*Journal of Hydrology*, 130 (1992) 231–249
Elsevier Science Publishers B.V., Amsterdam



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# A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa

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(Received 11 April 1990; revised and accepted 23 March 1991)

ABSTRACT

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.

An analysis of the factors influencing infiltration and runoff was carried out using data obtained under simulated rainfall conditions on 87 plots in arid and semi-arid areas of West Africa, arranged in a hierarchical sequence. One of the key factors to emerge from this typological classification is the type of surface crust. Together with faunal activity, vegetation cover and surface roughness, this parameter permits the inclusion of a 'unit surface' factor in the classification system. Each unit surface is characterized in terms of genetic, morphological and hydrological properties.

At a higher level, the combination of these unit surfaces allows a 'soil surface features unit' to be defined, based on an original mapping method. The samples, once defined in this system, were found to correspond to homogeneous criteria both in terms of evolution dynamics and hydrological behaviour. Furthermore, such cartography could be successfully extrapolated through remote sensing image analysis, making possible a classification of the runoff capability of small watersheds based on objective and standardized criteria.

## INTRODUCTION

A better understanding of basic hydrological processes is critical for effective watershed management, particularly in semi-arid countries of West Africa where inadequacy of water supply is a major limitation to development. Reliable predictions of runoff from ungauged catchments are therefore essential. To permit the extrapolation of results to unstudied watersheds, typical parameters of flow and surface runoff, especially those of 10-year flood (volume, maximal flow, flood hydrograph) have been related to physiographical and environmental characteristics of the watershed (size, shape and slope, type of climate, rocks, soils, vegetation). However, whatever the method, either in the explanatory synthesis of flow (Dubreuil and Vuillaume, 1975;

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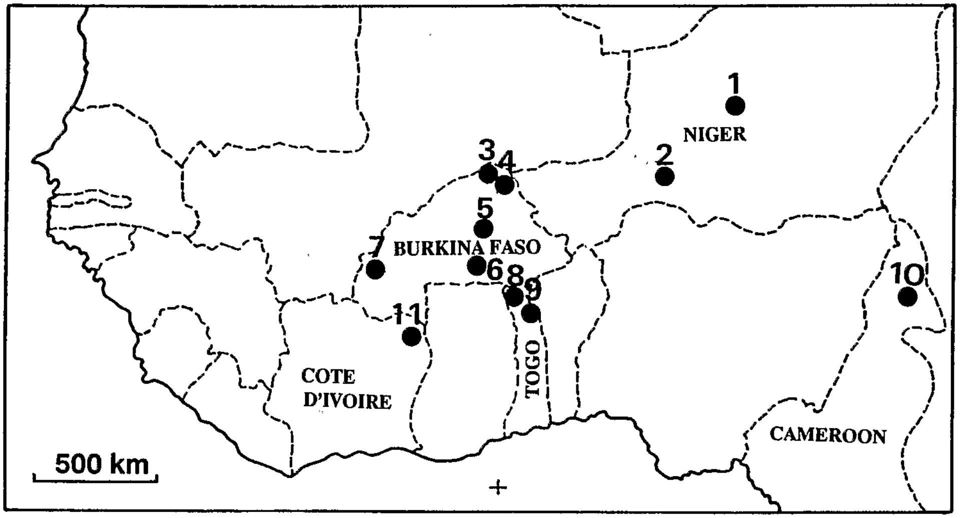


Fig. 1. Location map. The names of the study sites are given in Table 4.

Dubreuil et al., 1975; Rodier, 1975), or in the prediction of the 10-year floods of small basins (Rodier and Auvray, 1965; Puech and Chabi-Gonni, 1983), all analyses have fallen short of expectations owing to the difficulty in quantifying the runoff characteristics of different soils or the average permeability of watersheds. Thus, a knowledge of factors influencing infiltration is critical.

In the semi-arid zones, topography seems to have a minor influence on runoff production (Dunne and Leopold, 1978) compared with surface conditions, such as vegetation cover (Smith and Leopold, 1942; Wilcox et al., 1988) and surface crusting, as shown by researchers in Israel (Morin and Benyamini, 1977) and in Mali (Hoogmoed and Stroosnijder, 1984). Nevertheless, the data are widely dispersed and it is unclear whether they can be derived readily from one region to another. This situation called for the implementation of a programme involving hydrologists and soil scientists.

