programme de recherche

SPS

International Symposium Remote Sensing and GIS as tools for monitoring soils in the environment. Ouagadougou, Burkina Faso

PHYSICAL MEASUREMENTS ON A DEGRADED WATERSHED UNDER SYLVO-PASTORAL LAND USE: SILMIOUGOU

Thursday February 9, 1995

Leo Stroosnijder and
Willem Hoogmoed

ent et Gestion
e Sylvo-Pastoral au Sahel

lienne de l'Université Agronomique Wageningen Pays-Bas
rsité de Ouagadougou Burkina Faso

PHYSICAL MEASUREMENTS ON A DEGRADED WATERSHED UNDER SILVO-PASTORAL LANDUSE: SILMIOUGOU

Leo Stroosnijder[1] and Willem Hoogmoed[2]

INTRODUCTION

Silmiougou is a 12.5 ha small (sub-)watershed north of Kaya, Sanmatenga province of Burkina Faso with an average annual rainfall of 650 mm, see Figure 1. This watershed is heavily degraded, with a sparse vegetation of some shrubs, trees and grasses. In this paper, some information on methodologies, measurements on weather, landscape, physical and chemical soil properties and runoff and erosion is presented as well as some preliminary results.

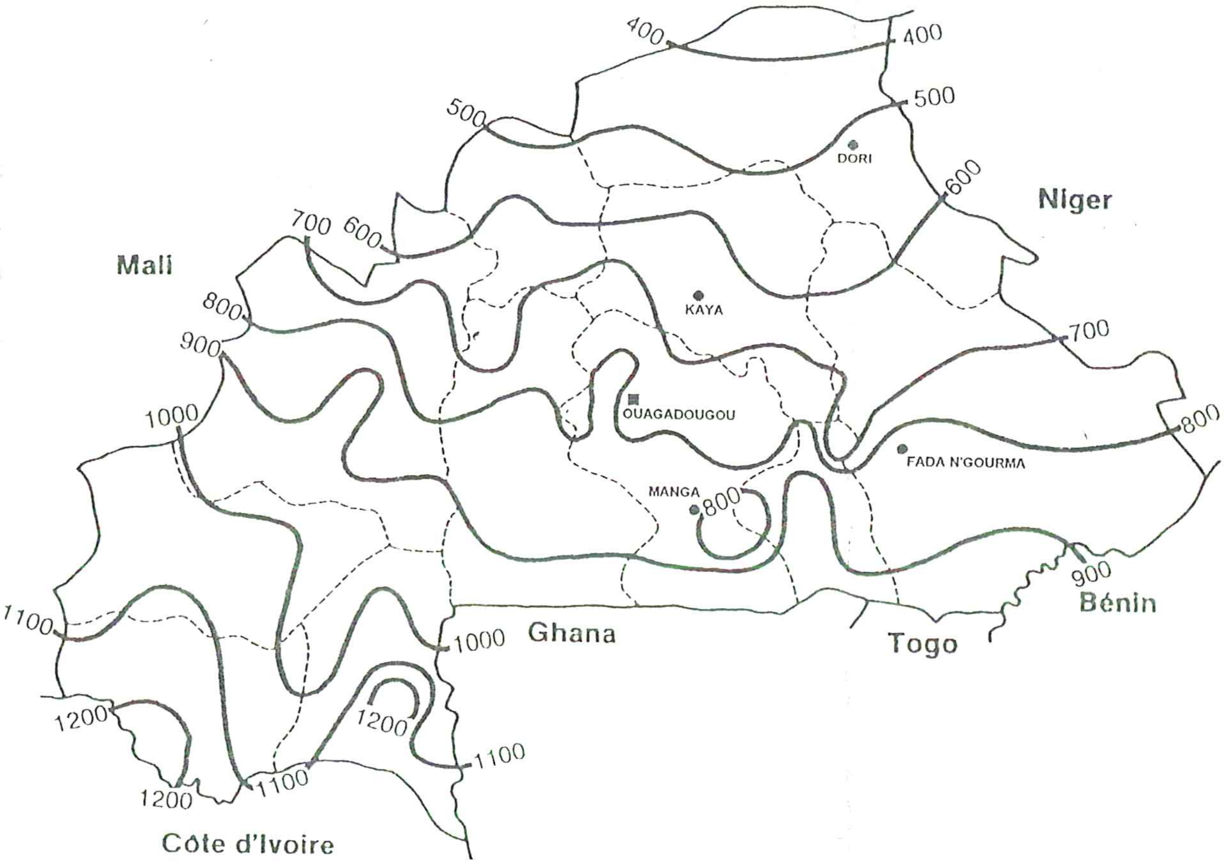

Figure 1 *Isohyets of Burkina Faso, West Africa.*

[1] Wageningen Agricultural University, Department of Irrigation and Soil & Water Conservation, Nieuwe Kanaal 11, 6709 PA, Wageningen, Netherlands.
[2] Wageningen Agricultural University, Department of Soil Tillage, Diedenweg 20, 6703 GW Wageningen, Netherlands.

