvb11:

SLOPE:1-3 %
SURF.STONES:some 5-10% small iron stone concretions
GRASS COVER:30-50 %
SEALING:slight sealing (slightly hard crust less than 0,5 cm thick)
EROSION:Slight to Moderate water erosion
SOIL DEPTH:At a depth of 15 cm an indurated layer of iron stone concretions is present.
SAMPLES:5-10 cm, 1 bag and rings GRvb11A1, GRvb11A2 and GRvb11A3
30-35 cm, no samples; indurated layer
55-60 cm, no samples; indurated layer
REMARK(S):-Till 15 cm a loamy profile is present.
-Frequent iron stone concretions are present in the profile.
-Sample pit is located some metres from degraded spots with no grass cover characterized by a thick crust and a lot of surface runoff.

B) SAMPLING IN THE GREENSCHIST AREA

B1) Clusters in the geological-soil sub-unit 'greenschist area, valley bare' (GSvb).

Cluster GSvb1-3 with the sample pits GSvb1, GSvb2 and GSvb3:

COORDINATES:UTM 706172 DMS 13-03-04 N.
1443599 DMS 1-05-55 W.
LAND ELEMENT:Valley (edge of valley, close to lower slope of high greenschist hills)
LAND USE:Traditional dryland farming
CROP(S):Sorghum just harvested
REMARK(S):-3 pits are located some 50 to 75 metres from the foot of high greenschist hills

Sample pit GSvb1:

SLOPE:4-5 %
SURF.STONES:some 5 % gravel and stones
SEALING:Almost no sealing
EROSION:very slightly water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb1A1, GSvb1A2 and GSvb1A3
30-35 cm, 1 bag and rings GSvb1B1, GSvb1B2 and GSvb1B3
55-60 cm, 1 bag and rings GSvb1C1, GSvb1C2 and GSvb1C3
REMARK(S):-loamy to sandy loam profile,deeper in the profile more loamy.
-some gravel present in the whole soil profile and from a depth of 60 cm to at least 70 cm little greenschist stones are present.

Sample pit GSvb2:

SLOPE:4-5 %
SURF.STONES:some 5 % gravel and stones
SEALING:Almost no sealing

EROSION:very slightly water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb2A1, GSvb2A2 and GSvb2A3
30-35 cm, 1 bag and rings GSvb2B1, GSvb2B2 and GSvb2B3
55-60 cm, 1 bag and rings GSvb2C1, GSvb2C2 and GSvb2C3
REMARK(S):-loamy to sandy loam profile,deeper in the profile more loamy.
-some gravel present in the whole soil profile and from a depth of 60 cm to at least 70 cm little greenschist stones are present.

Sample pit GSvb3:

SLOPE:4-5 %
SURF.STONES:some 5 % gravel and stones
SEALING:Almost no sealing
EROSION:very slightly water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb3A1, GSvb3A2 and GSvb3A3
30-35 cm, 1 bag and rings GSvb3B1, GSvb3B2 and GSvb3B3
55-60 cm, 1 bag and rings GSvb3C1, GSvb3C2 and GSvb3C3
REMARK(S):-loamy to sandy loam profile,deeper in the profile more loamy.
-some gravel present in the whole soil profile and from a depth of 60 cm to at least 70 cm little greenschist stones are present.

Cluster GSvb4-6 with the sample pits GSvb4, GSvb5 and GSvb6:

COORDINATES:UTM 706334 DMS 13-03-11 N.
1443782 DMS 1-05-50 W.
LAND ELEMENT:Valley (around 150 metres from lower slope greenschist hills)
LAND USE:Traditional dryland farming
CROP(S):Sorghum just harvested
REMARK(S):-3 pits are located some 150 metres from the foot of high greenschist hills.
-some harvest remainders are present on the field in which the cluster is located

Sample pit GSvb4:

SLOPE:around 3 %
SURF.STONES:some 2 % gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb4A1, GSvb4A2 and GSvb4A3
30-35 cm, 1 bag and rings GSvb4B1, GSvb4B2 and GSvb4B3
55-60 cm, 1 bag and rings GSvb4C1, GSvb4C2 and GSvb4C3
REMARK(S):-Till a depth of around 15 cm relatively dark coloured fine sandy layer (horizon) present;From a depth of 15 cm till at least 70 cm a loamy fine sand texture is present.
-The texture of this sample pit seems to be a bit finer than the textures of the sample pits of cluster GSvb1-3.
-In the whole profile some pieces of greenschist are present (low concentration).

-At a depth of some 35 cm a thin stony layer is present.

Sample pit GSvb5:

SLOPE:around 3 %
SURF.STONES:some 2 % gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb5A1, GSvb5A2 and GSvb5A3
30-35 cm, 1 bag and rings GSvb5B1, GSvb5B2 and GSvb5B3
55-60 cm, 1 bag and rings GSvb5C1, GSvb5C2 and GSvb5C3
REMARK(S):-Till a depth of around 15 cm relatively dark coloured fine sandy layer (horizon) present;From a depth of 15 cm till at least 70 cm a loamy fine sand texture is present.
-The texture of this sample pit seems to be a bit finer than the textures of the sample pits of cluster GSvb1-3.
-In the whole profile some pieces of greenschist are present (Low concentration).

Sample pit GSvb6:

SLOPE:around 3 %
SURF.STONES:some 2 % gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb6A1, GSvb6A2 and GSvb6A3
30-35 cm, 1 bag and rings GSvb6B1, GSvb6B2 and GSvb6B3
55-60 cm, 1 bag and rings GSvb6C1, GSvb6C2 and GSvb6C3
REMARK(S):-Till a depth of around 15 cm relatively dark coloured fine sandy layer (horizon) present;From a depth of 15 cm till at least 70 cm a loamy fine sand texture is present.
-The texture of this sample pit seems to be a bit finer than the textures of the sample pits of cluster GSvb1-3.
-In the whole profile some pieces of greenschist are present (Low concentration).

Cluster GSvb7-9 with the sample pits GSvb7, GSvb8 and GSvb9:

COORDINATES:UTM 706356 DMS 13-03-19 N.
1444025 DMS 1-05-49 W.
LAND ELEMENT:Valley (around 500 metres from lower slope greenschist hills)
LAND USE:Traditional dryland farming
CROP(S):Sorghum just harvested
REMARK(S):-3 pits are located some 500 metres from the foot of high greenschist hills.
-some harvest remainders are present on the field in which the cluster is located

Sample pit GSvb7:

SLOPE:around 1-2 %
SURF.STONES:Almost no surface stones are present

SEALING:At some places around pit slight sealing
EROSION:very slight water erosion, slight wind erosion
SOIL DEPTH:Deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb7A1, GSvb7A2 and GSvb7A3
30-35 cm, 1 bag and rings GSvb7B1, GSvb7B2 and GSvb7B3
55-60 cm, 1 bag and rings GSvb7C1, GSvb7C2 and GSvb7C3
REMARK(S):-Top layer has a loamy sand texture gradually changing to a more loamy texture deeper in the profile.
-A relatively loose top layer is present and a relatively compact and cemented deeper profile is present. The top layer is less compact and the deeper profile however is more compact than for the sample pits GSvb8 and GSvb9.
-In the deeper profile (40-70 cm) concretions of iron and manganese are found.