To gain a better insight into the runoff production processes, a sprinkling infiltrometer was designed (Asseline and Valentin, 1978) to simulate on 1 $m^2$ plots. The data obtained in various French-speaking African countries (Niger, Burkina Faso, Togo, Ivory Coast and Cameroon; Fig. 1) permitted a determination of the factors influencing infiltration and runoff over a large geographical area and the establishment of a hierarchy among them (Albergel et al., 1986a; Valentin, 1986). Statistical analysis of data obtained from 87 tests plots of the semi-arid zone (mean annual rainfall < 850 mm) showed that three surface conditions: vegetation cover, faunal activity and intensity of surface crusting accounted for 84% of the variance of infiltration ratio.

The object of this paper is to present a typological classification of surface conditions. It is based on the concept of 'unit surface'. This represents a homogeneous body of land surface at a given time. It is composed of the grass cover, the soil surface and superficial layers that have been subjected to changes resulting from meteorological, faunal, or human-induced factors (Casenave and Valentin, 1989). This concept permits relevant characterization of the semi-arid environment in terms of hydrological properties and classification of the runoff capability of small watersheds based on objective and standardized criteria.

## MATERIAL AND METHODS

### *The ORSTOM rainfall simulator*

The device consists of a sprinkler system mounted at a height of 4 m connected to a constant flow pump. An oscillating motion is applied to the nozzle. Any change in the oscillating angle modifies the area of the irrigated surface and hence the simulated rainfall intensity on the experimental 1 $m^2$ plot, in a range between 30 and 150 mm $h^{-1}$. Kinetic energies of artificial rainfall range from 14 to 25 J $mm^{-1}$ $m^{-2}$ at 30 and 150 mm $h^{-1}$, respectively, and thus are very similar to those of natural tropical rainfall (Valentin, 1991). Accumulated waterflows are collected in a graded tank and measured with a high-accuracy water level recorder (accurate to 10 s and 0.1 mm; Asseline and Valentin, 1978).

### *Simulated rainfall procedure*

In order to simulate realistic conditions, the procedure used had to respect a certain number of constraints regarding the intensity and number of rainfall events. The following limits were set:

(1) rainfall events must be unimodal to reflect the most common form in the Sahel area;

(2) the volume of rainfall should not exceed the depth of daily rainfall of annual or decennial frequency. These amounts refer to the long-term records at the nearest rain-gauge station;

(3) simulated rainfall on an experimental plot should not exceed the mean annual rainfall;

(4) the parameters of intensity, duration, and frequency should be in accordance with those of the study area.

Each experimental plot was submitted to a series of showers, usually six, separated by drying periods ranging from 12 to 72 h. The range of intensities varied between 30 and 150 mm $h^{-1}$. Each plot permitted the study of the behaviour of a 'unit surface', whereas, each experimental site, consisting of three to five plots permitted the hydrological characterization of a 'surface features unit'.

As the direct measurement of soil moisture in the gravelly soils, which occur commonly in the semi-arid area, is problematic, the initial soil moisture was evaluated using an index of exponential form which takes into account the volume of the previous rainfall events as well as the elapsed time between them. This antecedent precipitation index (API) is currently used for inputs into hydrological models (Alikhan et al, 1972; Papadakis and Pruel, 1973). Blanchard et al. (1981) and Rosenthal et al. (1982) related API to surface soil-moisture content. The 0.5 value for $\alpha$ in eqn. (1) was found best adapted to simulate the variations of the soil moisture in the upper 5 cm (Casenave, 1982). This is shown in the equation:

$$IK_n = (IK_{n-1} + P_{n-1})e^{-\alpha t} \qquad (1)$$

where $IK$ is the value of the index before rain $n$, $IK_{n-1}$ is the value of the index before rain $n-1$, $P_{n-1}$ is the depth of rainfall $n-1$, and $t$ is the time in fraction of days, separating rain $n-1$ from the beginning of rain $n$.