CLIMATE

An automatic weather station was operational from August 1992 to March 1994 on the watershed, measuring temperature (of the air, in the soil under vegetation and under a bare soil), relative air humidity, wind speed and direction, radiation and albedo, rainfall (intensity). In addition to these values, rainfall and other weather data were collected from meteo stations in Fada, Ouagadougou and Dori. A special analysis was carried out on rainfall intensities (based on digitizing the recording raingauge output and subsequent computer analysis) of the last 15 years for Dori. Figure 2 presents the intensity pattern of a typical shower. In the Semi Arid Tropics very intensive rain showers occur and 15% of rainfall has an intensity > 100 mm/hour, see Figure 3. In order to quantify not only the water balance but also the nutrient balance rainfall was analysed for its chemical composition.

Indications of erosivity indices, like kinetic energy, Hudson's energy index, Lal's intensity index, Wischmeier's R value, were calculated based on rainfall intensity analysis. The analysis also allows estimations of runoff (per rainstorm or per season). The erosive power of showers increases exponentially with the size of the showers, see Figure 4. For a shower of 40 mm the erosivity index EI30 is about 1000 [J.mm/m^2.h] for each mm of rain and this value doubles till 2000 [J.mm/m^2.h] for each mm of rain for a shower of 80 mm.

In Figure 5 values for sky and soil radiation are given for September 1992. Dividing these values during daytime gives albedo values as presented in Figure 6.

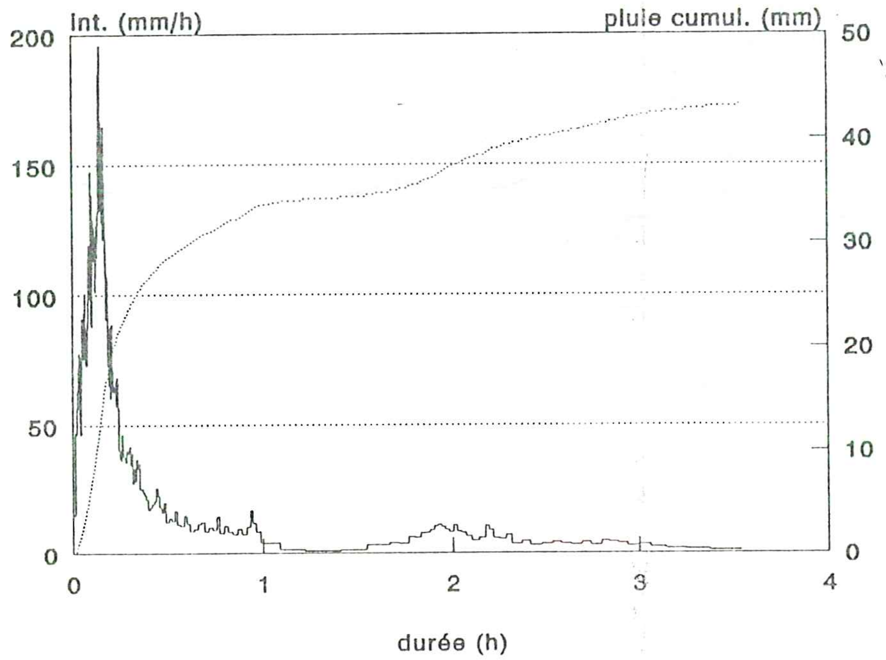

Figure 2 *Intensity pattern of a typical shower in northern Burkina Faso (June 2, 1993).*

