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Land surface conditions of the Niamey region: ecological and hydrological implications

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Land surface conditions of the Niamey region: ecological and hydrological implications

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Abstract

A land surface map of the region of Niamey (2–3°E, 13–14°N), Niger, derived from a classification of SPOT multispectral satellite data with 20 × 20-m resolution, is described. Sixteen distinct classes were defined based on landform, vegetation soil crust type and land use. The classification system was designed to emphasize the role of these factors in hydrological and ecological processes. The primary purpose was to provide information for integrating local-scale measurements of land–atmosphere interactions in HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment) up to a region 1° × 1° square, and to assist hydrologists in interpreting the spatial distribution of soil moisture. A large number of ground descriptions were integrated with high spatial resolution multispectral satellite reflectance data. Since most of the hydrological and atmospheric observations in HAPEX-Sahel were carried out in only three land cover types (tiger bush on the plateaux, fallow savanna and millet fields in the sand valley or plains), the 16 classes were merged successively into nine then six so that three final maps were produced, each one reflecting a different degree of aggregation.

Some difficulties could not be resolved. One stemmed from the continuum linking land left fallow and cultivation. This uncertainty can be a problem since bush-fallow and cropped fields are hydrologically and ecologically quite distinct. Another major difficulty was the detection of sparse vegetation cover using the satellite data.

Each surface condition class was assigned a range of runoff capability parameters derived from numerous rainfall simulation tests conducted in the Sahelian zone. Consequently, runoff production could be assessed for each 20 × 20-m pixel. However, due to the endoreic nature of the watersheds in the region, the use of the map to predict runoff production must be restricted to small areas ranging from the pixel size to catchments of 1–10 km^2.

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1. Introduction

There is a growing concern among the international scientific community about climatic change as a result of increased atmospheric content of greenhouse gases. The study of such changes requires models driven by data for grids several hundred kilometres square. Compared with oceans, terrestrial surfaces are highly complex owing to relief, the variety of vegetation cover and types and human activities. In this context, the region of Niamey, Niger, has been selected as a site for HAPEX-Sahel, a large-area study of land–atmosphere interactions.

The Sahelian environment could be considered as rather simple and homogeneous. A rapid ground survey showed that the Niamey area consists of a mosaic of three distinct units: shrub bush on the plateaux (locally referred as tiger bush because of its banded pattern), fallow savanna and millet fields (Goutorbe et al., 1994). Three supersites, each between 100 and 400 km^2, were established in the 1° × 1° square incorporating Niamey (Fig. 1). Each supersite consisted of at least three sub-sites, one in each of the three units. There was therefore a need for information that would facilitate extrapolating the point, ground-based measurements to the supersite scale and to the 1° square scale. A few maps already exist that describe the region including a geological map at a scale of 1:2 000 000 (Greigert and Pougnet, 1967) and a soil map (1:500 000; Gavaud and Boulet, 1967). Also more detailed surveys have been carried out in the East Central (ECSS; Nagumo, 1993) and in the West Central Supersites (WCSS; Legger and van der Aa, 1994). Soil–geomorphic relationships of the Niamey region have been outlined by Wilding and Daniels (1989). However no geomorphological, vegetation or recent land use maps are available.

Soil water balance in the Sahel is controlled more by surface than by deep soil conditions (Collinet and Valentin, 1979; Chevallier and Valentin, 1984; Hoogmoed and Stroosnijder, 1984). In particular soil crusts, which develop even on very sandy soils in the region, impede infiltration (Hoogmoed, 1986; Valentin, 1986). Nine main types of crust were distinguished according to number and texture of microlayers (Casenave and Valentin, 1992). Cultivation, vesicular porosity, faunal activity and surface coverage by surface coarse fragments also play major roles in the partition of rainfall between infiltration and runoff, as has been clearly shown by numerous rainfall simulation tests throughout the Sahelian region (Casenave and Valentin, 1989). Vesicular porosity forms when the air is entrapped as a result of the low crust diffusivity. This type of porosity is not functional in transmitting water as these vesicular pores are not interconnected. It is therefore considered as a useful indicator of unfavourable conditions for infiltration. Conversely, faunal activity increases infiltration through the macroporosity it generates. Such an effect can be assessed through the determination of the percentage of surface occupied by earthworm casts or termite harvesting constructions. The influence of coarse fragments is more ambiguous. Where large gravel-size coarse fragments prevail, infiltration decreases with increasing stone cover, especially if the stones are embedded in a soil crust, as in desert pavements. Conversely, infiltration is enhanced by stone cover where small free coarse fragments are dominant (Valentin and Casenave, 1992). These results led Casenave and Valentin (1992) to propose an infiltration capability classification system based on the combination of these surface parameters, resulting in

11 major types of 'unit surfaces'. In order to represent a larger range of surface conditions, some additional criteria had to be included in the system as modifiers (vegetation cover, topsoil texture and surface roughness), resulting in 26 sub-classes, each one being related to hydrologic properties (Casenave and Valentin, 1992). This simple, efficient system has improved surface hydrological modelling in the Sahelian region (Albergel, 1987; Perez, 1994). Since vegetation cover and soil crusts affect reflectance, these surface conditions can be mapped using remotely sensed data. Maps derived from satellite images have proved to be satisfactory for hydrological modelling at the scale of about 250 km^2 in northern Burkina Faso (Chevallier et al., 1985; Albergel et al., 1987).

The objectives of this study are: (1) to provide information for integrating local-scale measurements up to the 1° square; (2) to evaluate the representativeness of the ground measurement sites; (3) to test the use of remote sensing data for runoff prediction in the region.

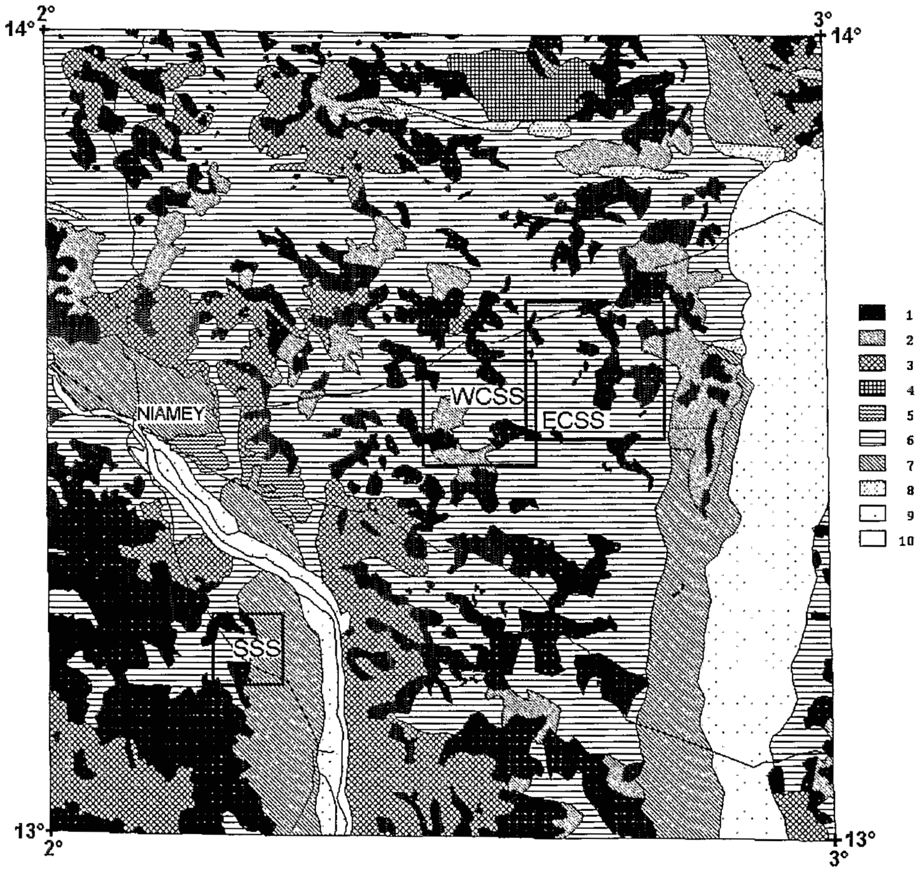

Fig. 1. Soil map and location of the three supersites (SSS, South Supersite; WCSS, West Central Supersite; ECSS, East Central Supersite). The French legend has been adapted and simplified from Gavaud and Boulet (1967). MU, mapping unit. Approximate equivalent Soil Survey Staff (1975), below, mainly based on Wilding and Daniels (1989).