### *Hydraulic variables*

A certain number of variables were selected to characterize runoff and infiltration of each unit surface.

#### *Depth of surface runoff*

The set of simulated rainfall events on a given plot permits the establishment of the relationship between the depth of surface runoff $L_r$ (mm), the depth of rainfall $P_u$ (mm) and the initial soil moisture, evaluated through the index $IK$ (Casenave, 1982):

$$L_r = AP_u + BIK + CP_uIK + D \qquad (2)$$

This equation is applied to every main unit surface (Table 1).

#### *The prerunoff rainfall* $\bar{P}_r$

'$P_r$' is the depth of rainfall infiltrated or stored on the surface before runoff occurs. As it depends upon antecedent soil moisture, two values were considered: $P_{rd}$ corresponding to extremely dry soil ($IK = 0$, $pF > 4.2$), and $P_{rw}$ corresponding to an almost saturated soil ($IK > 80$, $pF$ well below 3).

TABLE 1

Depth of surface runoff for types of unit surfaces

| Surface type | Depth of surface runoff |
|---|---|
| C1 | $L_r = 0.20\,P_u + 0.03\,IK + 0.004\,P_uIK - 3.0$ |
| C2 | $L_r = 0.35\,P_u + 0.04\,IK + 0.004\,P_uIK - 3.0$ |
| C3 | $L_r = 0.90\,P_u + 0.05\,IK + 0.002\,P_uIK - 10.0$ |
| TW | $L_r = 0.05\,P_u + 0.01\,IK + 0.001\,P_uIK - 1.0$ |
| W | $L_r = 0.10\,P_u + 0.05\,IK + 0.002\,P_uIK - 3.0$ |
| DRY | $L_r = 0.30\,P_u + 0.01\,IK + 0.003\,P_uIK - 8.0$ |
| ST2 | $L_r = 0.50\,P_u + 0.02\,IK + 0.004\,P_uIK - 10.0$ |
| ST3 | $L_r = 0.85\,P_u + 0.01\,IK + 0.003\,P_uIK - 8.0$ |
| SED | $L_r = 0.80\,P_u + 0.08\,IK + 0.001\,P_uIK - 12.0$ |
| ERO | $L_r = 0.95\,P_u + 0.09\,IK + 0.001\,P_uIK - 9.0$ |
| G | $L_r = 0.99\,P_u + 0.05\,IK + 0.001\,P_uIK - 6.0$ |

*Infiltration ratios*

For each simulated rainfall, the depth of infiltrated rainfall is calculated as the difference between the rainfall depth and the runoff depth. After the experiments are completed in a given plot, the infiltration ratio is defined as:

$$K_i = (SL_i/SP_u) \times 100 \tag{3}$$

where $SL_i$ with cumulated depth of infiltration, and $SP_u$ is the cumulated depth of rainfall.

Besides this ratio, which accurately reflects the average infiltration capability of the unit surface, two other ratios were calculated for a given rainfall of 50 mm and two levels of antecedent soil moisture:

$$K_{i_0} = [P_u - L_r(P_uIK)]/P_u \tag{4}$$

where $P_u = 50$ and $IK = 0$ (dry soil).

$$K_{i_{20}} = [P_u - L_r(P_uIK)]/P_u \tag{5}$$

where $P_u = 50$ and $IK = 20$ (wet soil).

*Critical rainfall intensity*

The relation between the rainfall intensity, $I$ (mm h$^{-1}$), and the maximum runoff intensity, $R_x$ (mm h$^{-1}$), was assessed after each simulated rainfall event (Casenave, 1982). This regression curve, which is generally a straight line, intersects the abscissa at a point which is the critical rainfall intensity below which no runoff occurs at a given antecedent soil moisture. In this study, we considered the critical value $I_l$ as assessed for the highest $IK$ index. As the soil, under these conditions, is almost saturated, the value of $I_l$ is very similar to the hydraulic saturated coefficient $K_{sat}$ (Valentin, 1991) and can be considered as a characteristic of the unit surface.