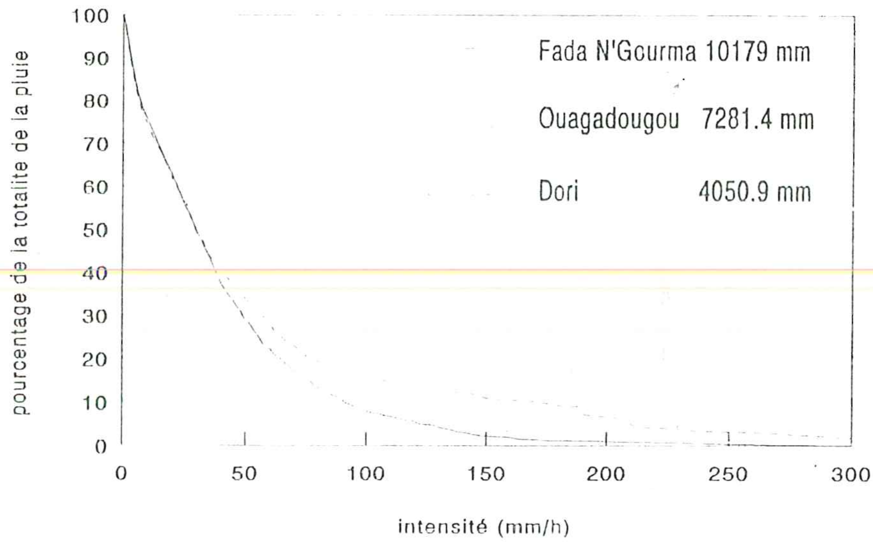

Figure 3 *Rainfall intensity analysis for three locations in Burkina Faso.*

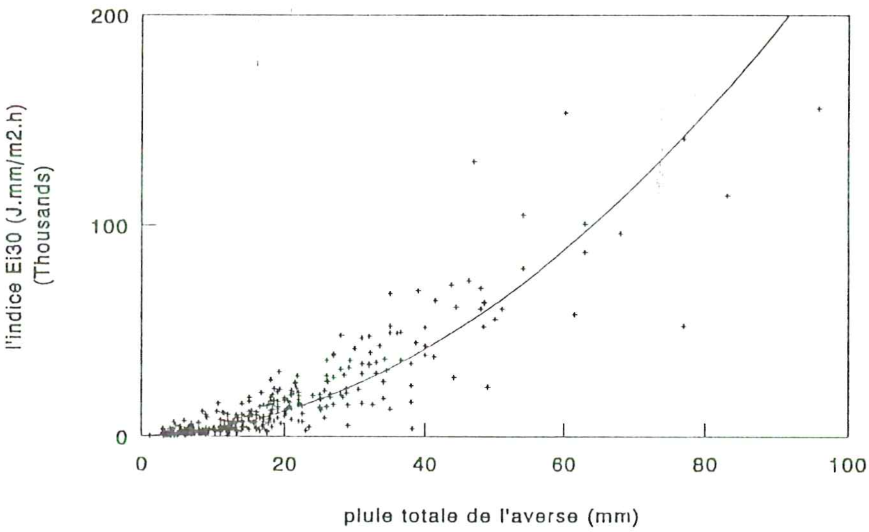

Figure 4 *Erosivity index as a function of shower size for Burkina Faso, West Africa.*

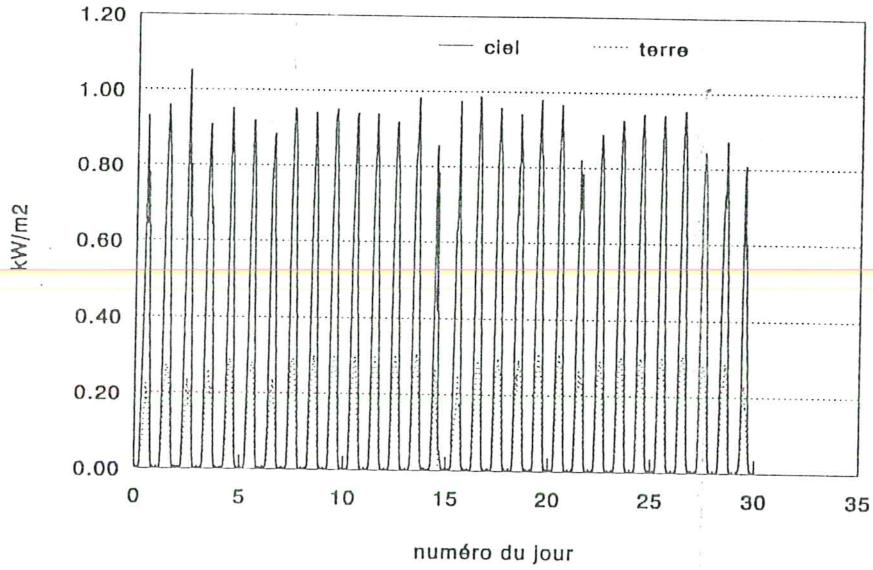

Figure 5 *Sky and soil radiation (kW/m²) for September 1992, Silmiougou, Burkina Faso*

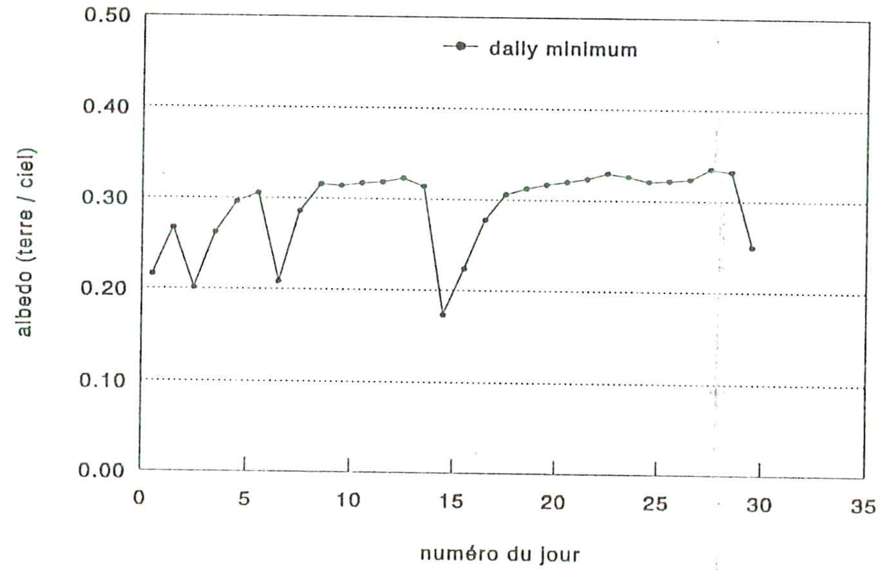

Figure 6 *Daily minimum albedo values for bare soil in September 1992, Silmiougou, Burkina Faso.*

LANDSCAPE AND WATERSHED

The landscape in Silmiougou shows some hills (with steep slopes) and valley-bottoms (bas-fonds) but is dominated with rather flat very long slopes called glacis. Shape and elevations of the watershed were determined using various methods:

1. a topographic survey with a levelling instrument
2. building a digital height model using various types of software: SPATANAL (semi-variogrammes), MAPIT (geostatistical interpolation), SURFER (contours).
3. import in a geographical information system (IDRISI 4.0)
4. digitalisation (based on field observations) of surface phenomena like crusts, gullies, annual and perennial vegetation using TOSCA
5. analysis of raw data with IDRISI (slopes, percentage cover, flowpaths etc.)