MU	French classification (CPCS, 1967)	Approximate equivalent ISSS et al. (1994)	Approximate equivalent Soil Survey Staff (1975)
1	Sols peu évolué d'érosion, régiques à faciès ferrugineux	Skeletic Leptosols	Petroferric Kanhaplustalfs, loamy skeletal
2	Sols ferrugineux non ou peu lessivés, évolués, sur formation sableuse du MN, séries très rubéfiées de plateau	Ferralic Arenosols	Psammentic Paleustalfs, sandy
3	Sols ferrugineux lessivés faiblement différenciés sur mélange de sables éoliens et de produits issus de grès argileux, associés à des sols regiques et des sols ferrugineux peu lessivés	Arenic Lixisols (Yermi-Eutric Regosols + Ferralic Arenosols)	Psammentic Haplustalfs, sandy
4	Sols ferrugineux peu lessivés, évolués, sur formation sableuse du MN, associés à des sols ferrugineux lessivés, des sols à pseudogley, des sols bruts d'apport, sur roche argileuse et à des sols regiques sur sables éoliens	Cambic Arenosols (Arenic Lixisols + Arenic Gleysols)	Psammentic Haplustalfs, sandy
5	Sols minéraux bruts d'érosion, lithosols, sur conglomérat ferruginisé	Lithic Leptosols	Lithic Ustorthents
6	Sols ferrugineux peu lessivés, évolués sur formation sableuse du MN	Cambic Arenosols	Psammentic Haplustalfs, sandy
7	Sols ferrugineux peu lessivés, évolués sur formation sableuse du MN	Cambic Arenosols	Psammentic Haplustalfs, sandy
8	Sols isohumiques brun-rouge subarides peu différenciés sur sables pauvres en argile et limon (ergs récents)	Protic Arenosols Ustoxic Quartzipsamments	
9	Sols ferrugineux tropicaux peu lessivés peu différenciés, associés à des sols ferrugineux à action de nappe, à des sols à gley, à des sols à alcalis	Protic Arenosols (+Arenic Gleysols + Sodic Solonchaks)	Typic Ustipsamments (+Aquic Quartzipsamments)
10	River Niger	–	–

2. Material and methods

2.1. The study area

The dry season lasts from October to May and the mean annual rainfall is about 560 mm in Niamey (see more detailed papers included in this issue on climatic aspects).

The HAPEX-Sahel (Fig. 1) 1° square is dominated by a complex geological formation of loamy sandstone of Miocene deposits called the Continental Terminal. It covers the Precambrian crystalline basement complex, part of the pan-African shield. The Continental Terminal is locally covered with sand deposits of late Quaternary age which form dunes oriented ENE–WSW, mostly in the northern and the north-western parts of the square.

The landscape is dominated by dissected plateaux with soils formed of between 25 and 85 cm of gravely loam (35–60% silt and clay) over cemented ironstone or gravel (Manu et al., 1991). Most of these plateaux soils are acid (pH < 5.0). The plateaux may be covered with sand up to 4 m thick. Soils on these sand deposits are very similar to those in the sand-filled valleys. The valley system starts below the relatively steep plateau escarpments. In some locations, and more specifically in the southern part of the square, no scarp occurs because the sands of the plateaux are continuous with the valley sands. Close to the scarps the soils are shallow and contain ironstone gravel, but a few metres downslope the sand

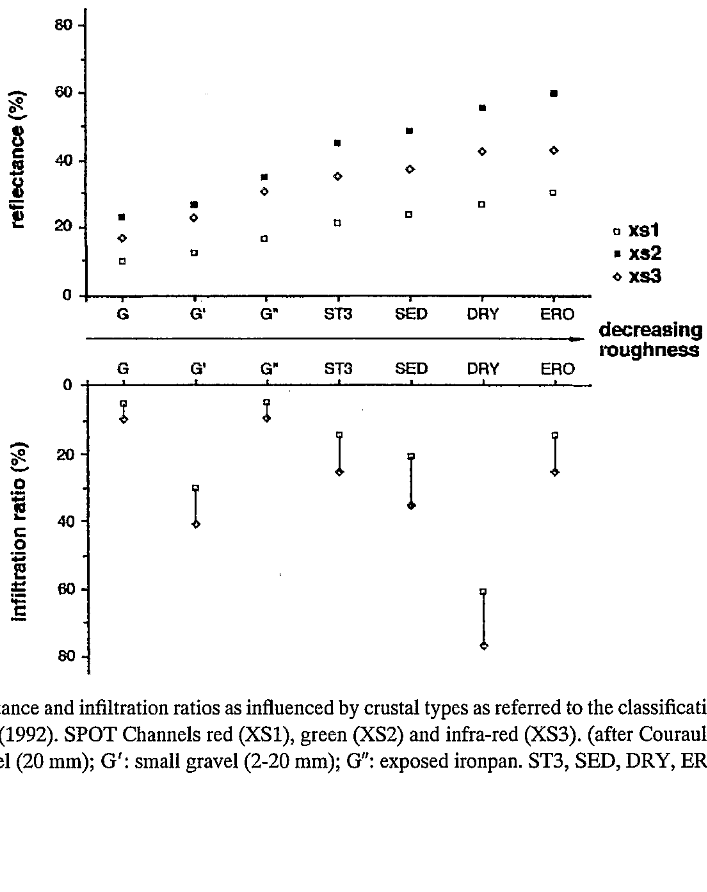

Fig. 2. Reflectance and infiltration ratios as influenced by crustal types as referred to the classification of Casenave and Valentin (1992). SPOT Channels red (XS1), green (XS2) and infra-red (XS3). (after Courault et al., 1991b). G: large gravel (20 mm); G′: small gravel (2-20 mm); G″: exposed ironpan. ST3, SED, DRY, ERO, see Table 2.

Table 1
Digitized maps incorporated in the GIS

Type of map	Scale	Source	Information
Soil	1:500,000	Gavaud and Boulet, 1967	Soil types
Soil	1:50,000	Pias and Rieffel, 1978	Irrigated soils
Topographic	1:200,000		Terrain, hydrologic networks, roads, villages
Topographic	1:50,000		Terrain, hydrologic networks, roads, villages

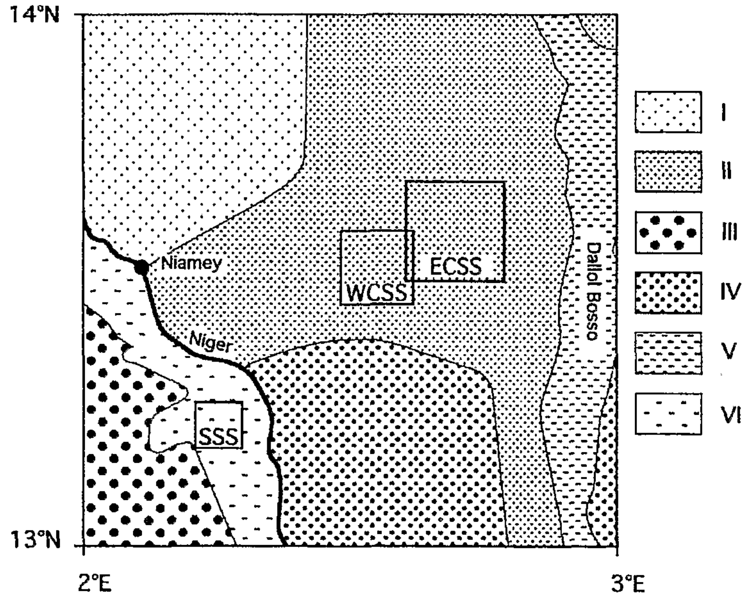

Fig. 3. Major features of the six main geographical sub-regions of the 1° square. (Adapted from Courault et al., 1991a.) NDVI, normalized difference vegetation index.

Unit	NDVI range	Main features	Area (%)
I	Low	Low density of plateaux	17.5
II	Low–median	Dissected plateaux with steep escarpments ana distinct tiger bush, sandy hillslopes cropped with millet	41.1
III	Median–high	One massive plateau, dense bush with more or less circular bare spots (spotted bush) and some tiger bush	7.8
IV	High	Plateaux without steep escarpment, very distinct tiger bush, narrow sandy valleys	13.1
V	High	Dallol Bosso, large valley, intensively cultivated, shallow water-table	12.6
VI	High	Alluvial sand deposits of the Niger valley, rainfed millet and irrigated rice	7.9

deposits are usually very thick (9.3 m in the ECSS, Lamotte, 1992) including more or less expressed argillic horizons. These sandy, aeolian deposits adjacent to the plateaux are referred to as 'sandy skirts' in the Sahel, where there are extensively cultivated with millet. Their topsoil has 10% of silt and clay, and falls into the class that is most vulnerable to crusting (Poesen, 1986; Van der Watt and Valentin, 1992). Downslope the thickness of this sandy and loamy sand soils gradually decreases so that iron-indurated layers are