## RESULTS: THE TYPOLOGICAL CLASSIFICATION OF THE MAIN ARID AND SEMI-ARID UNIT SURFACES

### *Identification criteria*

As previously mentioned in the Introduction, the statistical analysis of results obtained has demonstrated that infiltration capacity depends upon surface characteristics. In decreasing order of influence, these are: surface crust, vegetation cover, faunal activity, surface roughness, vesicular porosity, and soil texture.

*The main surface crusts in the arid and semi-arid areas*
From analysis of the processes and factors involved in surface crusting, Casenave and Valentin (1989) proposed a morphogenetically based classification of the main surface crusts in the arid and semi-arid areas of West Africa. Thus, nine main types of crust were differentiated according to texture and number and texture of microlayers (sandy or plamic, namely made of fine particles) as well as structure of the outcropping microlayer (Table 2, Fig. 2).

*Vegetation (or crop) cover*
Vegetation cover is defined broadly to include the living plants as well as organic residues on the ground surface. This cover protects the soil against external factors (rain, wind) which mainly influence superficial rearrangement of soil particles.

*Faunal activity*
Faunal activity has a direct impact on infiltration through the increased 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.

*Soil surface roughness*
Irregularities of the ground ranging from 5 to 50 cm, either natural or human-induced, account for the surface roughness, a factor which is likely to reduce runoff and increase surface water storage. It is characterized by its relief and the rate of obstruction, which is calculated according to the continuity of the obstacle and the angle it forms with the steeper slope.

TABLE 2

Main features and properties of the different types of surface crust in the semi-arid zone of West Africa

| Type | Structure | Thickness (mm) | Strength | Porosity |
|---|---|---|---|---|
| Drying | Massive single sandy microhorizon | 5–10 | Very low | High |
| Structural 1 | Rough surface made of coalescing partially slaked aggregates | > 10 | Low | Moderate |
| Structural 2 | Laminated, a sandy microlayer over a thin seal of finer particles | 1–3 | Moderate | Moderate |
| Structural 3 | Laminated, coarse sandy layer at the top vesicular fine sandy layer, seal of finer particles at the bottom | 1–3 | Moderate | Low |
| Erosion | Smooth surface made of a single seal of fine cemented particles | < 1 | High | Very low |
| Aeolian | Laminated, interbedding of sandy microlayers | 2–50 | Low | High |
| Runoff depositional | Laminated, interbedding of sandy microlayers and seals of finer particles | 2–50 | Moderate | Low |
| Sedimentary | Laminated, larger particles at the top, finer at the bottom | 2–50 | Moderate | Low |
| Gravel | Laminated, similar to structural 3, including coarse fragments | 2–30 | High | Very low |

*Vesicular porosity*

One finds, very frequently, in the microlayers of surface crusts, some vesicles which are more or less abundant and can account for high porosity (Figueira and Stoops, 1983; Valentin, 1991). However, this type of porosity is not functional in transmitting water as the pores are not interconnected. They are formed when the air is entrapped as a result of the low soil diffusivity (Evenari et al., 1974). Such porosity can be considered as a useful indicator of unfavourable conditions for infiltration. Indeed, a highly significant relationship can be established between the abundance of the vesicular pores, as assessed in the surface microlayers, and the surface runoff capacity measured under rainfall simulation (Albergel et al., 1986a).

*Soil texture*

The texture of the top soil, to a depth of 40 cm, plays a role as a modifier in the typological system. Three textural classes were identified: sandy (sand