Slopes in this watershed were classified in 5 classes:

Slope class	% slope	% of watershed
1	< 1	40
2	1-2	33
3	2-3	15
4	3-5	6
5	> 5	6

The median slope of the watershed is 1.2 %

Table 1 *Typical slope classes for rangelands in northen Burkina Faso.*

Recently, a digital elevation model was made for parts of the Sanmatenga province (including Silmiougou) using a sophisticated GPS (global positioning system). This systems is able to produce quickly highly accurate information on X,Y and Z dimensions. The system is, however, very expensive.

Special attention was given to the *crust cover:* inventories were made on the basis of visual observations, using the classification as proposed by Casenave and Valentin (1989) as a guideline, and supported by measurements of the infiltration capacity. When degraded, glacis are partly bare and covered with 5 surface types:

1. Recent sandy dunes formed by deposition of aeolian sand. These small dunes are 10-50 cm high and cover an area of 2-20 m2 and often covered with rapid germinating pioneer vegetation.
2. Older dunes where erosion has taken place, the soil surface contains more silt than the recent dunes, there is less vegetation cover and more algae growth. Crust type 2 is a succession (in development) of type 1.
3. Gravel (laterite concretions) pavements.
4. Heavily developed B-crusts which is supposed a succession of crust type 3 after removal of the protecting pavement.
5. Depositional (sedimentary) crusts.

Results of crust observations for Silmiougou are given in Figure 7 and their classification according to their runoff properties into 6 classes is presented in Table 2. Class 1 represents agricultural field and classes 2-6 are sylvo-pastoral areas.