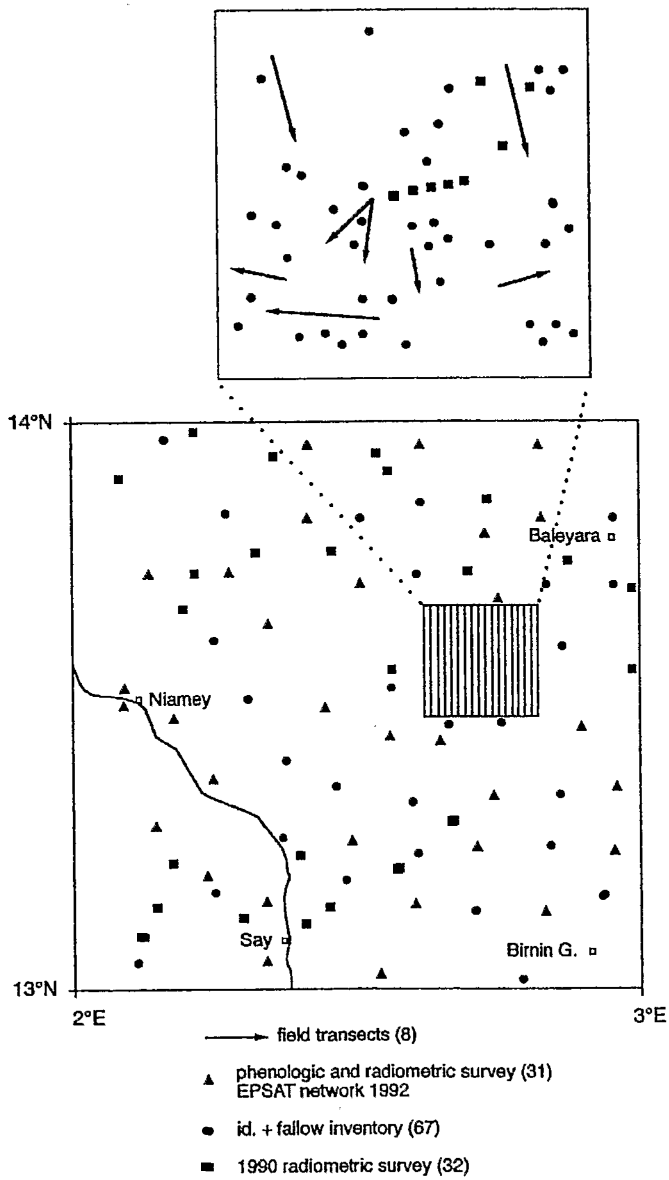

Fig. 4. Location of ground observations and transects.

locally exposed. A convex toe-slope segment generally links the slope to the stream bed. Water and wind erosion are severe in these toe-slopes along with the segments directly adjacent to the plateau scarps. A striking feature of these sand valley system is their lack of clayey sediments, with the exception of the floors of the very few ponds.

Terrace sands cover several levels of ironstone. International Cereal Research Institute for Semi-Arid Tropics (ICRISAT) Sahelian Center at Sadoré is located on these soils (West et al., 1984; Hoogmoed and Klaij, 1990). Morphologically, the soils on these sand plains and those of the valley sand systems are equivalent. Nevertheless the soils of the valley sand systems are much more susceptible to water erosion and water recharge, via run-on from adjacent plateaux (Wilding and Daniels, 1989).

The eastern fringe of the 1° square consists of the Dallol Bosso. Whether this is a fossil valley or a reactivated fault in the Precambrian basement is still disputed. A comprehensive study of soils in the Dallol Bosso has been conducted by Bui (1986). Nearly 80% of this unit is covered with dunes, and 20% with ancient channels (Bui et al., 1989). Many of these channels are plugged by sand and form closed depressions that are often alkaline and gleyed where the water table is shallow (Bui et al., 1990).

2.2. Basic principles and mapping approach

Two basic principles guided our study. Firstly, we assumed that surface conditions identified in the field could be recognized on satellite images. This assumption was checked by field radiometric measurements. Not only did the soil surface colour, and more specifically its Munsell colour code, influence the reflectance but also, for a given colour, the reflectance of various types of crusts decreased with soil roughness (Courault et al., 1991b; Fig. 2). Secondly it was assumed that runoff parameters could be assigned to each type of surface condition, which is consistent with the classification system of Sahelian unit surfaces (Casenave and Valentin, 1992).

The mapping of the region was performed in four steps. First, a preliminary map of the main sub-regions was derived from ground survey and a geographical information system (GIS) containing images from various satellites and existing maps. Second, a map of surface conditions was produced from an extensive ground survey and satellites images of 1988. Third, a map of the East Central Supersite (ECSS) was derived from detailed and quantified field studies associated with SPOT multispectral images of 1992. Finally, three maps of the region were produced with different numbers of classes.

2.3. Preliminary map development

A number of existing soil and topographic maps were digitized (Table 1) and incorporated in a GIS with the National Ocean and Atmospheric Administration (NOAA) high resolution picture transmission (1 × 1 km) advanced very high resolution radiometer (AVHRR) red and near-infrared (Channels 1 and 2) data for 24–28 October 1988 and 10–20 October 1990. A classification using thresholds of the normalized difference vegetation index (NDVI) derived from the red and near-infrared channels of the AVHRR and the soil map (1:500 000) resulted in the delineation of six sub-regions (Fig. 3; Courault et al., 1991a).

Since the digitized topographic maps were unable to delineate the plateaux properly, high spatial resolution data were added. A Landsat multi spectral sensor (MSS) scene of 1 February 1990 that covered part of the square provided some complementary information after a supervised classification, but most helpful were six SPOT multispectral images of 24 October 1988 covering almost the whole 1° square. The SPOT false colour composites clearly separated plateaux (dark green), sandy hillslopes (light green and blue), and valley bottoms (white or very pale blue). The combination of these data sets resulted in the production of a mask for the plateaux which was used to resolve confusion between some dark bare soils of the plateaux and dark, densely vegetated fallow on sandy soils.

2.4. Map of the East Central Supersite

Eight transects through the ECSS ranging in length between 2 and 4 km were surveyed in September 1992 (Fig. 4). Along these transects, 127 homogeneous units were recognized on the basis of: landform; slope gradient; land use (duration of the fallow period, type of crops); woody vegetation cover (%) in six height classes (0.25, 0.25–0.50, 0.50–1.00, 1–2, 2–4, 0.4 m); herbaceous layer cover in three height classes (0.25, 0.25–0.50, 0.50 m); dominant woody and herbaceous species; 'unit surface' class following the scheme of Casenave and Valentin (1992). These transects were used in the interpretation of the SPOT images of 5 October 1992. After a supervised classification, the 127 units were placed in 13 classes (Loireau, 1993).

2.5. Surface condition maps of the 1° square

Six multispectral SPOT scenes acquired on 25 September 1992, were classified. Atmospheric corrections were carried out using the simplified method for the atmospheric

Table 2
Main features of the major crustal types in the region of Niamey (after the classification of soil crusts of Valentin and Bresson, 1992)

Crustal types	Thickness (mm)	Porosity[a]	Other major features
Drying (DRY)	0.5–2	High	Slight cementation of the surficial sandy grains
Structural three layers (ST3)	1–3	Low	Coarse sandy layer at the top, vesicular fine sandy layer, seal of fine particles at the bottom
Sedimentation (SED)	2– > 50	Very low	Fine particles at the top, coarser particles at the bottom, possible vesicles
Erosion (ERO)	< 1	Very low	Exposed seal made of fine particles, possible vesicles
Gravel (G)	2–30	Very low	Similar to the ST3 type including coarse fragments and much pronounced vesicular porosity

[a] Excluding vesicular porosity.

Table 3
Main characters of the major unit surfaces of the Niamey region (after the classification system of Casenave and Valentin, 1992). The diagnostic criteria are in bold

Characters	Unit surfaces											
	TW	DR1	ST31	ST32	SED1	ERO1	ERO2	G1	C11	C21	C23	C31
Cultivated	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Termite structures (%)	> **30**	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30
Crustal type	No	**DRY**	**ST3**	**ST3**	**SED**	**ERO**	**ERO**	**G**	–	–	–	–
Vegetation cover (%)	> 50	> 50	< **50**	> **50**	–	–	–	–	< **50**	–	–	–
Texture of the topsoil	–	–	–	**s**	–	–	**s**	–	–	**s**	**c**	–
Coarse fragments (%)	< 40	< 40	< 40	< 40	< 40	< 40	< 40	> **40**	< **40**	< 40	< 40	< 40
Vesicular porosity (%)	0	0	> 30	–	–	–	–	> 30	> **5**	**5–30**	**5–30**	> **30**

TW, termite-worms; DR, drying; ST3, structural three layers; SED, sedimentation; ERO, erosion; G, gravel; C, cultivated; s, sandy; c, clayey.