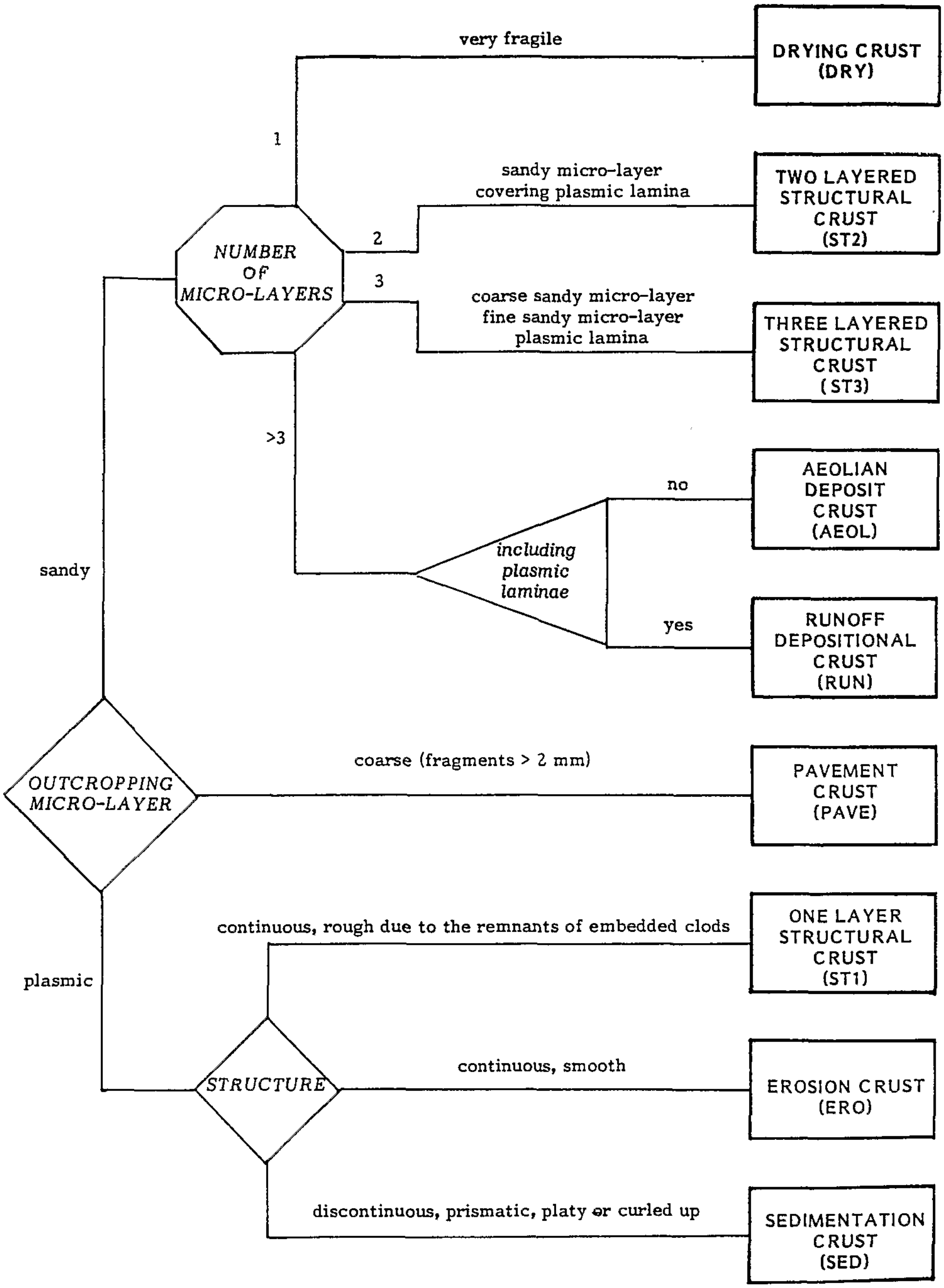


Fig. 2. Diagram of the main Sahelian crusts.

fraction > 90%), clayey (clay fraction > 40%) and medium (sand fraction < 90% and clay fraction < 40%). Several studies have shown that the texture most prone to sealing consists of approximately 90% sand and 10% silt or clay (Poesen, 1988).

### The key of the unit surfaces

#### Non-tested surfaces

Some unit surfaces of the arid and semi-arid areas, though identified, were not tested by rainfall simulation. These include:

(1) Outcrops of rocks or iron pans. Besides the fact that it is impossible to anchor a plot under these conditions, their infiltration capability largely depends on the density and the width of fracture networks.