Silmiougou: crust features

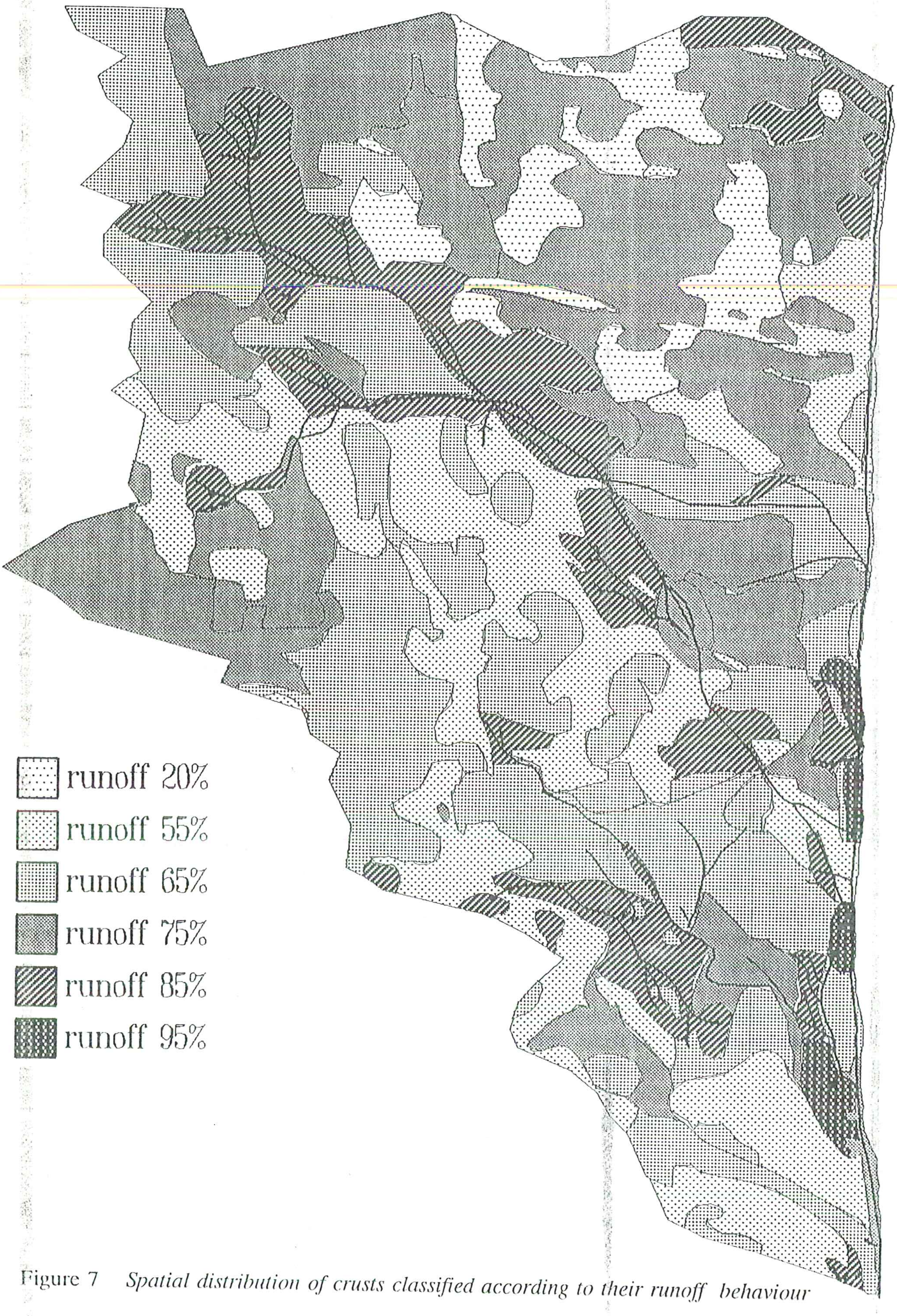

Figure 7 *Spatial distribution of crusts classified according to their runoff behaviour*

Crust class	% of watershed	% runoff seasonal	%runoff 89 mm
1	8	16	20
2	21	25	55
3	27	55	65
4	29	60	75
5	14	65	85
6	1	70	95
crust weighted mean runoff:		**49 %**	**64 %**

Table 2 *Typical crust classes for rangelands in northen Burkina Faso and weighted mean runoff for a whole season and a design storm of 89 mm.*

One should distinguish macro- and micro-roughness. The former is related to the drainage pattern while the latter determines the storage capacity of the surface for free water before it starts running over the soil. This storage capacity is refelected in the threshold rainfall below which no runoff will occur. This threshold is b/a where b and a are parameters in the runoff equation: $R=aP-b$.

PHYSICAL AND CHEMICAL SOIL PROPERTIES

A detailed knowledge of soil physical characteristics is necessary for two purposes:

(1) to evaluate the soil degradation processes (though as yet it is not known which parameters are the best indicators of soil degradation), and

(2) to allow the application of physically valid simulation models used in the study of vegetation (crop) growth and soil and water conservation

The following parameters were measured:

saturated hydraulic conductivity (laboratory: constant head method),
unsaturated hydraulic conductivity (field: disc or tension infiltrometer),
moisture retention (laboratory: pressure plate equipment),
various soil densities (field: bulk, laboratory: small structural elements, solid phase),
aggregate stability (laboratory: tensile strength, waterdrop impact, dispersion, wet sieving, slump test),
crust formation (field: rainfall simulator)

The value of field capacity can be derived from the moisture retention curves and varies between pF 2.0 and pF 2.5. However, this value was also be determined in the field using a direct method. Long duration infiltration on a 1 m2 square surface provides a saturated soil profile. After 24 hrs or 48 hrs of redistribution the moisture content in the profile was determined and called field capacity. Comparing this value with the moisture retention curves indicates that FC is closely related to the moisture content at a pF 2.0. With moisture retention curves and field capacity known, available water was calculated for the major soils:

	Soil Type	pF 2.0	pF 4.2	available moisture (mm/mm)
1	Recent dunes	0.248	0.024	0.224
2	Older dunes	0.222	0.046	0.176
3	Laterite soil	0.267	0.107	0.160
4	B-crusted soil	0.280	0.189	0.091

Table 3 *Typical pF and available moisture data for 4 different crusted soils on rangelands in northen Burkina Faso.*

Table 4 shows some physical characteristics of the soil underlying the most important crust types.

crust type	tensile strength kPa	slump on immersion %	clay/silt ratio	sand (<53μm) %	gravel (> 2 mm) %	bulk density g/cm^3
Drying	1,3	25	0,56	83	0,3	1,57
Algae	28	19	0,62	68	0,3	1,59
Gravel	89	39	1,43	47	48	1,74
B-crust	90	27	3,33	51	5	1,66

Table 4. *Some physical and mechanical characteristics of the soil underlying the important crust types on Silmiougou.*

The sandy soils on which the drying and algae crusts have developed, show a high percentage of sand, a small amount of silt and a bulk density of just under 1.60, which is normal for these soils. The algae crusting soil clearly has collected more silt and clay material, which becomes evident in the increased tensile strength and a lower slump percentage (less slump = more stable). The gravelly soil and the crusted soil where gravel has been removed are heavier (approx. 50% clay and silt). Their tensile strength is accordingly higher. This does not mean, however, that the fine material is more stable than sand: soil from the gravel crust showed the lowest stability under the slump test.
This may explain why on this soiltype after removal of the protective gravel pavement the crust becomes stronger and denser, seen the high runoff coefficient (Table 4).

RUNOFF AND EROSION

Runoff as a result of natural rainfall from typical surfaces on the Silmiougou watershed was collected from small (1 m^2) plots. These plots were made of sheet metal measuring 0.8 x 1.25 m (length along slope), with a collecting system consisting of an 80 l barrel, dug into the soil. So, only the total volume of runoff could be assessed.

Runoff of individual rain showers appeared to be well correlated with shower size. Linear regressions with R=aP-b, in which R [mm] is the runoff and P [mm] the shower size, show high correlations. The higher a is the better the correlation is. In the above equation is a [--] the slope of the linear regression and often called the runoff coefficient and b the intercept with the dependent R-axis. This makes b/a [mm] the threshold rainfall volume above which runoff starts so that the above equation is only defined for P>b/a. Results for young and older dunes are given in Figure 8 and for gravel pavement and structural B-crusts in Figure 9. Regression results are given in Table 5.