Table 4
Percentages of unit surfaces in each map unit

Map unit	Unit surfaces (after the classification of Casenave and Valentin, 1992)												Source
	TW	DR1	ST31	ST32	SED1	ERO1	ERO2	G1	C11	C21	C23	C31	
1	95	5											A
2			20		10	30		40					A
3			20	25		50		5					A
4		5	20			40		35					C
5						50		50					C
6		55		20			25						C
7		77		5			18						B
8		90		5			5						C
9		82		3			15						D
10		10		45			45						A
11		55		30			15						B
12									53	40		7	A
13									20	74		6	B
14									65		35		A
15									5		35	60	E

Sources: A, Rajot and Estèves (1994); B, Loireau (1993); C, C. Valentin (unpublished data); D, Delabre (1993); E, A. De Rouw (unpublished data).

correction (SMAC) method (Rahman and Dedieu, 1994). A mosaic was prepared to create a single image covering most of the 1° square. Geometric correction was performed to register the mosaic to the 1:200 000 topographic map, using 26 control points. A supervised Sebestyen classification method based on the minimization of elliptic distances was used. Training sites were obtained from the preliminary classification of the 1° square (d'Herbès et al., 1992) and the map of the ECSS (Loireau and d'Herbès, 1994). Depending on the required level of simplification, three classifications having 16, nine and six classes were created (d'Herbès et al., 1994), since the main objective was to conform as much as possible with the three units defined before the survey for the selection of experimental sites: bush savanna of the plateaux, millet fields and fallow. The attributes of each class were assessed from field data including (Fig. 4):

- 98 observations in a regular grid over the whole 1° square including a description of landform, land use, vegetation cover per layer and type (woody and herbaceous) and surface conditions (Ouattara, 1992);
- 32 additional observations throughout the 1° square on unit surface types (C. Valentin, unpublished data, 1992);
- 67 observations in various types of bush fallow, 27 in the ECSS plus 40 elsewhere in the 1° square, including landform, surface conditions (vegetation and crustal type), biomass and the duration of the fallow period (Delabre, 1993);
- 20 transects, each 100 m long, on millet fields of the ECSS including crop cover and crustal type (A. de Rouw, unpublished data, 1992);
- 30 transects 500–2000 m in length across the plateaux of the ECSS including slope gradient, vegetation type and cover and crustal type (Delbaere, 1994).

Table 5
Legend with 16 map units of the map of surface conditions. Region of Niamey, 1:200 000, SPOT scenes 25 September 1992

Class no.	Main features	Woody cover (%)	Herbaceous cover (%)	Main soil crust[a]	Runoff ratios (%)		Area[b] (%)
					Dry	Wet	
1	Plateau: dense vegetation	> 50	< 10	No	3	6	5.2
2	Plateau: bare soil	0	0	Gravel	77	82	15.1
3	Plateau: sparse vegetation	20–50	< 10	Erosion	23	27	7.9
4	Hillslope ironpan	< 10	< 15	Erosion	76	81	3.2
5	Degraded hillslope	< 10	< 5	Gravel–erosion	81	87	7.7
6	Old dense shrub fallow	25–50	25–50	Drying	30	35	1.3
7	Old mid-dense shrub fallow	15–25	50–75	Drying	24	29	15.9
8	Old sparse shrub fallow	10–15	> 75	Drying	18	23	2.8
9	Mid-old high grass fallow	10–15	50–75	Drying	22	27	12.4
10	Mid-old low grass fallow	5–10	< 50	Erosion–structural	48	55	5.2
11	Recent fallow	< 5	50–75	Structural	27	33	1.1
12	Hillslope high density field	< 5	25–35	Structural	25	32	8.9
13	Hillslope low density field	< 5	15–25	Structural	33	39	3.9
14	Valley bottom high density field	< 5	25–50	Structural	20	27	6.0
15	Valley bottom low density field	< 5	15–25	Erosion	52	60	3.0
16	Surficial waters	–	–	–	–	–	0.5

[a] See Table 2.
[b] Percent of the classified area which is slightly smaller than the 1° × 1° square.

Finally, unit surface type maps of four small watersheds in the ECSS were helpful in labelling classes (Rajot and Estèves, 1994).

2.6. Runoff prediction and validation

Each unit surface, as referred to the classification system of Casenave and Valentin (1992), can be assigned two values of the runoff ratio (ratio between runoff and rainfall); a dry value that corresponds to a dry soil and a wet value for the same amount of rainfall (50 mm) but for soil that is wet but not saturated. The proportion of the unit surfaces within each mapping unit enables the computation of predicted values of runoff ratios for the whole area. In the two simplified maps with nine and six classes, ranges of runoff ratio were assigned with mean values weighted by the area of each mapping unit. The predicted runoff was compared with literature data for plots in similar environments in Niger and Burkina Faso.

3. Results

3.1. Maps of surface conditions for the 1° square

Soil crusts were placed in five classes (Table 2) and unit surfaces in 12 classes (Table 3).

Table 6
Legend with nine map units of the map of surface conditions. Region of Niamey, 1:200 000, SPOT scenes 25 September 1992

Map unit	Class no.[a]	Main features	Vegetation cover[b] (%)	Main soil crust[c]	Runoff ratios[d] (%)				Area (%)
					Dry range	Mean	Wet range	Mean	
1	1	Plateau: dense vegetation	W: 25–75; H: 10	No	0–5	3	0–10	6	5.2
2	2	Plateau: bare soil	W: 0; H: 0	Gravel	70–80	77	75–85	82	15.1
3	3	Plateau: sparse vegetation	W: 20–50; H: 10	Erosion	20–30	23	25–35	27	7.9
4	4, 5	Degraded hillslope	W: 10; H: 5–15	Erosion	75–85	80	80–90	85	10.9
5	6, 7, 8	Old fallow (7 years)	W: 10–50; H: 25– > 75	Drying	15–35	24	20–40	29	20.0
6	9, 10, 11	Recent fallow (7 years)	W: 5–15; H: 75	Drying	20–50	30	25–60	35	18.7
7	12, 13	Hillslope fields	W: 5; H: 15–35	Structural	20–35	27	30–40	34	12.8
8	14, 15	Valley bottom fields	W: 5; H: 15–50	Structural	15–55	31	25–65	38	9.0
9	16	Surficial waters	–	–	–		–	–	0.5

[a] See Table 5.
[b] W, woody layer; H, herbaceous layer.
[c] See Table 2.
[d] After Table 4, Table 5 and the classification of surface units; Casenave and Valentin (1992).

Table 7
Legend with six map units of the map of surface conditions. Region of Niamey, 1:200 000, SPOT scenes 25 September 1992

Map unit	Class no.[a]	Main features	Vegetation cover[b] (%)	Main soil crust[c]	Runoff ratios[d] (%)				Area (%)
					Dry range	Mean	Wet range	Mean	
1	1	Plateau: dense vegetation	W: 25–75; H: 10	No	0–5	3	0–10	6	5.2
2	2, 3	Plateau: bare soil	W: 0–50; H: 10	Gravel	20–80	58	25–85	63	23.0
3	4	Degraded hillslope	W: 10; H: 5–15	Erosion	75–85	80	80–90	85	10.9
4	5, 6	Bush-fallow	W: 5–50; H: 25– > 75	Drying	15–50	27	20–60	32	38.7
5	7, 8	Fields	W: 5; H: 15–50	Structural	15–55	29	25–65	36	21.8
6	9	Surficial waters	–	–	–	–	–	–	0.5

[a] See Table 5.
[b] W, woody layer; H, herbaceous layer.
[c] See Table 2.
[d] After Table 4, Table 5 and the classification of surface units; Casenave and Valentin (1992).

The most detailed classification consisted of 16 classes of land surface conditions. The percentage of unit surfaces in each of the 16 classes are given in Table 4, and the means and ranges of runoff ratio of each mapping unit are given in Table 5. The same information for the two summarized maps is given in Table 6 (nine classes) and in Table 7 (six classes).

The nine class map is shown in Fig. 5. The location of each unit in a schematic toposequence is shown in Fig. 6.

3.1.1. Plateau: dense vegetation

This unit occurs mostly in Sub-regions III and IV (Fig. 3). It consists of shrub vegetation with bare patches in an ill-defined pattern, or with a banded pattern where the ratio vegetation/bare soil exceeds 1 (Ambouta, 1984). In diffuse vegetation, the cover may be overestimated. Due to the litter cover, the soil crust hardly develops or is rapidly disrupted by termite activity. This mapping unit has been categorized as a TW surface in the classification of Casenave and Valentin (1992) despite the absence of worms and less than 700 mm rainfall. This is because the very porous surface conditions under these dense thickets were considered to be very similar to those observed under moister climatic conditions. Such a designation seems valid since the thickets receive significant run-on from the bare patches (Galle and Peugeot, 1993).

3.1.2. Plateau: bare soil

In this class, woody vegetation cover is less than 16% which is the lower limit for detection by SPOT (Huete, 1986). It includes not only the bare patches in the tiger bush but also, the denuded plateaux in the vicinity of Niamey, the plateau escarpments, and a few, very poor millet fields on the sandy deposits of the plateaux. As a whole, this unit is characterized by a repeated sequence of impervious crusts (Thiéry et al., 1995), with structural crusts upslope, followed by erosion crusts and gravel crusts midslope and sedimentation crusts downslope (Valentin and Bresson, 1992). Such surface features generate intense runoff (Peugeot et al., 1997). Escarpments are mainly covered with free gravel that is not embedded in crusts (Rajot and Estèves, 1994), so that infiltration there may be relatively high despite the steep slopes (Valentin and Casenave, 1992).