Sample pit GSvb8:

SLOPE:around 1-2 %
SURF.STONES:Almost no surface stones are present
SEALING:At some places around pit slight sealing
EROSION:very slight water erosion, slight wind erosion
SOIL DEPTH:Deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb8A1, GSvb8A2 and GSvb8A3
30-35 cm, 1 bag and rings GSvb8B1, GSvb8B2 and GSvb8B3
55-60 cm, 1 bag and rings GSvb8C1, GSvb8C2 and GSvb8C3
REMARK(S):-A loamy sand texture is present in the whole profile.
-A relatively loose top layer (0-5 cm) is present. From a depth of 5 cm till 40 cm the profile is very slightly compact, but compacter than for sample pit GSvb7. From a depth of 40 cm the profile is slightly compact, but less compact than for sample pit GSvb7.
-From a depth of 30 cm the profile is slightly moist.

Sample pit GSvb9:

SLOPE:around 1-2 %
SURF.STONES:Almost no surface stones are present
SEALING:At some places around pit slight sealing
EROSION:very slight water erosion, slight wind erosion
SOIL DEPTH:Deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvb9A1, GSvb9A2 and GSvb9A3
30-35 cm, 1 bag and rings GSvb9B1, GSvb9B2 and GSvb9B3
55-60 cm, 1 bag and rings GSvb9C1, GSvb9C2 and GSvb9C3
REMARK(S):-A loamy sand texture is present in the whole profile.
-A relatively loose top layer (0-5 cm) is present. From a depth of 5 cm till 40 cm the profile is slightly compact, compacter than for sample pit GSvb7 and a bit compacter than for sample pit SVb8. From a depth of 40 cm the profile is slightly compact, but less compact than for sample pit GSvb7.
-From a depth of 30 cm the profile is slightly moist.

B2) Cluster and sample pit in the geological-soil sub-unit 'greenschist area, valley stone' (GSvs)

Cluster GSvs1-3 with the sample pits GSvs1, GSvs2 and GSvs3:

COORDINATES:UTM 709133 DMS 13-06-24 N.
1449729 DMS 1-04-15 W.
LAND ELEMENT:Valley (edge of valley, close to the lower slope of of a small greenschist hill)
REMARK(S):-3 pits are located close to a small greenschist hill with greenschist outcrops at its top.
-2 pits (GSvs2 and GSvs3) were located on a field and 1 pit (GSvs1) was located in communal grazing area.

Sample pit GSvs1:

LAND USE:Traditional (communal) grazing
GRASS COVER:> 70 %
SLOPE:Around 3 %
SURF.STONES:some 10 % gravel and stones
SEALING:very slightly sealing
EROSION:very slightly water erosion
SOIL DEPTH:65 cm
SAMPLES:5-10 cm, 1 bag and rings GSvs1A1, GSvs1A2 and GSvs1A3
30-35 cm, 1 bag and rings GSvs1B1, GSvs1B2 and GSvs1B3
55-60 cm, 1 bag and rings GSvs1C1, GSvs1C2 and GSvs1C3
REMARK(S):-loamy to clay loam profile.
-Some gravel is present in the whole soil profile and from a depth of 50 cm little greenschist stones are present.
-All around small dikes of stones are present to protect the soil against erosion.

Sample pit GSvs2:

LAND USE:Traditional dryland farming
CROP(S):Sorghum
SLOPE:Around 2 %
SURF.STONES:some 5-10 % gravel and stones
SEALING:very slightly sealing
EROSION:very slightly water erosion
SOIL DEPTH:30 cm
SAMPLES:5-10 cm, 1 bag and rings GSvs2A1, GSvs2A2 and GSvs2A3
30-35 cm, no samples, bedrock
55-60 cm, no samples, bedrock
REMARK(S):-loamy profile.
- Gravel is present in the whole soil profile and from a depth of 10 cm little greenschist stones are present.
-Around the field a small dike of stones is present to protect the soil against water erosion. The stones were removed from the field to make it better workable. For this reason the amount of surface stones outside the field is much higher than on the field.

Sample pit GSvs3:

LAND USE:Traditional dryland farming
CROP(S):Sorghum/haricot vert
SLOPE:Around 2 %
SURF.STONES:some 15 % gravel and stones
SEALING:very slightly sealing
EROSION:very slightly water erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings GSvs3A1, GSvs3A2 and GSvs3A3
30-35 cm, 1 bag and rings GSvs3B1, GSvs3B2 and GSvs3B3
55-60 cm, 1 bag and rings GSvs3C1, GSvs3C2 and GSvs3C3
REMARK(S):-loamy profile.
-Gravel and a few stones are present in the whole soil profile.
-Around the field a small dike of stones is present to protect the soil against water erosion.
-From a depth of 40 cm some white coloured concretions are present.

Sample pit GSvs4 (single pit not part of a cluster):

COORDINATES:UTM 710364 DMS 13-05-07 N.
1447377 DMS 1-03-36 W.
LAND USE:Traditional dryland farming
CROP(S):Sorghum
LAND ELEMENT:Valley (edge of valley, close to the lower slope of of a small greenschist hill)
SLOPE:Around 3 %
SURF.STONES:some 30 % gravel and stones
SEALING:No sealing
EROSION:very slightly water erosion
SOIL DEPTH:60 cm
SAMPLES:5-10 cm, 1 bag and rings GSvs4A1, GSvs4A2 and GSvs4A3
30-35 cm, no samples, too many stones
55-60 cm, no samples, too many stones
REMARK(S):-loamy to clay loam profile.
-Till a depth of 15 cm some gravel and some stones are present.
-From a depth of 15 cm till 60 cm a lot of gravel and many stones are present under which angular greenschist (and also redschist ?!) stones and silcrete concretions.
-Around the field a small dike of stones is present to protect the soil against erosion.