Main crust types	Runoff formula	Threshold [mm]	corr
Drying crust	R=0.50*P - 3.5	7.0	0.68
Algae crust	R=0.82*P - 3.5	4.3	0.81
Gravel pavement	R=0.78*P - 3.5	4.5	0.92
B-crust	R=0.95*P - 3.5	3.7	0.94

Table 5 *Runoff formulas and runoff threshold values for typical surfaces on degraded sylvopastoral soils in northen Burkina Faso.*

The causes of erosion: detachment (by impact of raindrops) or entrainment (by overland flow) were studied with fine screens covering experimental plots. Results are:

<u>For Silvopastoral Land Use:</u>
Runoff with protection = 117 % of the runoff without protection
Erosion = 30 % of the erosion without protection
<u>For Agricultural Land Use:</u>
Runoff with protection = 125 % of the runoff without protection
Erosion = 60 % of the erosion without protection

The reduction in erosion as the result of protecting the soil with a screen means that detachment (due to raindrop impact) is an important erosion cause on unprotected bare soils and that this is more important on rangeland than on agricultural fields. In the latter case entrainment (due to overland flow) is important as well.

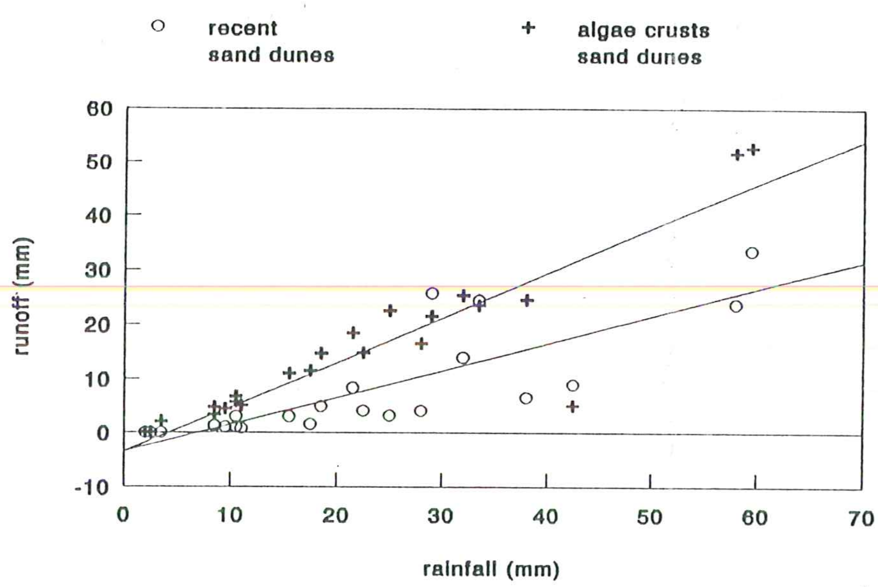

Figure 8 *Runoff as a lineair function of rainfall for recent and degraded (due to algae crust) sand dunes on Sahelian rangeland.*

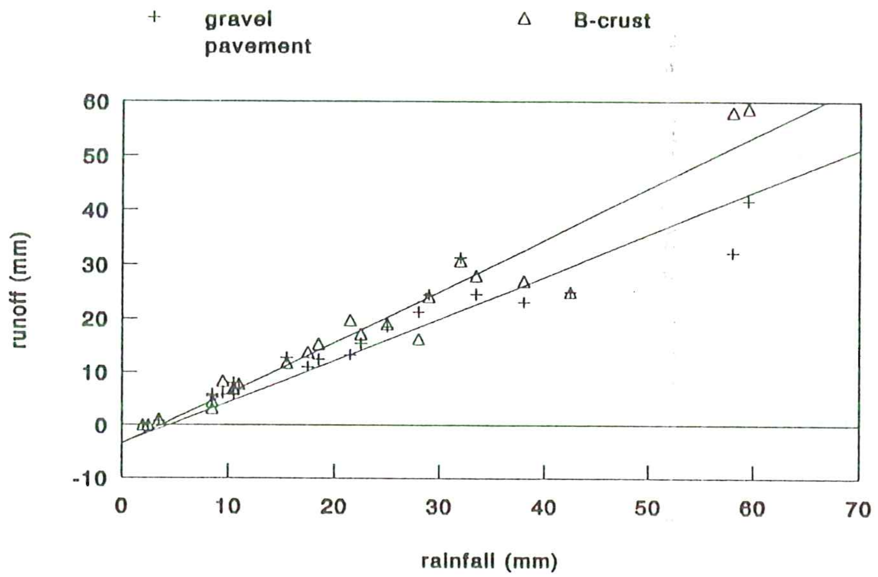

Figure 9 *Runoff as a lineair function of rainfall for degraded sylvo-pastoral soils with a gravel pavement and a B-crust.*

The process of crust formation and resulting runoff was measured under a rainfall simulator (type ORSTOM) using a T-jet nozzle spraying water from a height of approx. 4 m on a 1 m^2 plot (1 x 1m). The rainfall simulator tests yield a curve showing the decrease of infiltration rate as a function of time or cumulative rainfall. This study showed that crusts on Silmiougou soils develop rapidly, after being broken by tillage, under influence of cumulative rainfall, see Figure 10, and that the rate of crust formation is strongly determined by the organic matter content of the soil.