3.1.3. Plateau: sparse vegetation

This class comprises three main types of vegetation: (1) sparse shrub bush, diffuse or

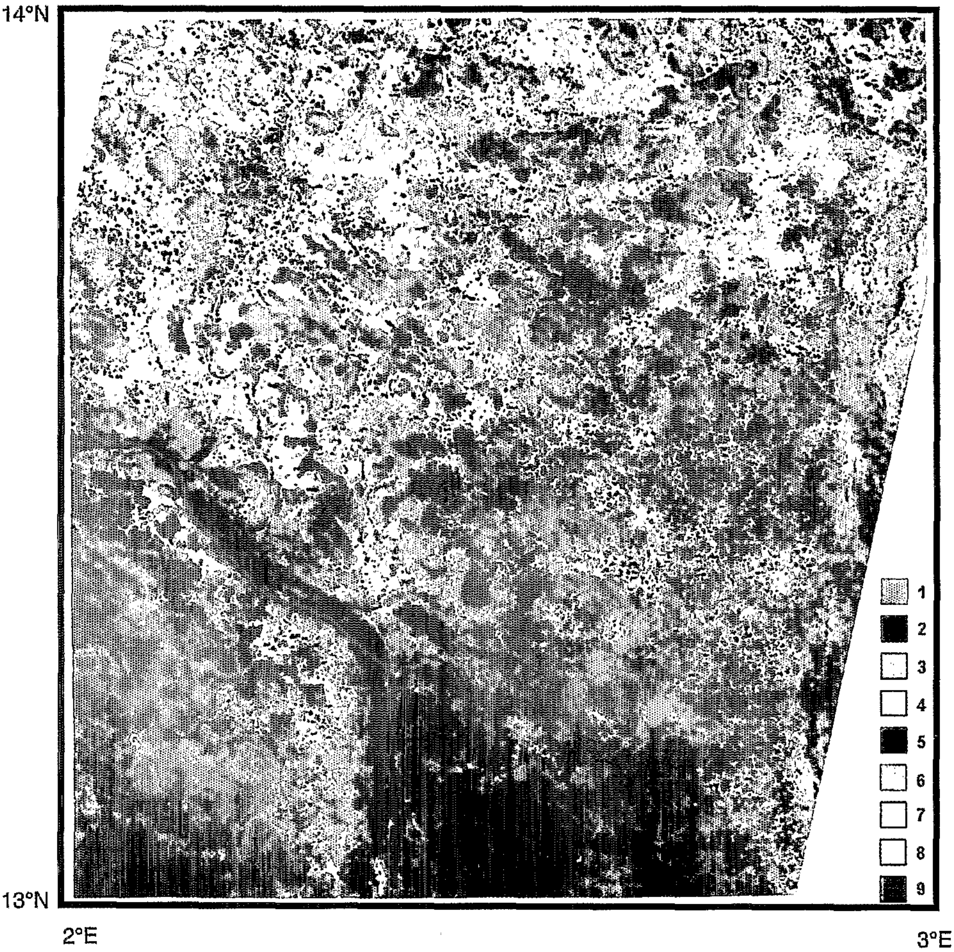

Fig. 5. Land surface conditions map of the 1° × 1° square incorporating Niamey, with nine classes (see legend Table 6).

slightly patterned, (2) tiger bush with a ratio of vegetation/bare soil cover 1, mainly in Sub-regions II and III, (3) park bush with tall *Acacia albida* Del. trees. This latter type occurs in Sub-region I, on sand deposits on the plateaux where millet is extensively cropped under the trees and fallows are very rare. Due to the composite nature of this unit, the values for the runoff ratios must be used with caution.

3.1.4. Hillslope ironpan

This unit is encountered mainly in Sub-regions I and II at the foot of the sandy skirts. It is characterized by the presence of a shallow ironpan that may outcrop. The indurated layer is occasionally more elevated, forming an obstacle to the general drainage from the sandy skirt. Little vegetation occurs on the upper part of these mounds which is generally seriously crusted. Woody vegetation is concentrated on the lower peripheral zones.

3.1.5. Degraded land

This unit is characterized by the extremely low cover of both woody and herbaceous vegetation. It is seriously affected by crusting and is eroded by wind and water. It occurs primarily on the upper slopes of the sandy skirt at the foot of the plateau scarp and on the lower convex hillslope segments. Where land is overused, especially in the vicinity of Niamey, this unit can cover entire hillslopes.

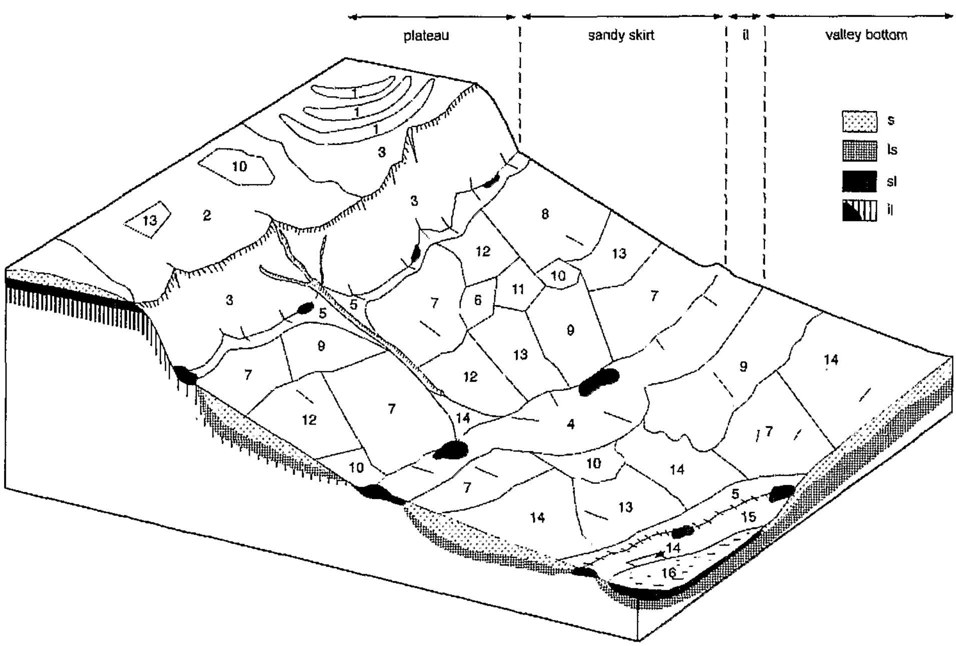

Fig. 6. Idealized diagram of a typical toposequence of the Niamey region, with typical location of the 16 classes (see legend Table 4). s, sand; ls, loamy sand; sl, sandy loam; il, indurated layer.

Table 8
Annual average of maximal runoff ratios recorded from various runoff plots in Niger and Burkina Faso

Location	Main features	Plot size (m^2)	Rainfall (mm)	Maximal runoff ratio (%)	Source	Classes[a]
Banizoumbou, ECSS, Niger	Bare interband in the tiger bush	130	560	76	Peugeot et al. (1997)	2
Galmi, Plot no. 11, southern Niger	Bare soil on plateau	50	455[b]	81	Collinet (1988)	2
Loumbila, central Burkina Faso	Gravelly bare soil	50	518[b]	82	Collinet (1988)	4
Hamdallaye, Niamey region, Niger	Bare eroded soil on convex slope	40	560	95	Zanguina (1994)	5
Banizoumbou, ECSS, Niger	Bare eroded soil on convex slope	43	560	90	Rajot and Estèves (1994)	5
Oursi, Plot no. 3, northern Bukina Faso	Bare eroded soil	50	306[b]	88	Collinet (1988)	5
Oursi, protected plot, northern Burkina Faso	Protected grass savanna	2838	319	25	Piot and Millogo (1980)	8
Banizoumbou, ECSS, Niger	Degraded fallow	100	560	66	Peugeot et al. (1997)	10
Oursi, Plot 1, northern Burkina Faso	Degraded fallow	50	357[b]	50	Collinet (1988)	10
Galmi, Plot no. 31, southern Niger	Degraded fallow	50	548[b]	59	Collinet (1988)	10
Saria, Plot no. 3, central Burkina Faso	Recent fallow	100	678	33	Roose (1981)	11
Oursi, cultivated plot, northern Burkina Faso	Millet	3105	319	33	Piot and Millogo (1980)	12
Banizoumbou, ECSS, Niger	Low dense millet	100	560	41	Peugeot et al. (1997)	13
Gampela, Plot no. 3, central Burkina Faso	Low dense millet	5000	347	42	Roose and Piot (1984)	13
Galmi, Plot 4, southern Niger	Low land millet	50	491[b]	62	Collinet (1988)	15

[a] As referred to in Table 5.
[b] Simulated rainfall.