C) SAMPLING IN THE REDSCHIST AREA

C1) Cluster in the geological-soil sub-unit 'redschist area, valley bare' (RSvb)

Cluster RSvb1-3 with the sample pits RSvb1, RSvb2 and RSvb3:

COORDINATES:UTM 708445 DMS 13-04-35 N.
1446373 DMS 1-04-39 W.
LAND ELEMENT:Valley
LAND USE:Traditional dryland farming

CROP(S):Sorghum just harvested
REMARK(S):-some harvest remainders are present on the fields in which the cluster is located
-cluster is located in valley between two cuirasse-redschist hills (redschists are covered by an ironcrust).

Sample pit RSvb1:

SLOPE:around 1 %
SURF.STONES:< 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings RSvb1A1, RSvb1A2 and RSvb1A3
30-35 cm, 1 bag and rings RSvb1B1, RSvb1B2 and RSvb1B3
55-60 cm, 1 bag and rings RSvb1C1, RSvb1C2 and RSvb1C3
REMARK(S):-Sandy loam texture is present in the whole profile.
-In the whole profile very few stones and sporadic fine gravel are present.
-From a depth of 50 cm a red coloured cemented and compact layer is present (iron crust in development). In sample pit RSvb2 such a layer is present between a depth of 20-45 cm.

Sample pit RSvb2:

SLOPE:around 1 %
SURF.STONES:< 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings RSvb2A1, RSvb2A2 and RSvb2A3
30-35 cm, 1 bag and rings RSvb2B1, RSvb2B2 and RSvb2B3
55-60 cm, 1 bag and rings RSvb2C1, RSvb2C2 and RSvb2C3
REMARK(S):-Sandy loam texture is present in the whole profile.
-In the whole profile very few stones and sporadic fine gravel are present.
-Between a depth of 20 and 45 cm a red coloured cemented and compact layer is present (iron crust in development). In sample pit RSvb1 such a layer is present from a depth of 50 cm.

Sample pit RSvb3:

SLOPE:around 1 %
SURF.STONES:< 2 % fine gravel
SEALING:Almost no sealing
EROSION:Almost no water erosion,very slightly wind erosion
SOIL DEPTH:deeper than 70 cm
SAMPLES:5-10 cm, 1 bag and rings RSvb3A1, RSvb3A2 and RSvb3A3
30-35 cm, 1 bag and rings RSvb3B1, RSvb3B2 and RSvb3B3
55-60 cm, 1 bag and rings RSvb3C1, RSvb3C2 and RSvb3C3
REMARK(S):-Sandy loam texture is present in the whole profile.
-In the whole profile very few stones and sporadic fine gravel are present.
-Till a depth of 20 cm the profile is slightly compact. Between a depth of 20 and 45 cm a red coloured layer is present, which is not cemented and compact like in sample pit RSvb2. The deeper

profile, from a depth of 45 cm is very loose.
-From a depth of 45 cm the profile is wet. The site of this sample pit is a great part of the afternoon located in the shadow of some big trees. The best explanation for the wet layer however may be that subsurface flow from the adjacent cuirasse-hill is present.

# ANNEX C: RESULTS OF MEASUREMENT OF THE SOIL PHYSICAL PROPERTIES

## ANNEX C1: Results of measurement of texture

In this annex the texture or grain size distribution, measured for the different soil layers (S.L.), A (5-10cm), B (30-35cm) C (55-60cm), of the different clusters, is given. In each table of this annex the relative weight proportions of the various size classes are given as weight percentages (%) of the the total mass of the soil samples. For each soil layer the texure class (T.Cl.), according to the texture triangle of the Soil Survey Staff (1951) of the United States Department of Agriculture (USDA), is given.

Table C1.1:Measured textures for cluster GRvb1-3.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GRvb1A | 11.7 | 3.8 | 17.1 | 66.9 | 0.5 | SL |
| GRvb1B | 5.4 | 8.0 | 9.0 | 76.6 | 1.0 | LS |
| GRvb1C | 7.1 | 4.9 | 8.0 | 78.2 | 1.9 | LS |
| GRvb2A | 2.6 | 3.6 | 11.4 | 82.1 | 0.4 | LS |
| GRvb2B | 5.4 | 6.0 | 13.7 | 74.3 | 0.4 | LS |
| GRvb2C | 10.9 | 4.8 | 9.9 | 73.5 | 1.0 | SL |
| GRvb3A | 1.0 | 0.2 | 15.0 | 83.6 | 0.4 | LS |
| GRvb3B | 13.8 | 4.9 | 9.9 | 70.1 | 1.5 | SL |
| GRvb3C | 23.1 | 5.1 | 9.8 | 59.9 | 2.2 | SCL |

Table C1.2:Measured textures for cluster GRvb4-6.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GRvb4A | 11.4 | 2.4 | 9.4 | 74.8 | 2.1 | SL |
| GRvb4B | 8.6 | 2.7 | 7.4 | 78.8 | 2.4 | LS |
| GRvb4C | 10.8 | 4.5 | 12.4 | 70.7 | 1.5 | SL |
| GRvb5A | 7.0 | 3.7 | 9.8 | 76.0 | 3.5 | SL |
| GRvb5B | 5.5 | 3.5 | 5.9 | 82.6 | 2.7 | LS |
| GRvb5C | 10.0 | 4.5 | 7.9 | 75.9 | 1.8 | SL |
| GRvb6A | 6.0 | 5.0 | 13.5 | 74.7 | 0.9 | SL |
| GRvb6B | 5.6 | 6.0 | 12.3 | 75.4 | 0.7 | SL |
| GRvb6C | 11.2 | 4.5 | 11.7 | 70.4 | 2.3 | SL |

Table C1.3:Measured textures for cluster GRvb7-9.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GRvb7A | 5.6 | 5.4 | 8.2 | 77.8 | 3.0 | LS |
| GRvb7B | 21.9 | 10.3 | 16.0 | 50.6 | 1.3 | SCL |
| GRvb8A | 6.9 | 4.9 | 9.4 | 77.0 | 1.8 | LS |
| GRvb8B | 20.7 | 4.9 | 7.5 | 65.5 | 1.4 | SCL |
| GRvb8C | 21.8 | 4.4 | 6.5 | 66.4 | 1.1 | SCL |
| GRvb9A | 2.8 | 2.8 | 10.4 | 82.6 | 1.6 | LS |
| GRvb9B | 20.5 | 5.3 | 4.9 | 67.9 | 1.5 | SCL |

Table C1.4:Measured textures for cluster GRvb10-11.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GRvb10A | 5.1 | 4.9 | 7.7 | 4.9 | 80.7 | LS |
| GRvb10B | 19.4 | 5.5 | 8.4 | 5.5 | 64.5 | SL |
| GRvb11A | 7.0 | 6.2 | 10.3 | 6.2 | 74.0 | LS |