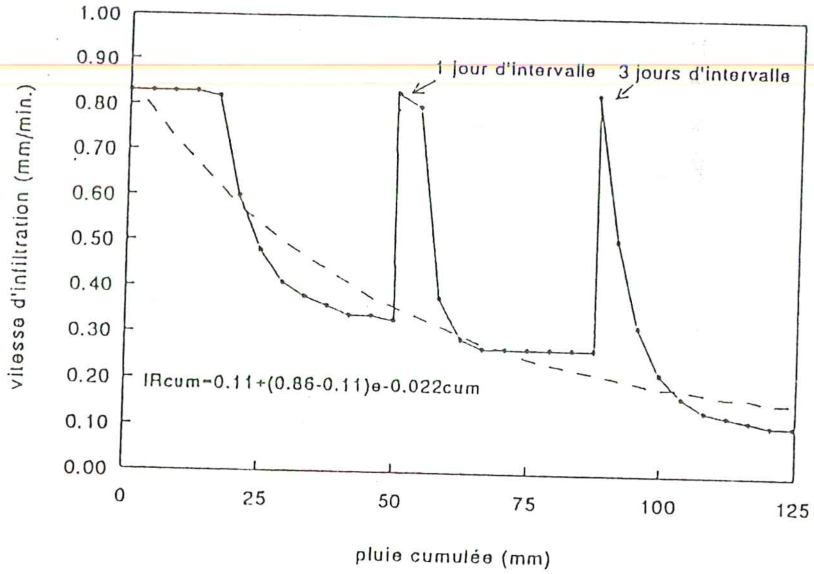

Figure 10 *Infiltration rate as a function of cumulative rainfall after crust breaking for degraded sylvo-pastoral soils with only 0.24 % soil organic matter.*

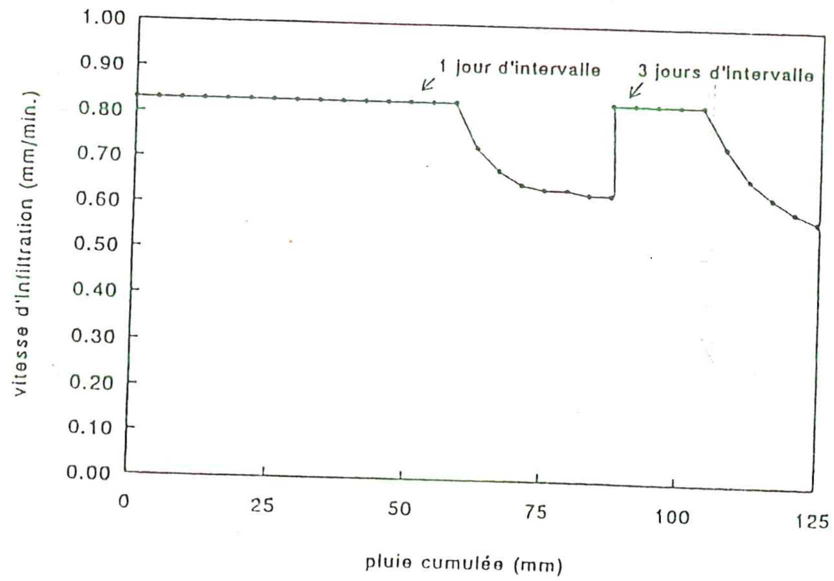

Figure 11 *Infiltration rate as a function of cumulative rainfall after crust breaking for agricultural soils with 1.24 % soil organic matter.*

Soil loss shows a poor correlation with shower size, shower intensity or erosivity. This is probably due to soil deposited on the experimental plots by wind erosion. Therefore, soil loss is often expressed in the units [kg/ha.mm rain]. For silvopastoral land use values range between 3 and 45 [kg.ha.mm rain] so that annual soil loss ranges between 2 and 30 [t/ha.year].

Plant nutrients are lost through soil loss as well as in the runóff water. In the runoff water we have measured in 1993 in Silmiougou about 40 [g/ha.mmrunoff] of plant available N. The annual runoff of degraded sylvopastoral areas is about 50% so that at an isohyet of 650 [mm/yr], the runoff amounts 325 [mm/yr] containing 13 [kgN/ha]. The 650 mm of rain brings about 10 [kgN/ha] so that the net loss due to runoff is 3 [kg/ha.yr].

Nutrient erosion can be expressed in terms of total elements or in terms of available nutrients, both methods have pros and cons. Results show that the majority of the total elements is in the eroded sediment while the majority of the plant available nutrients is in the runoff water (see Table 6 presenting 1994 data). Effects of long-term gradual nutrient loss on yield and the costs and benefits of conservation technology have been calculated. Taking into account the nutrient conserving function of certain conservation technology can make this technology economically viable.