3.1.6. Old dense shrub fallow (7 years)

Owing to the shortening of the fallow period in the region, this unit, which includes a relatively dense woody cover, is uncommon and occurs mostly in Sub-regions II and IV on sandy valleys and dunes. In the lowest zones and depressions, the ubiquitous *Guiera senegalensis* J.F.Gmel. is replaced by *Piliostigma reticulatum* (D.C.) Hochst. Generally these fallows are found at some distance from the villages.

3.1.7. Old mid-dense shrub fallow (7 years)

This unit is common in every sub-region. *Guiera senegalensis* is the most common woody species, with the exception of the plateau sand deposits in Sub-region I and on the sandy plain of Sub-region VI where *Combretum glutinosum* Perr. ex D.C. can locally form mono-specific communities.

3.1.8. Old sparse shrub fallow (7 years)

This unit occurs on sandy upper slopes in each of the sub-regions, except for V and VI. It consists of a dense herbaceous layer with few scattered bushes. The scarcity of trees and shrubs may result from the transport of *Guiera senegalensis* seeds by overland flow.

3.1.9. Mid-old high grass fallow (3–7 years)

Together with Unit 7, this unit forms the major fallow area of the region. It occurs mostly in Sub-regions II and IV. It is characterized by a poor shrub cover and a relatively dense layer of annual herbs, including *Aristida mutabilis* Trin. et Rupr., *Cenchrus biflorus* Roxb. and *Digitaria gayana* (Kunth.) Stapf. ex A. Chev. (0.25–0.50 m high) in the early and *Ctenium elegans* Kunth. (1 m high) in the late rainy season.

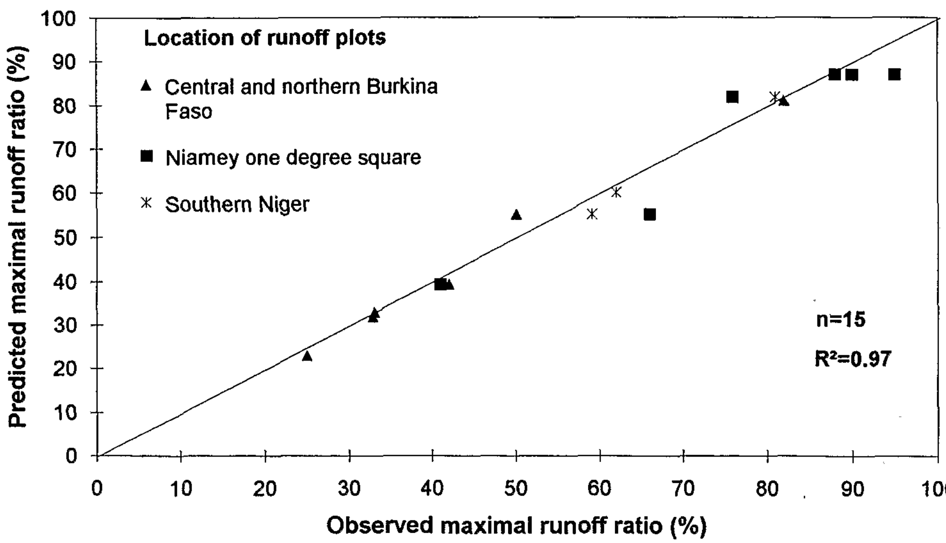

Fig. 7. Observed maximal runoff ratio (Table 8) and predicted wet runoff ratio (Table 5) values of maximal runoff ratio.

3.1.10. Mid-old low grass fallow (3–7 years)

This unit occurs in Sub-regions I, II, V and VI, mostly on sandy skirts, dunes and plateaux and in the lower parts of hillslopes. *Guiera senegalensis* forms a sparse mono-specific shrub layer. This unit consists of a mosaic of bare spots capped with erosion crusts and sandy micro-mounds covered with a herb layer in which *Zornia glochidiata* D.C. is the most abundant species. These surface conditions are very common throughout the Sahelian zone and have high runoff ratios.

3.1.11. Recent fallow (3 years)

This poorly represented unit consists of a patchy herbaceous layer with a very sparse woody component. The cover is not sufficient to protect the soil surface from the impact of rainfall, and structural and erosion crusts tend therefore to develop.

3.1.12. Hillslope high density field

This unit consists of plots cropped with pearl millet (*Pennisetum glaucum*) where stand establishment has been successful. The hand-tool used by farmers for periodic weedings (usually twice during the crop season) disrupts the structural crusts that tend to develop on the soil surface and the runoff production depends therefore upon the cumulated rainfall since the last weeding operation (Peugeot et al., 1997).

3.1.13. Hillslope low density field

This unit consists of plots where millet did not establish satisfactorily. Cowpea (*Vigna unguiculata*) is frequently intercropped with poor millet but does not provide any significant cover to the soil.

3.1.14. Valley bottom high density field

This unit consists of sandy valley bottoms where millet or sorghum (*Sorghum bicolor*) are frequently intercropped with cowpea, sorrel (*Hibiscus sabdariffa*), or sesame (*Sesamum indicum*). Soil moisture conditions favour the development of a substantial vegetation cover which limits crusting and favours infiltration. This unit also includes the sandy fans of the gullies located at the bottom of the sandy skirts. (Fig. 6).

3.1.15. Valley bottom low density field

This unit occupies fragile, convex toe-slopes. Soils are slightly richer in silt and clay than the previous unit and are more prone to crusting. Unlike Unit 14, the soil cover remains sparse and is insufficient to limit runoff and consequent water erosion.

3.1.16. Surficial waters

In addition to the Niger River, this unit includes temporary water courses and ponds.

3.2. Hydrological validation

Fifteen sites in Niger and northern Burkina Faso for which field observations of runoff ratios are available were classified according to the 16 map classes described here. These sites fell into nine of the 16 classes (Table 8). For each site the wet runoff ratio in Table 5 was plotted against the field measurements of the maximal runoff ratio (Fig. 7). A good agreement was observed.

4. Discussion

Many difficulties encountered in this study arose from the requirements to maintain as much as possible the preliminary classification system adopted in the overall HAPEX-Sahel measurement campaign that consisted of just tiger bush, bush-fallow and millet classes.

By way of illustration, all shrub bushland on the plateaux cannot be regarded as tiger bush. In a detailed study, based on the structure of individual thickets, Ambouta (1984) distinguished five types: diffuse, spotted, leopard, punctuated and tiger bush. The resolution of multispectral scenes of SPOT (20 m) did not enable us to detect individual thickets that are most often 15–30 m broad. This problem was alleviated by the use of panchromatic SPOT images with a higher resolution (10 m) which indicated that the bushland type seems to be controlled, at least partly, by slight variations in slope gradient (Delbaere, 1994).

SPOT HRV images cannot detect a sparse bush cover lower than 16% (Huete, 1986). However, even a low density of *Guiera senegalensis* bushes may play an important role in the dynamics and the hydrological behaviour of a bush-fallow (Delabre, 1993). Conversely, a dense herbaceous layer of mature *Cassia mimosoïdes* L. can be readily detected, and possibly confused with a dense woody cover because of its dark colour when dry, but this type of cover has quite different hydrological and ecological characteristics from a dense woody cover (Loireau, 1993).

Compared with field observations, remote sensing data tend to overestimate the area occupied by millet fields (Loireau, 1993). In particular, the extent of map Unit 11 (recent fallow) has certainly been underestimated since recent fallows can easily be confused with fields. Farming practices in the Sahel mean that a field cannot be regarded as a stable entity over time. The area cleared during the dry season generally exceeds the area that is actually sown during the following rainy season. Owing to the erratic character of rainfall, farmers often have to sow several times in the early season and each time the sown area may change depending of the available labour. Similarly, the frequency of weeding operations, which have an important effect on soil cover, crusting and runoff capability is highly variable according to rainfall regime and labour availability. Consequently in late September (the date of the SPOT HRV scenes), a range of situations can be found, from a millet field without weeds and a large proportion of bare and crusted soil, to a bush-fallow which has been cleared a few months previously and where vegetation regrowth has been extensive. Such a source of confusion can lead to very equivocal image classification and hydrological predictions. Moreover owing to the temporal variability, extrapolation of the data collected in July or August using a map derived from late September can be misleading.

4.1. Sites representativeness

The issue of site representativeness must be addressed at each stage of upscaling, from the local measurements site to supersite, from the supersite to the 1° square, from the 1°

square to the Sahelian region. For the first aggregation step, the 1° square map can help to determine the class of a local measurement site and thus its representativeness within a supersite. For the ECSS, the map based on a more thorough classification of the 1992 SPOT data provides the most accurate basis for extrapolation.