Table C1.5:Measured textures for cluster GSvb1-3.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GSvb1A | 17.3 | 2.0 | 9.8 | 70.5 | 0.5 | SL |
| GSvb1B | 12.4 | 3.6 | 12.8 | 71.2 | 0.1 | SL |
| GSvb1C | 14.8 | 2.8 | 10.0 | 72.4 | 0.1 | SL |
| GSvb2A | 11.1 | 4.4 | 11.5 | 72.4 | 0.7 | SL |
| GSvb2B | 10.2 | 3.4 | 13.2 | 73.1 | 0.3 | SL |
| GSvb2C | 10.8 | 3.4 | 13.0 | 72.6 | 0.3 | SL |
| GSvb3A | 10.8 | 2.4 | 9.6 | 76.9 | 0.4 | SL |
| GSvb3B | 11.3 | 2.8 | 12.5 | 72.8 | 0.6 | SL |
| GSvb3C | 16.3 | 4.2 | 10.3 | 68.6 | 0.6 | SL |

Table C1.6:Measured textures for cluster GSvb4-6.

| S.L. | < 2$\mu$m | 2-20$\mu$m | 20-50$\mu$m | 50$\mu$m-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GSvb4A | 10.8 | 6.8 | 13.8 | 68.5 | 0.3 | SL |
| GSvb4B | 9.6 | 3.6 | 10.6 | 76.2 | 0.2 | LS |
| GSvb4C | 5.2 | 4.2 | 15.4 | 75.1 | 0.2 | SL |
| GSvb5A | 7.6 | 4.2 | 13.0 | 75.2 | 0.2 | SL |
| GSvb5B | 5.2 | 8.2 | 12.5 | 73.7 | 0.6 | SL |
| GSvb5C | 7.4 | 3.4 | 12.4 | 76.6 | 0.3 | LS |
| GSvb6A | 8.1 | 5.2 | 8.9 | 77.0 | 0.9 | LS |
| GSvb6B | 13.6 | 5.6 | 14.5 | 66.2 | 0.4 | SL |
| GSvb6C | 13.1 | 4.2 | 15.9 | 66.3 | 0.4 | SL |

Table C1.7:Measured textures for cluster GSvb7-9.

| S.L. | < 2$\mu$m | 2-20$\mu$m | 20-50$\mu$m | 50$\mu$m-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GSvb7A | 5.6 | 7.6 | 12.9 | 73.3 | 0.7 | SL |
| GSvb7B | 14.8 | 7.7 | 11.3 | 65.1 | 1.1 | SL |
| GSvb7C | 15.2 | 8.3 | 14.2 | 61.1 | 0.9 | SL |
| GSvb8A | 9.1 | 6.2 | 15.7 | 68.3 | 0.8 | SL |
| GSvb8B | 6.2 | 4.0 | 13.2 | 76.4 | 0.3 | LS |
| GSvb8C | 5.4 | 3.8 | 14.1 | 76.2 | 0.5 | LS |
| GSvb9A | 8.8 | 10.4 | 15.9 | 64.5 | 0.4 | SL |
| GSvb9B | 15.0 | 6.6 | 15.6 | 62.8 | 0.3 | SL |
| GSvb9C | 7.2 | 4.0 | 12.3 | 76.0 | 0.6 | LS |

Table C1.8:Measured textures for cluster GSvs1-3.

| S.L. | < 2$\mu$m | 2-20$\mu$m | 20-50$\mu$m | 50$\mu$m-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GSvs1A | 14.7 | 20.6 | 3.9 | 58.9 | 1.9 | SL |
| GSvs1B | 34.5 | 9.8 | 14.8 | 39.4 | 1.7 | CL |
| GSvs1C | 34.7 | 11.7 | 16.0 | 35.1 | 2.7 | CL |
| GSvs2A | 23.7 | 10.4 | 17.2 | 45.4 | 3.5 | SCL |
| GSvs3A | 23.7 | 11.5 | 19.2 | 44.5 | 1.3 | L |
| GSvs3B | 30.7 | 12.6 | 20.3 | 36.1 | 0.5 | CL |
| GSvs3C | 33.7 | 12.0 | 14.4 | 38.5 | 1.5 | CL |

Table C1.9:Measured texture for sample pit GSvs4.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| GSvs4A | 8.9 | 6.3 | 14.9 | 60.5 | 9.3 | SL |

Table C1.10:Measured textures for cluster RSvb1-3.

| S.L. | < 2μm | 2-20μm | 20-50μm | 50μm-1mm | 1-2mm | T.Cl. |
|---|---|---|---|---|---|---|
| RSvb1A | 2.8 | 4.0 | 16.3 | 76.4 | 0.7 | LS |
| RSvb1B | 8.7 | 6.9 | 13.2 | 69.8 | 1.7 | SL |
| RSvb1C | 3.7 | 18.5 | 12.1 | 63.2 | 2.4 | SL |
| RSvb2A | 5.5 | 4.8 | 16.5 | 72.4 | 0.8 | SL |
| RSvb2B | 17.5 | 7.3 | 11.4 | 62.1 | 1.8 | SL |
| RSvb2C | 2.4 | 7.1 | 16.4 | 72.6 | 1.6 | SL |
| RSvb3A | 0.0 | 5.2 | 14.8 | 79.9 | 0.4 | LS |
| RSvb3B | 12.6 | 3.7 | 11.9 | 71.9 | 0.2 | SL |
| RSvb3C | 12.6 | 3.6 | 14.4 | 69.4 | 0.2 | SL |

ANNEX C2: Results of measurement of the bulk density and the saturated hydraulic conductivity

In the next tables the measured values of the bulk density (BD) and saturated hydraulic conductivity (Ksat) for the different soil layers, A (5-10cm), B (30-35cm) and C (55-60cm) of the different clusters are given. For all the tables it applies that BD1, BD2 and BD3 are indicating the values of the BD for respectively the first, second and third sample taken out of a certain soil layer. Ksat1 and Ksat2 are indicating the values of the Ksat for respectively the first and second sample taken out of the soil layer.