	Silvopastoral			Agricultural		
	In Sedim	In Runoff	%in Sedim	In Sedim	In Runoff	%in Sedim
C	118	23	84	361	17	96
total N	13	7	67	28	14	67
avail N	0.2	6.6	3	0.2	13.7	2
total P	1.5	0.0	100	4.8	0.1	99
avail P	0.0	0.0	---	0.0	0.1	0
avail K	1.1	3.3	25	1.1	7.6	13

Table 6: *Distribution of annual losses of nutrients (kg/ha.year) between sediment and runoff for two types of land use on degraded sandy loam soils in Burkina Faso.*

The eroded sediment always contains higher concentrations of organic matter and nutrients that the top soil from which it originates. This phenomenon is called enrichment. The ratio between the concentration of an element in the sediment to that in the soil is called the enrichment factor (indice de sélectivité). Enrichment factors for total elements are higher (2-4) than for available nutrients (1-2), see Table 7.

	Silvopastoral				Agricultural			
	Soil	Sedim	Enrm	Runoff	Soil	Sedim	Enrm	Runoff
C [%]	0.6	2.1	3	---	0.7	1.7	2.4	---
TOC [ppm]	---	---	---	6.0	---	---	---	5.4
totalN [%]	0.06	0.24	4.0	---	0.05	0.13	2.6	---
availN [ppm]	42	----	---	1.67	7	10.3	1.5	2.95
totalP [ppm]	105	277	2.6	---	75	219	2.9	---
availP [ppm]	0.44	---	---	0.00	0.02	---	---	0.01
availK [ppm]	94	---	---	0.80	53	50.3	0.95	1.56
pH	6.5	---	---	---	6.2	---	---	---

Codes: --- no data available
Note: TOC determines 82% of C determined with Kurmies

Table 7: *Chemical analysis of the original soil, the erosion sediment and runoff for two types of land use on degraded sandy loam soils in Burkina Faso.*

One can use the runoff relations in combination with crust areas for upscaling the information till the watershed scale. This is especially important for the design of Soil & Water Conservation technology. For that case one uses not only an average seasonal rainfall distribution but also a so-called design rain shower. This is the shower with an occurrence chance of once in ten years which is for Silmiougou 89 mm. By multiplying the relative contributions of the various crust surfaces with their respecctive runoff coefficents one obtains a seasonal runoff of 49% of 650 mm and a design runoff of 64% of the 89 mm, see also Table 2. This latter value is compared with the ORSTOM-method for the calculation of the design discharge: V10 = P10 * A * Kr * S, in which: V10 is the 1 in 10 years design discharge, P10 is the 1 in 10 year design precipitation (89 mm based on 30 years of records), A felects the size of the watershed (A = 1 for < 25 km2), S is the permeability class of the watershed and Kr is a factor for vegetation cover (1 for degraded Sahelian vegetation). For a choice of permeability class P2=0.75, for slope class R3, V10 = 8344 m^3 which implies a runoff % of 75 % or if P3=0.35 is chosen V10 = 3894 m^3 and the runoff is 35 %. The above calculated crust weighted mean of 64% is in between these values.

ACKNOWLEDGEMENT

A number of students have contributed to the results presented here. Their reports are given in the references.

REFERENCES

Bleumink, A., 1993. 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. Student report nr. 21.

Coolegem, L., 1994. Recherche des intensités de la pluie dans trois stations à Burkina Faso. Student report nr. 26

Dijk, K. van, 1994. Evaluation des mesures de régénération des terres dégradés à Zana Mogho, Burkina Faso. Student report nr. 22

Geelhoed, R., 1995. Ecoulement des nutriments dans ruisellement et sediment et l'importance relative d'entrainement. Student report nr.xx

Haas, M. de, 1994. Assessment of aggregate stability of Sahelian soils from Burkina Faso. Student report nr. 11

Hien, F., 1995. Régeneration de l'espace sylvo-pastorale au Sahel: Une etude de l'effet de mesures de conservation des eaux et des sols au Burkina Faso. Tropical Resource Management Papers nr. 7, Wageningen Agricultural University, 240 p.

Janssen, I., 1994. De invloed van korsten op afstroming en nutriëntenverliezen in de Sahel. Student report nr. 24

Poutsma, S.J.T., 1992. Geografische Informatie Systemen en Bodem- en Water-conservering, een praktijkvoorbeeld. Student report nr. 2

Rietkerk, M., 1992. Les différences locales du sol et la capacité de régénération: Une étude pour le régénération des écosystèmes sylvo-pastoraux Sahéliens, dans la Forêt Classée de Yabo (Burkina Faso). Student report nr. 1

Tammes, B., 1993. L'effet de la matière organique des sols sableux au Burkina Faso sur la formation des croutes et sur l'érosion. Carte des états de surface du bassin versant de Silmiougou. Student report nr. 6

Wijnhout, J.D. and A.J. Otto, 1994. Physical properties of soils in the Kaya Area, Burkina Faso. Student report nr. 30

Wit, A. de, 1993. L'effet du bilan hydrique sur la croissance des arbres tropicaux: une étude sur la distance optimale des diquettes à l'aide de quantité d'eau utilisée par l''acacia Seyal. Student report nr. 4