(2) Vertisols. For a similar reason, the mesh of the crack network in most cases is greater than 1 $m^2$, these soils were not taken into account in the classification system. Yet, referring to the experience of the authors, values ranging from 5 to 15% for $K_i$, $K_{i_0}$ and $K_{i_{20}}$ can be confidently expected in the heart of the rainy season. For the same period, values for $I_l$, $P_{rd}$ and $P_{rw}$ can be estimated at 1–5 mm $h^{-1}$, 5–10 mm and 0–5 mm, respectively.

(3) Pervious granite arenas. These surfaces, previously identified in watersheds in northern Chad have not been described in the study area.

(4) Shifting sand dunes. Their infiltration ratio can be reliably evaluated at 95–100%.

#### Hydromorphic soils

Hydromorphy conspicuously influences infiltration, but in practice, any type of unit surface may occur on hydromorphic soils and the measured values of infiltration vary greatly accordingly. As the wetting front seldom reaches 80 cm in the study area, three classes were distinguished according to the depth, $d$ (cm), of the hydromorphic features. These depth classes refer to the densest rooting zones of grass (0–20 cm) and trees (0–40 cm):

(1) 40 cm $< d <$ 80 cm: the average values of infiltration parameters associated with unit surface type must be reduced by 20–30%;

(2) 20 cm $< d <$ 40 cm: reduction of 40–60%;

(3) 0 cm $< d <$ 20 cm: reduction of 80–100%.

### The main types of unit surfaces

The typological classification of unit surfaces is based upon a number of criteria which have been defined above. The determination key, as referred to in the main criteria, is presented in Fig. 3. In order to represent the whole