Table C2.1:Measured BD- and Ksat-values for the cluster GRvb1-3.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GRvb1A | 1.48 | 1.49 | 1.51 | 3.84 | 2.17 |
| GRvb1B | 1.67 | 1.60 | 1.60 | 3.92 | 4.28 |
| GRvb1C | 1.46 | 1.71 | 1.51 | 0.94 | 0.46 |
| GRvb2A | 1.50 | 1.53 | 1.49 | 15.14 | 16.45 |
| GRvb2B | 1.43 | 1.46 | 1.49 | 4.45 | 7.33 |
| GRvb2C | 1.59 | 1.64 | 1.58 | 1.41 | 2.21 |
| GRvb3A | 1.59 | 1.64 | 1.61 | 11.13 | 10.81 |
| GRvb3B | 1.58 | 1.55 | 1.56 | 9.44 | 10.33 |
| GRvb3C | 1.61 | 1.62 | 1.63 | 1.39 | 1.56 |

Table C2.2:Measured BD- and Ksat-values for the cluster GRvb4-6.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GRvb4A | 1.59 | 1.46 | 1.59 | 1.02 | 1.75 |
| GRvb4B | 1.53 | 1.60 | 1.67 | 3.67 | 3.14 |
| GRvb4C | 1.63 | 1.56 | 1.64 | 3.08 | 4.41 |
| GRvb5A | 1.66 | 1.72 | 1.67 | 4.07 | 7.64 |
| GRvb5B | 1.52 | 1.59 | 1.59 | 5.16 | 8.09 |
| GRvb5C | 1.64 | 1.59 | 1.62 | 3.23 | 6.99 |
| GRvb6A | 1.55 | 1.64 | 1.60 | 1.33 | 2.21 |
| GRvb6B | 1.60 | 1.66 | 1.62 | 3.77 | 2.76 |
| GRvb6C | 1.68 | 1.79 | 1.68 | 3.67 | 0.49 |

Table C2.3:Measured BD- and Ksat-values for the cluster GRvb7-9.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GRvb7A | 1.57 | 1.67 | 1.64 | 0.31 | 0.46 |
| GRvb7B | 1.65 | 1.66 | 1.61 | 1.92 | 0.79 |
| GRvb8A | 1.64 | 1.65 | 1.64 | 0.20 | 0.21 |
| GRvb8B | 1.64 | 1.62 | 1.59 | 1.72 | 1.24 |
| GRvb8C | 1.66 | 1.68 | 1.68 | 0.44 | 0.64 |
| GRvb9A | 1.55 | 1.56 | 1.54 | 0.42 | 0.80 |
| GRvb9B | 1.69 | 1.65 | 1.65 | 2.65 | 2.48 |

Table C2.4:Measured BD- and Ksat-values for the cluster GRvb10-11.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GRvb10A | 1.72 | 1.73 | 1.75 | 4.51 | 3.91 |
| GRvb10B | 1.62 | 1.66 | 1.72 | 3.61 | 1.30 |
| GRvb11A | 1.63 | 1.63 | 1.57 | 16.70 | 11.70 |

Table C2.5:Measured BD- and Ksat-values for the cluster GSvb1-3.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GSvb1A | 1.52 | 1.55 | 1.49 | 5.29 | 4.49 |
| GSvb1B | 1.43 | 1.53 | 1.50 | 4.69 | 5.34 |
| GSvb1C | 1.65 | 1.58 | 1.58 | 1.42 | 1.56 |
| GSvb2A | 1.40 | 1.44 | 1.43 | 8.26 | 7.94 |
| GSvb2B | 1.53 | 1.50 | 1.55 | 5.63 | 6.59 |
| GSvb2C | 1.60 | 1.53 | 1.60 | 1.96 | 3.01 |
| GSvb3A | 1.41 | 1.38 | 1.48 | 8.84 | 13.73 |
| GSvb3B | 1.58 | 1.57 | 1.63 | 2.20 | 2.11 |
| GSvb3C | 1.57 | 1.51 | 1.64 | 1.37 | 2.77 |

Table C2.6:Measured BD- and Ksat-values for the cluster GSvb4-6.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GSvb4A | 1.29 | 1.36 | 1.35 | 9.23 | 10.78 |
| GSvb4B | 1.46 | 1.51 | 1.38 | 10.84 | 12.23 |
| GSvb4C | 1.35 | 1.43 | 1.51 | 10.40 | 9.55 |
| GSvb5A | 1.41 | 1.42 | 1.42 | 9.17 | 9.48 |
| GSvb5B | 1.39 | 1.42 | 1.40 | 9.70 | 12.36 |
| GSvb5C | 1.53 | 1.52 | 1.49 | 6.11 | 5.84 |
| GSvb6A | 1.49 | 1.48 | 1.43 | 6.71 | 5.60 |
| GSvb6B | 1.50 | 1.49 | 1.52 | 6.46 | 5.80 |
| GSvb6C | 1.55 | 1.58 | 1.59 | 2.56 | 2.90 |

Table C2.7:Measured BD- and Ksat-values for the cluster GSvb7-9.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GSvb7A | 1.28 | 1.28 | 1.30 | 7.35 | 7.23 |
| GSvb7B | 1.46 | 1.51 | 1.44 | 4.39 | 3.08 |
| GSvb7C | 1.64 | 1.58 | 1.48 | 0.80 | 1.08 |
| GSvb8A | 1.46 | 1.50 | 1.44 | 10.68 | 4.25 |
| GSvb8B | 1.44 | 1.46 | 1.47 | 9.13 | 8.83 |
| GSvb8C | 1.58 | 1.51 | 1.50 | 6.50 | 6.68 |
| GSvb9A | 1.45 | 1.41 | 1.50 | 11.30 | 5.46 |
| GSvb9B | 1.41 | 1.43 | 1.48 | 7.87 | 7.31 |
| GSvb9C | 1.55 | 1.48 | 1.51 | 7.24 | 6.40 |

Table C2.8:Measured BD- and Ksat-values for the cluster GSvs1-3.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GSvs1A | 1.61 | 1.65 | 1.70 | 4.95 | 3.13 |
| GSvs1B | 1.67 | 1.65 | 1.57 | 0.00 | 0.00 |
| GSvs1C | 1.59 | 1.73 | 1.73 | 0.30 | 0.00 |
| GSvs2A | 1.70 | 1.67 | 1.68 | 1.29 | 1.34 |
| GSvs3A | 1.52 | 1.57 | 1.55 | 1.66 | 1.29 |
| GSvs3B | 1.59 | 1.62 | 1.60 | 8.37 | 0.00 |
| GSvs3C | 1.72 | 1.72 | 1.78 | 0.00 | 0.00 |

Table C2.9:Measured BD- and Ksat-values for sample pit GSvs4.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| GSvs4A | 1.65 | 1.58 | 1.61 | 2.53 | 2.15 |

Table C2.10:Measured BD- and Ksat-values for cluster RSvb1-3.