One way to examine the representativeness of the supersites is to explore the extent to which they represent the sub-regions. Fig. 3 clearly shows that the two largest supersites (ECSS and WCSS) are located in Sub-region II, the largest within the 1° square. The southern supersite is located near the ICRISAT Sahelian Center, in the smallest sub-regions (VI and III). The sub-site on the plateau in the southern supersite was in tiger bush which is more representative of Sub-region II than III. Altogether, the three supersites can be considered as representative of nearly 50% of the 1° square. In the context of the Sahel as a whole, it seems sensible to have not sampled Sub-region V (Dallol Bosso), the characteristic of which can be considered as rather localized. However the lack of measurements in Sub-regions I, III and IV is more serious. In particular, the variability of vegetation types on the plateaux has not be fully accounted for; the plateaux in Sub-regions I and IV are generally more covered with sand deposits than in Sub-region II, and vegetation patterning is more conspicuous in Sub-region II than in Sub-regions I, III and IV.

The representativeness of the surface conditions in the 1° square is indicated by a regional inventory (Casenave and Valentin, 1989). The choice of the Niamey 1° square led to an over-representation of the plateaux and sandy environments. Two important surface conditions in the Sahel were not sampled; gravely and clayey plains. For gravely plains, data collected in sites belonging to Class 4 are some help. Nevertheless the ubiquitous presence of sand in the 1° square renders it difficult to extrapolate the results to Vertisols and other clayey environments which can by no means be ignored in the Sahel especially when considering soil moisture–atmosphere interactions.

Another problem lies in the representativeness of the vegetation of the 1° square in the context of the Sahel as a whole. Its most obvious character is its extremely poor species diversity of both herbs and woody species. The predominance of *Guiera senegalensis* in almost all landforms and soils seems to be very rare in the Sahel. In the absence of any comparison in the literature between the Niamey region and other parts of the Sahel of biomass production or biodiversity, firm conclusions cannot be drawn. However the Niamey region is generally regarded as very poor in biodiversity and productivity (P. Hiernaux, personal communication, 1992), possibly because of the very low soil fertility. Soils are primarily derived from the Continental Terminal, either directly or through aeolian and alluvial sand deposits that originated from these parent materials. As shown by West et al. (1984) at the ICRISAT Centre, these soils are very low in mineral reserves and lack minerals which can weather to release nutrients like phosphate and other exchangeable bases. The very low clay and organic matter content further reduces natural fertility of these soils (Bationo and Mokwunye, 1991).

4.2. Surface conditions and runoff production

Recent studies in the ECSS confirm the major role of surface conditions on runoff (Peugeot et al., 1997), and hence on soil moisture distribution (Galle and Peugeot, 1993; Seghieri et al., 1994). In particular, it was shown that the type of surface crust as referred to the classification of Valentin and Bresson (1992) controls infiltration (Vandervaere et al., 1994) and evaporation (Le Fèvre et al., 1994). Since the predicted values of runoff ratio are derived from data obtained on 1-m^2 microplots in other Sahelian region, two issues must be addressed: (1) can these data been used in the Niamey region; (2) to what extend can they be extrapolated to larger areas? Considering Table 8 and Fig. 7, it appears that the use of the classification of Sahelian unit surfaces (Casenave and Valentin, 1992) can be applied in the region at scales ranging from 50 m^2 to 5000 m^2. This means that the aggregation of unit surfaces into a map unit works with respect to predicted runoff ratio for areas that correspond approximately to the dimensions of 1 to 5 pixels on SPOT multispectral images. This, along with preliminary results indicating that combining remote sensing data and the unit surface method can be applied satisfactorily at the scale of small watersheds of northern Burkina Faso (Chevallier et al., 1985; Albergel et al., 1987), seem to suggest that the combination of remote sensing and unit surface classification can be used up to the watershed scale. However, it might be hazardous to apply this method at scales larger than fields, hillslopes and pond catchments because, for larger watersheds, the hydrological network is too discontinuous in the region of Niamey, due to the aeolian and colluvial sand deposits in the valley bottoms and possibly fractures in the Continental Terminal (Estèves and Lenoir, 1994).

Merging the 16 classes into nine and six classes resulted in ranges of the mean runoff ratio that could not be distinguished between classes, particularly in the cases of bush-fallow and millet fields (Table 6 and Table 7).

5. Conclusion

1. Some possible confusion between recent bush-fallows and millet fields occurred because of the limitation of SPOT data which can not detect woody cover lower than 16%. This corresponds to a whole range of conditions between a freshly cleared land that is left uncultivated to a regularly weeded millet field, leading to confusing ecological and hydrological interpretations.
2. The supersites selected for the HAPEX-Sahel study can be considered as representative of nearly 50% of the surface conditions of the whole 1° × 1° square, but some major Sahelian components such as clayey plains were not measured. Extrapolation of data collected during the campaign to the whole Sahelian region may also be hindered by the local conditions in the region of Niamey as indicated by the very low diversity of herbaceous and woody species.
3. Predicted values of runoff ratio were found to be consistent with observed values collected from runoff plots in the Niamey region and in other, similar Sahelian situations.
4. This simple hydrological model can be regarded as satisfactory to predict runoff production for small areas, e.g. pixel (20 × 20 m), fields, hillslope and catchments supplying ponds of 1–10 km^2. It can assist therefore hydrologists and ecologists in explaining the distribution of soil moisture and vegetation at this scale. However, runoff prediction from remote sensing data cannot be applied to larger areas because of the discontinuity of the hydrological network in the region.

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References

Albergel, J., 1987. Genèse et prédétermination des crues au Burkina Faso. Du m^2 au km^2, étude des paramètres hydrologiques et de leur évolution. Ph.D. Dissertation, University of Paris, 336 pp.

Albergel, J., Chevallier, P. and Lortic, B., 1987. D'Oursi à Gagara: transposition d'un modèle de ruissellement dans le Sahel (Burkina Faso). Hydrol. Cont., 2: 77–86.

Ambouta, K.J.M., 1984. Contribution à l'édaphologie de la brousse tigrée de l'Ouest nigérien. Doctor-Engineer Thesis, University of Nancy, 116 pp.

Bationo, A. and Mokwunye, A.U., 1991. Alleviating soil fertility constraints to increased crop production in West Africa; the experience in the Sahel. Fert. Res., 29: 95–115.

Bui, E.N., 1986. Relationships between pedology, geomorphology and stratigraphy in the Dallol Bosso of Niger, West Africa. Ph.D. dissertation, Texas A&M University, College Station, Texas.

Bui, E.N., Mazzulo, J.M. and Wilding, L.P., 1989. Using quartz grain size and shape analysis to distinguish between aeolian and fluvial deposits in the Dallol Bosso of Niger (West Africa). Earth Surf. Landforms, 14: 157–166.

Bui, E.N., Dixon, J.B., Shafdan, H. and Wilding, L.P., 1990. Geomorphic features and associated iron oxides of the Dallol Bosso of Niger (West Africa). Catena, 17: 41–54.

Casenave, A. and Valentin, C., 1989. Les États de Surface de la Zone Sahélienne. Influence sur L'infiltration. ORSTOM, Paris, Collection "Didactiques", 230 pp.

Casenave, A. and Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. J. Hydrol., 130: 231–249.

Chevallier, P. and Valentin, C., 1984. Influence des microorganisations pelliculaires superficielles sur l'infiltrabilité d'un type de sol sahélien. Bull. Groupe Fr. d'Humidimétrie Neutronique, 17: 9–22.

Chevallier, P., Claude, J., Pouyaud, B. and Bernard, A., 1985. Pluies et Crues au Sahel. Hydrologie de la Mare d'Oursi (Burkina Faso). 1976–1981. ORSTOM, Paris, Collection Travaux et Documents No. 190, 251 pp.

Collinet, J., 1988. Comportements hydrodynamiques et érosifs de sols de l'Afrique de l'Ouest. Evolution des matériaux et des organisations sous simulation de pluies. Ph.D, University of Strasbourg, 521 pp.

Collinet, J. and Valentin, C., 1979. Analyse des différents facteurs intervenant sur l'hydrodynamique superficielle. Nouvelles perspectives. Applications agronomiques. Cah. ORSTOM, Sér. Pédol., 17: 283–328.

Courault, D., d'Herbes, J.M., Valentin, C. and Rémy, D., 1991a. Etude de la variabilité spatiale du comportement hydrodynamique des sols au Niger à partir d'images satellitaires. In: 5th Int. Colloq. Physical Measurements and Signatures in Remote Sensing. 14–18 January 1991, Courchevel, France. ESA SP-319, pp. 601–604.

Courault, D., d'Herbes, J.M. and Valentin, C., 1991b. Caractéristiques spectrales des principales organisations de la surface du sol du Niger. In: M. Pouget (Editor), Caractérisation et Suivi des Milieux Terrestres en Régions Arides et Tropicales. ORSTOM, Paris, Collection Colloques et Séminaires, pp. 39–47.

Commission Pédologique de Classification des Sols (CPCS), 1967. Classification des Sols. Ecole Nationale Supérieure d'Agronomie, Grignon, France, 87 pp.

d'Herbès, J.M., Courault, D., Timouk, F. and Valentin, C., 1992. Spatio-carte des états de surface du degré carré de Niamey. ORSTOM, HAPEX-Sahel, SALT, Niamey.

d'Herbès, J.M., Valentin, C. and Mougenot, B., 1994. Spatiocarte SPOT des états de surface du degré carré de Niamey, échelle 1:200 000, scènes du 25 Septembre 1992. ORSTOM, Niamey.