| Soil Layer | BD1 (g/cm3) | BD2 (g/cm3) | BD3 (g/cm3) | Ksat1 (cm/h) | Ksat2 (cm/h) |
|---|---|---|---|---|---|
| RSvb1A | 1.57 | 1.50 | 1.53 | 8.45 | 9.23 |
| RSvb1B | 1.49 | 1.51 | 1.45 | 7.84 | 5.01 |
| RSvb1C | 1.60 | 1.51 | 1.58 | 2.83 | 4.54 |
| RSvb2A | 1.55 | 1.57 | 1.48 | 3.91 | 3.71 |
| RSvb2B | 1.45 | 1.45 | 1.40 | 9.02 | 6.64 |
| RSvb2C | 1.46 | 1.39 | 1.32 | 5.39 | 5.51 |
| RSvb3A | 1.46 | 1.47 | 1.43 | 12.84 | 18.15 |
| RSvb3B | 1.37 | 1.38 | 1.41 | 21.26 | 19.54 |
| RSvb3C | 1.40 | 1.42 | 1.41 | 13.48 | 10.27 |

## ANNEX C3: Results of measurement of the soil moisture characteristic

In the next tables the soil moisture characteristics for the different soil layers (S.L.), A (5-10cm), B (30-35cm) and C (55-60cm), of the different clusters are given. In each table for different pF-values the volumetric soil moisture contents are given as percentages (%) of the total volumes of the samples used. The available water capacity (by volume) was calculated by subtraction of the volumetric soil moisture content at pF2 (field capacity) from that at pF4.2 (permanent wilting point).

Table C3.1:Measured soil moisture characteristics for cluster GRvb1-3.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GRvb1A | 44 | 35 | 28 | 26 | 25 | 23 | 19 | 7 | 21 |
| GRvb1B | 38 | 21 | 17 | 14 | 10 | 10 | 8 | 6 | 11 |
| GRvb1C | 40 | 20 | 17 | 16 | 14 | 13 | 10 | 7 | 10 |
| GRvb2A | 42 | 28 | 18 | 16 | 11 | 10 | 8 | 3 | 15 |
| GRvb2B | 44 | 30 | 23 | 20 | 15 | 14 | 11 | 4 | 19 |
| GRvb2C | 38 | 23 | 19 | 17 | 14 | 13 | 11 | 7 | 12 |
| GRvb3A | 38 | 26 | 21 | 15 | 12 | 8 | 6 | 4 | 17 |
| GRvb3B | 40 | 27 | 23 | 21 | 19 | 15 | 13 | 7 | 16 |
| GRvb3C | 38 | 31 | 29 | 26 | 25 | 23 | 22 | 12 | 17 |

Table C3.2:Measured soil moisture characteristics for cluster GRvb4-6.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GRvb4A | 40 | 21 | 19 | 17 | 15 | 13 | 11 | 7 | 12 |
| GRvb4B | 38 | 23 | 22 | 19 | 17 | 15 | 14 | 7 | 15 |
| GRvb4C | 37 | 24 | 22 | 19 | 17 | 15 | 14 | 9 | 13 |
| GRvb5A | 38 | 20 | 19 | 16 | 15 | 14 | 13 | 6 | 13 |
| GRvb5B | 40 | 20 | 18 | 16 | 14 | 12 | 11 | 5 | 13 |
| GRvb5C | 38 | 22 | 20 | 18 | 16 | 15 | 14 | 8 | 12 |
| GRvb6A | 38 | 21 | 19 | 16 | 15 | 13 | 12 | 5 | 14 |
| GRvb6B | 37 | 23 | 21 | 18 | 16 | 14 | 13 | 6 | 15 |
| GRvb6C | 38 | 23 | 21 | 19 | 17 | 15 | 14 | 9 | 12 |

Table C3.3:Measured soil moisture characteristics for cluster GRvb7-9.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GRvb7A | 37 | 22 | 19 | 18 | 15 | 14 | 12 | 4 | 15 |
| GRvb7B | 37 | 27 | 25 | 24 | 23 | 22 | 21 | 15 | 10 |
| GRvb8A | 37 | 28 | 26 | 25 | 24 | 23 | 22 | 7 | 19 |
| GRvb8B | 38 | 27 | 23 | 22 | 20 | 19 | 17 | 12 | 11 |
| GRvb8C | 35 | 29 | 27 | 25 | 24 | 23 | 22 | 15 | 12 |
| GRvb9A | 40 | 21 | 18 | 16 | 15 | 14 | 11 | 4 | 14 |
| GRvb9B | 37 | 27 | 25 | 23 | 22 | 21 | 19 | 14 | 11 |

Table C3.4:Measured soil moisture characteristics for cluster GVb10-11.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GRvb10A | 33 | 21 | 19 | 17 | 16 | 15 | 13 | 6 | 13 |
| GRvb10B | 36 | 23 | 22 | 20 | 19 | 18 | 17 | 11 | 11 |
| GRvb11A | 38 | 17 | 15 | 13 | 12 | 11 | 10 | 4 | 11 |

Table C3.5:Measured soil moisture characteristics for cluster GSvb1-3.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GSvb1A | 42 | 32 | 28 | 24 | 20 | 16 | 13 | 7 | 21 |
| GSvb1B | 43 | 34 | 29 | 28 | 25 | 23 | 18 | 9 | 20 |
| GSvb1C | 39 | 33 | 30 | 29 | 26 | 22 | 18 | 9 | 21 |
| GSvb2A | 45 | 30 | 24 | 20 | 17 | 13 | 11 | 6 | 18 |
| GSvb2B | 41 | 31 | 26 | 21 | 18 | 15 | 14 | 8 | 18 |
| GSvb2C | 39 | 31 | 28 | 25 | 22 | 18 | 15 | 9 | 19 |
| GSvb3A | 45 | 33 | 29 | 24 | 20 | 15 | 13 | 7 | 22 |
| GSvb3B | 40 | 33 | 29 | 25 | 23 | 20 | 17 | 10 | 19 |
| GSvb3C | 40 | 34 | 31 | 27 | 24 | 21 | 19 | 12 | 19 |

Table C3.6:Measured soil moisture characteristics for cluster GSvb4-6.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GSvb4A | 48 | 26 | 25 | 22 | 18 | 16 | 14 | 4 | 21 |
| GSvb4B | 44 | 23 | 22 | 20 | 18 | 14 | 11 | 5 | 17 |
| GSvb4C | 45 | 35 | 34 | 32 | 31 | 31 | 30 | 4 | 30 |
| GSvb5A | 45 | 26 | 25 | 22 | 19 | 16 | 14 | 4 | 21 |
| GSvb5B | 46 | 23 | 22 | 19 | 15 | 13 | 12 | 5 | 17 |
| GSvb5C | 42 | 26 | 24 | 23 | 19 | 18 | 17 | 5 | 19 |
| GSvb6A | 45 | 26 | 24 | 21 | 19 | 16 | 14 | 5 | 19 |
| GSvb6B | 42 | 27 | 26 | 23 | 20 | 18 | 16 | 8 | 18 |
| GSvb6C | 40 | 28 | 26 | 23 | 20 | 18 | 16 | 8 | 18 |

Table C3.7:Measured soil moisture characteristics for cluster GSvb7-9.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GSvb7A | 50 | 30 | 28 | 26 | 24 | 21 | 19 | 8 | 20 |
| GSvb7B | 43 | 30 | 28 | 27 | 25 | 23 | 22 | 10 | 18 |
| GSvb7C | 44 | 30 | 29 | 25 | 23 | 22 | 21 | 10 | 19 |
| GSvb8A | 45 | 28 | 26 | 22 | 19 | 17 | 16 | 6 | 20 |
| GSvb8B | 43 | 27 | 26 | 24 | 21 | 19 | 17 | 6 | 20 |
| GSvb8C | 42 | 28 | 26 | 24 | 23 | 21 | 19 | 5 | 21 |
| GSvb9A | 44 | 33 | 32 | 30 | 29 | 27 | 25 | 6 | 26 |
| GSvb9B | 45 | 32 | 31 | 28 | 25 | 23 | 21 | 9 | 22 |
| GSvb9C | 42 | 32 | 32 | 27 | 24 | 21 | 18 | 6 | 26 |

Table C3.8:Measured soil moisture characteristics for cluster GSvs1-3.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GSvs1A | 37 | 25 | 22 | 21 | 20 | 19 | 18 | 11 | 11 |
| GSvs1B | 37 | 34 | 33 | 32 | 31 | 30 | 29 | 23 | 10 |
| GSvs1C | 40 | 39 | 38 | 37 | 36 | 35 | 34 | 25 | 13 |
| GSvs2A | 35 | 33 | 31 | 29 | 28 | 27 | 26 | 15 | 16 |
| GSvs3A | 40 | 32 | 30 | 29 | 28 | 27 | 26 | 14 | 16 |
| GSvs3B | 39 | 38 | 36 | 35 | 35 | 33 | 33 | 20 | 16 |
| GSvs3C | 39 | 39 | 38 | 36 | 35 | 34 | 33 | 24 | 14 |

Table C3.9:Measured soil moisture characteristic for sample pit GSvs4.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| GSvs4A | 38 | 26 | 22 | 21 | 20 | 19 | 18 | 11 | 11 |

Table C3.10:Measured soil moisture characteristics for cluster RSvb1-3.

| S.L. | pF 0 | pF 1.7 | pF 2 | pF 2.3 | pF 2.7 | pF 3 | pF 3.5 | pF 4.2 | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|
| RSvb1A | 42 | 30 | 25 | 22 | 21 | 20 | 17 | 4 | 21 |
| RSvb1B | 41 | 34 | 24 | 23 | 21 | 20 | 17 | 7 | 17 |
| RSvb1C | 40 | 30 | 28 | 25 | 22 | 21 | 19 | 10 | 18 |
| RSvb2A | 41 | 27 | 20 | 18 | 16 | 15 | 13 | 4 | 16 |
| RSvb2B | 44 | 29 | 25 | 23 | 20 | 20 | 17 | 9 | 16 |
| RSvb2C | 45 | 37 | 34 | 28 | 26 | 25 | 21 | 9 | 25 |
| RSvb3A | 44 | 26 | 21 | 20 | 17 | 15 | 10 | 3 | 18 |
| RSvb3B | 47 | 25 | 21 | 17 | 15 | 14 | 11 | 7 | 14 |
| RSvb3C | 46 | 27 | 21 | 17 | 14 | 13 | 11 | 8 | 13 |

# PUBLICATIONS DEJA PARUES:

## Documents du projet (rouge)

| | | |
|---|---|---|
| 1 | B. van Koppen & N. Groesz | Research Proposal: "gender in the optimalization of tenure arrangements with regard to landesque capital" |
| 2 | J. Oostveen (red.) | Werkplannen juni 1991 |
| 3 | B. Lekanne dit Deprez | Silvopastorale gebieden als sociale ruimte bij de Mossi van Burkina Faso |
| 4 | E. Frederiks | Algemene informatie ten behoeve van bezoek aan de Universiteit van Ouagadougou |
| 5 | E. Frederiks | Programme Sahélien UAW: Activités 1985 - 1992 et l'avenir |
| 6 | M. Bloemberg (red.) | Rapport du 1er atelier du programme de recherche SPS à Ouagadougou (du 14 au 18 décembre 1992 |
| 7 | A. de Wit | Manuel pour mésurer la sève des arbres avec le "Dynamax sap flow system flow32" |
| 8 | L. Stroosnijder & W. Hoogmoed | Zelfevaluatie VF-Sahel (VF 91.61), februari 1993 |
| 9 | A. Ran | Hoe, wat, waar in Burkina Faso: studentenhandleiding Steunpunt Sahel |
| 10 | M. Rietkerk & F. Hien | Mesures de régénération au Sahel |
| 11 | A. Mando | Role des termites dans la régénération des sols dégradés au Sahel |
| 12 | L. Stroosnijder & W. Hoogmoed | "Management of natural resources in the sahel", subprogramme of the VF-programme "Sustainable land use in the tropics" |
| 13 | M.A. Mulders | Rapport sur les activités de télédetection du programme SPS, juillet 1992 - mai 1993 |
| 14 | M.A. Mulders, J. van Rooijen et A. Casterad | Data processing as preparation for soil and land degradation studies in Burkina Faso |
| 15 | A. Bleumink | Manuel pour l'utilisation de l'enregistreur de données DELTA-T logger |
| 16 | E. Frederiks (red.) | Rapport Annuel 1992, Antenne Sahéliene UO/UAW (version française et néerlandaise) |
| 17 | H.J.F. Savenije | Sylvicultural management practices in the Sudan and Sahel zone with an emphasis on the silvopastoral vegetations: a compilation of literature |
| 18 | J.W. Nibbering | Manuel de quelques techniques de mesures agro-économiques et le traitement des résultats |
| 19 | | Rapport Annuel 1993, Antenne Sahéliene UO/UAW, mars 1994 |
| 20 | J.W. Nibbering | Méthode et résultats de quelques transects effectués le long des routes de circulation pour inventorier l'état et l'utilisation des terroirs au niveau régional |