Delabre, E., 1993. Une Typologie Structurale des Jachères à *Guiera Senegalensis* du Sud-Ouest Nigérien. ENGREF, Montpellier, 56 pp.

Delbaere, E., 1994. Identification de la Structure des Écosystèmes Contractés Sahéliens par Télédétection Aérienne et Satellitaire. Facteurs du Milieu Déterminant ces Structures. ISTOM, Cergy-Pontoise, 75 pp.

Estèves, M. and Lenoir, F., 1994. Un exemple de fonctionnement hydrologique dans la région de Niamey: le bassin de Sama Dey. In: 20th Hydrological Meeting, ORSTOM, Montpellier, pp. 127–137.

Galle, S. and Peugeot, C., 1993. Soil water spatial distribution of tiger bush in Niger. In: American Geophysical Union Fall Meeting, Supplement to EOS, pp. 252–253.

Gavaud, M. and Boulet, R., 1967. Carte Pédologique de Reconnaissance de la République du Niger. Feuille de Niamey à 1/500.000. Vols. 1–3, ORSTOM, Dakar, 1120 pp.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer J., Dolman, A.J., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y.A., Monteny, B., Prince, S., Said, F., Sellers, P. and Wallace, J.S., 1994. HAPEX-Sahel: a large-scale study of land–atmosphere interactions in the semi-arid tropics. Ann. Geophysicae, 12: 53–64.

Greigert, J. and Pougnet, R., 1967. Notice explicative sur la carte géologique de la République du Niger à l'échelle du 1/2 000 000. B.R.G.M., Paris, 62 pp.

Hoogmoed, W.B., 1986. Crusting and sealing problems on West African soils. In: F. Callebaut, D. Gabriels and M. De Boodt (Editors), Assessment of Soil Surface Sealing and Crusting. Flanders Research Centre for Soil Erosion and Soil Conservation, pp. 48–55.

Hoogmoed, W.B. and Klaij, M.C., 1990. Soil management for crop production in the West African Sahel. I. Soil and climate parameters. Soil Tillage Res., 16: 85–103.

Hoogmoed, W.B. and Stroosnijder, L., 1984. Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. Soil Tillage Res., 4: 5–23.

Huete, A., 1986. Separation of soil plant spectral mixtures by factors analysis. Rem. Sens. Environ., 19: 237–251.

International Society of Soil Science (ISSS), International Soil Reference and Information Centre (ISRIC), Food and Agriculture Organization of the United Nations (FAO), 1994. World Reference Base for Soil Resources. Wageningen, Rome, 161 pp.

Lamotte, M., 1992. Etude pédologique en vue d'un suivi hydrique sur le bassin versant de Sama-Dey (Niger). ORSTOM, Bondy, France, 18 pp.

Le Fèvre, J., Lamotte, M. and Peugeot, C., 1994. L'évaporation pendant la saison humide au sein d'un sol sableux de la région de Niamey (Niger). In: 20th Hydrological Meeting, ORSTOM, Montpellier, pp. 243–260.

Legger, D. and van der Aa, M., 1994. Soils of the West central site, Niger. Hapex–Sahel 1992. Report, Wageningen Agricultural University, 31 pp.

Loireau, M., 1993. Caractérisation de l'espace et des resources à l'aide de la télédétection spatiale haute résolution. M.Sc., University of Montpellier, 123 pp.

Loireau, M. and d'Herbès, J.M., 1994. Cartographie des unités d'occupation des terres du Super-site central est (Banizoumbou) du programme Hapex–Sahel. In: 20th Hydrological Meeting, ORSTOM, Montpellier, pp. 307–322.

Manu, A., Geiger, C., Pfordresher, A., Taylo-Powell, E., Mahamane, S., Ouattara, M., Issaka, M., Salou, M., Juo, A., Puentes, R. and Wilding, L.P., 1991. Aménagement intégré des bassins versants agricoles (IMAW). Caractérisation d'un site de recherche pres de Hamdallaye, Niger. Bulletin de TropSoils, The Fuller Corporation, Bryan, Texas, No. 91-03, 82 pp.

Nagumo, F., 1993. Pedological environment and agro-ecological system of the Sudano–Sahelian zone in Niger, West Africa. Ph.D., University of Hokkaido, Japan, 90 pp.

Ouattara, L., 1992. Etude des relations pluviométrie–phénologie–production dans la zone sud-ouest du Sahel nigérien. M.Sc., Université de Niamey, 40 pp.

Perez, P., 1994. Genèse du ruissellement sur les sols cultivés du Sud Saloum (Sénégal). Du diagnostic à l'aménagement de parcelle. Ph.D. Dissertation, Montpellier, 250 pp.

Peugeot, C., Estèves, M., Rajot, J.L., Vandervaere, J.P. and Galle, S., 1997. Runoff generation processes: results and analysis of field data collected at the ECSS. J. Hydrol., this issue.

Pias, J. and Rieffel, J.M., 1978. Etude Pédologique du Plateau de Dyabou. République du Niger. ORSTOM, Paris, 43 pp.

Piot, J. and Millogo, E., 1980. Lutte contre l'aridité dans l'Oudalan. Etude du ruissellement et de l'érosion à Oursi-Kolel. Synthèse de 3 années (1977, 1978, 1979). CTFT, Ouagadougou, 17 pp.

Poesen, J., 1986. Surface sealing on loose sediments: the role of texture, slope and position of stones in the top layer. In: F. Callebaut, D. Gabriels and M. De Boodt (Editors), Assessment of Soil Surface Sealing and Crusting. Flanders Centre for Soil Erosion and Soil Conservation, pp. 354–362.

Rahman, H., and Dedieu, G., 1994. SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum. Int. J. Remote Sensing, 15(1): 123–143.

Rajot, J.L. and Estèves, M., 1994. Cartographie des états de surface de petits bassins versants de la région de Niamey. ORSTOM, Niamey, 10 pp.

Roose, E., 1981. Dynamique Actuelle de Sols Ferrallitiques et Ferrugineux Tropicaux d'Afrique Occidentale. Etude Expérimentale des Transferts Hydrologiques et Biologiques de Matières sous Végétations Naturelles ou Cultivées. ORSTOM, Paris, Collection Travaux et Documents, No. 130, 569 pp.

Roose, E. and Piot, J., 1984. Runoff, Erosion and Soil Fertility Restoration on the Mossi Plateau (Central Upper Volta). International Association for Hydrological Sciences, Publ. No. 144, pp. 485–498.

Seghieri, J., Galle, S. and Rajot, J.L., 1994. La brousse tigrée dans le Sahel nigérien: étude de la cofluctuation du stock hydrique et de la végétation annuelle. In: 20th Hydrological Meeting, ORSTOM, Montpellier, pp. 603–613.

Soil Survey Staff, 1975. Soil Taxonomy. A Basic System on Soil Classification for Making and Interpreting Soil Surveys. Soil Conservation Service, US Department of Agriculture, Agriculture Handbook No. 436, Washington, DC, USA, 754 pp.

Thiéry, J., d'Herbès, J.M. and Valentin, C., 1995. A model for simulating the genesis of banding patterns in Niger. J. Ecol., 83: 497–507.

Valentin, C., 1986. Surface crusting of arid sandy soils. In: F. Callebaut, D. Gabriels and M. De Boodt (Editors), Assessment of Soil Surface Sealing and Crusting. Flanders Research Center for Soil Erosion and Soil Conservation, Ghent, pp. 40–47.

Valentin, C. and Bresson, L.M., 1992. Morphology, genesis and classification of soil crusts in loamy and sandy soils. Geoderma, 55: 225–245.

Valentin, C. and Casenave, A., 1992. Infiltration into sealed soils as influenced by gravel cover. Soil Sci. Soc. Am. J., 56: 1167–1673.

Van der Watt, H.V.H. and Valentin, C., 1992. Soil crusting: the African view. In: M.E. Sumner and B.A. Stewart (Editors), Soil Crusting. Chemical and Physical Processes, Advances in Soil Science. Lewis Publ., Boca Raton, USA, pp. 301–338.

Vandervaere, J.P., Jaramillo, R.A., Peugeot, C. and Vauclin, M., 1994. Caractérisation hydrodynamique in situ de sols encroûtés. In: 20th Hydrological Meeting, ORSTOM, Montpellier, pp. 603–613.

West, L.T., Wilding, L.P., Landeck, J.K. and Calhoun, F.G., 1984. Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas A&M University System, College station, Texas.

Wilding, L.P. and Daniels, R., 1989. Soil–geomorphic relationships in the vicinity of Niamey, Niger. TropSoils Bulletin No. 89-01, Raleigh, USA, 34 pp.

Zanguina, I., 1994. Estimation des Pertes en Terre dans le Bassin Versant de Hamdallaye. INRAN, Niamey.

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