## Publications de l'Antenne (vert)

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|---|---|---|
| 1 | S. de Bie & C. Geerling | IUCN-Paper: "Ecological Limits to the conservation and sustainable exploitation of natural resources" |
| 2 | W. van Driel & A. Ran | Risques et contraintes pour l'intensification de la riziculture dans deux bas-fonds aménages de la province de la Comoë, Burkina Faso |
| 3 | J.J. Kessler & K.F. Wiersum | The multi-dimensional nature of silvo-pastoral areas in the Sahel region |
| 4 | L. Stroosnijder | Afrika studiedag 16 december 1992: "Ecologisch kwetsbare gebieden in Afrika" |
| 5 | L. Stroosnijder, W. B. Hoogmoed and J.J.A. Berkhout | Séminaire International sur la gestion agroclimatique des precipitations, décembre 1991: "Modelling effects of water conservation tillage in the semi-arid tropics" |
| 6 | W.B. Hoogmoed J.J.A. Berkhout L. Stroosnijder | Séminaire Internationale sur le travail du sol en zones arides et semi-arides, organisé par l'ANAFID, 22-23 april 1992: "Soil tillage options for water management under erratic rainfall conditions" |
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| 10 | K.F. Wiersum | Systèmes indigènes d'exploitation et de gestion de la végétation boisée au Sénégal: cadre d'analyse. In: La Foresterie Rurale au Sénégal: participation villageoise et gestion locale, Leiden Development Studies, No. 12: 135 - 159, 1993 |
| 11 | L. Stroosnijder | Population Density, Carrying Capacity and Agricultural Production Technology in the Sahel. Paper presented at the 1994 Danish Sahel Workshop, 6-8 January 1994, Sandberg Manor, Sonderborg, Denmark |
| 12 | A. Mando, W.F. van Driel & N. Prosper Zombré | Le rôle des termites dans la restauration des sols ferrugineux tropicaux encroûtés au Sahel. Contribution au 1er Colloque International de l'AOCASS: Gestion Durable des Sols et de l'Environnement en Afrique Tropicale, Ouagadougou, 6 - 10 décembre 1994 |
| 13 | A.H.M. Schutjes & W.F. van Driel | La classification locale des terres par les Mossi: paysans et pédologues parlent-ils le même langage ? Contribution au 1er Colloque International de l'AOCASS: Gestion Durable des Sols et de l'Environnement en Afrique Tropicale, Ouagadougou, 6 - 10 décembre 1994 |
| 14 | H.B. Tammes, R.B. Kaboré & W.F. van Driel | L'effet de la matière organique sur la formation des croûtes et l'érosion des sols sableux au Burkina Faso. Contribution au 1er Colloque International de l'AOCASS: Gestion Durable des Sols et de l'Environnement en Afrique Tropicale, Ouagadougou, 6-10 décembre 1994 |

## PUBLICATIONS DEJA PARUES (SUITE):

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|---|---|---|
| 15 | H.J.M Gijsbers<br>J.J. Kessler<br>M.K. Knevel | Dynamics and natural regeneration of woordy species in farmed parklands in the Sahel region (Province of Passore, Burkina Faso)<br>In: Forest Ecology and Management 64 (1994) 1-12 |
| 16 | J.J. Kessler | Usefulness of the human carrying capacity concept in assessing ecological sustainability of land-use in semi-arid regions. In Agriculture, Ecosystems & Environment 48 (1994) 273-284 |

### Rapports des étudiants (violet)

| | | |
|---|---|---|
| 1 | M. Rietkerk | Les differences locales du sol et la capacité de régénération: une étude pour la régénération des écosystèmes sylvo-pastoraux Sahéliens, dans la Forêt Classée de Yabo (Burkina Faso) |
| 2 | S.J.T. Poutsma | Geografische Informatie Systemen en bodem- en waterconservering: een praktijkvoorbeeld |
| 3 | J. van Etten | Mesures de rendement dans les Bas-fonds de Damana, Kawara et Moadougou, rapport de stage |
| 4 | A. de Wit | L'effet du bilan hydrique sur la croissance des arbres tropicaux: une étude sur la distance optimale des diguettes à l'aide de quantité d'eau utilisée par l'Acacia Seyal |
| 5 | A. Florijn | Etude sur l'impact hydrologique des digues filtrantes sur l'humidité volumétrique du sol dans le bas-fond de Noh |
| 6A | H.B. Tammes | Carte des états de surface du bassin versant de Solmiougou |
| 6B | H.B. Tammes | L'effet de la matière organique des sols sableux de Burkina Faso sur la formation des croûtes et sur l'érosion |
| 7 | F. Kologo | Evaluation des techniques de restauration des sols dans les zones sylvo-pastorales de la province du Sanmatenga |
| 8 | A. Belemviré | Contribution à l'étude de la cartographie des états de surface et à l'estimation de la biomasse ligneuse aérienne à partir de l'image Landsat Thematic Mapper. Essais de Mesures radiométriques au sol. Etudes menées au Kaya |
| 9 | S. Idi | Evaluation des contraintes socio-économiques et techniques des plantations villageoises dans le Sanmatenga: étude de cas |
| 12 | O. van Dam | Recherche du sol et de la télédétection à Kaya, Burkina Faso |
| 13 | J.C. den Boef | Les mesures de conversation des eaux et du sol dans trois villages de la province du Zoundwéogo. |
| 14 | P.A.J. Schaper | Les mesures de conservation des eaux et des sols dans trois villages de la province du Sanmatenga |
| 15 | A.R. Vriend | Un inventaire agro-socio-économique des ménages du plateau central du Burkina Faso |
| 16 | M.C. Minnaard | Une étude sociologique sur la coopération autour des mesures des conservations des eaux et des sols, dans un village Mossi, Burkina Faso. |
| 19 | T. Slaa | Contribution à la classification des espaces sylvo-pastoraux au niveau villageois dans le Sahel |
| 21a | A. Bleumink | La goutte qui se fait déborder la surface: une recherche indicative à l'influence du climat local sur la dégradation des états de la surface |
| 21b | A. Bleumink | La goutte qui se fait déborder la surface, supplément: les données obtenues de la station météo |
| 23 | K.O. Trouwborst | Soil moisture reserve development at soil-water conservation measures in Burkina Faso |
| 24 | I.H. Janssen | De invloed van korsten op afstroming en nutriëntenverliezen in de Sahel |
| 27 | L.A. Timmer | Une étude sur les buts et les types de taille du néré (Parkia biglobosa (Jacq.) Benth.) et la relation avec sa structure |
| 29 | A.T.A. Loozekoot | A plusieurs mains l'ouvrage avance! Une étude socio-économique de Barcé, Yakin et Salmintenga, trois villages dans la province de Zoundwéogo au sud de Burkina Faso |
| 30 | J.D. Wijnhoud/A.J. Otto | Physical proporties of soils in the Kaya area, Burkina Faso |

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