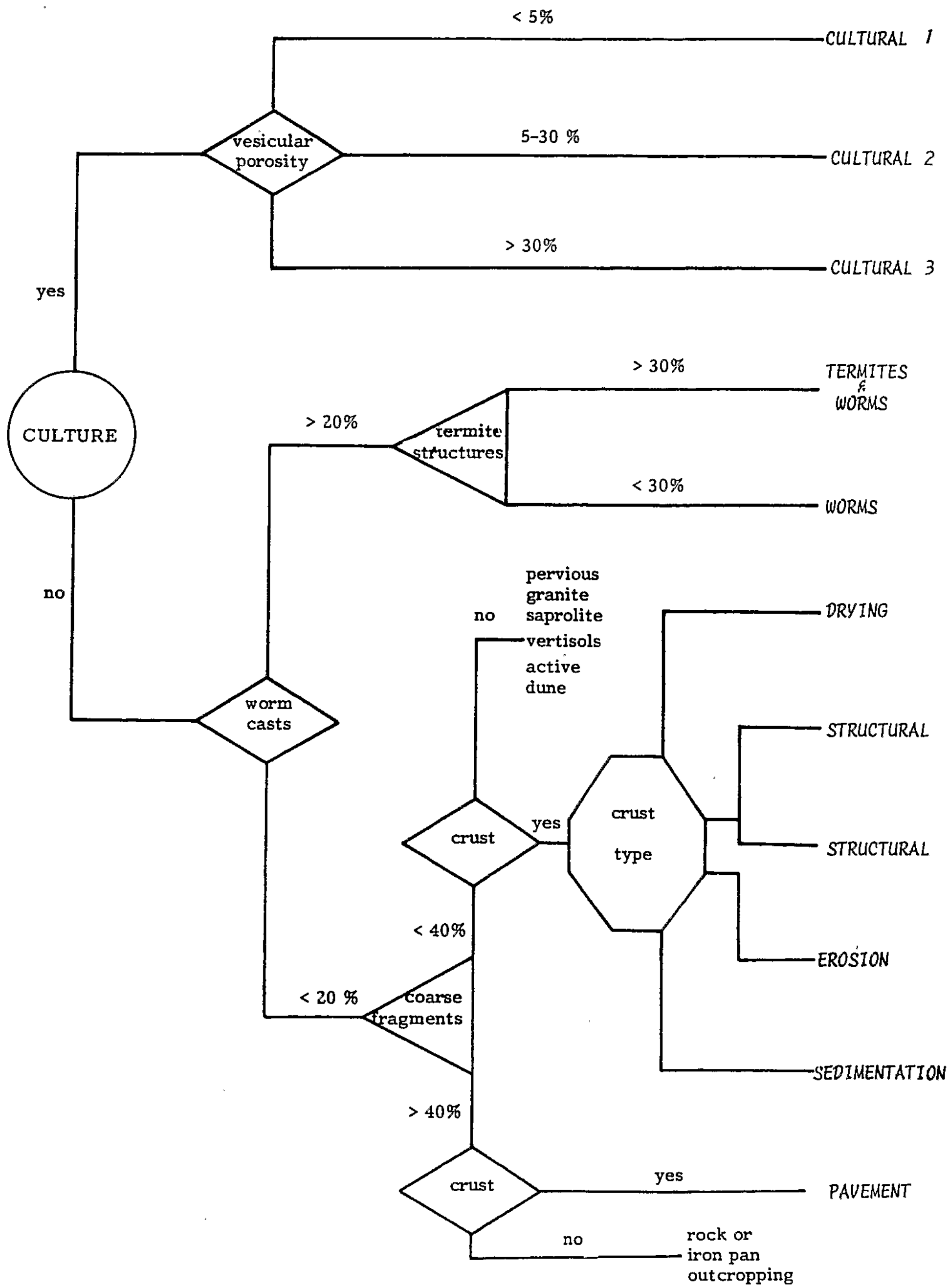


Fig. 3. Diagram of the main Sahelian unit surfaces.

TABLE 3

Infiltration values for the different types of unit surfaces

| Surface type | Modifiers | $K_i$ (%) | $K_{i_0}$ (%) | $K_{i_{20}}$ (%) | $I_l$ (mm h$^{-1}$) | $P_{rd}$ (mm) | $P_{rw}$ (mm) |
|---|---|---|---|---|---|---|---|
| C1 | – | 60–75 | 80–90 | 75–85 | 15–25 | 25–30 | 5–15 |
| C1 | 1 | 80–95 | 90–100 | 85–95 | 25–35 | 30–40 | 20–30 |
| C1 | 2 | 40–50 | 55–65 | 45–55 | 7–15 | 5–15 | 1–5 |
| C2 | – | 40–60 | 60–80 | 50–70 | 1–7 | 8–12 | 2–4 |
| C2 | 1 | 60–75 | 80–90 | 75–90 | 10–20 | 15–25 | 5–10 |
| C2 | 2 | 15–25 | 25–40 | 20–30 | 1–5 | 8–12 | 2–4 |
| C3 | – | 15–25 | 25–40 | 20–30 | 0–3 | 8–15 | 2–4 |
| C3 | 1 | 40–60 | 60–80 | 50–70 | 5–10 | 20–30 | 5–10 |
| TW | – | 85–100 | 95–100 | 90–100 | 25–40 | 25–35 | 10–20 |
| W | – | 70–85 | 90–100 | 85–95 | 10–15 | 25–35 | 10–20 |
| DRY | – | 60–75 | 80–90 | 75–85 | 10–20 | 20–30 | 10–20 |
| DRY | 1 | 40–50 | 60–70 | 50–60 | 5–10 | 10–20 | 1–5 |
| DRY | 2 | 85–100 | 90–100 | 90–100 | > 30 | > 30 | > 20 |
| ST2 | – | 40–55 | 60–75 | 50–65 | 5–15 | 10–20 | 3–6 |
| ST2 | 1 | 60–70 | 80–90 | 75–85 | 10–20 | 20–30 | 5–10 |
| ST3 | – | 15–25 | 25–40 | 20–30 | 0–5 | 3–7 | 2–5 |
| ST3 | 1 | 45–55 | 60–70 | 55–65 | 10–15 | 10–15 | 5–10 |
| SED | – | 20–35 | 35–55 | 25–45 | 0–2 | 4–10 | 4–7 |
| SED | 1 | 45–55 | 65–75 | 55–65 | 4–7 | 15–20 | 8–10 |
| ERO | – | 10–20 | 15–30 | 10–25 | 0–2 | 2–6 | 0–5 |
| ERO | 1 | 20–30 | 35–50 | 30–40 | 2–4 | 10–15 | 3–7 |
| G | – | 5–15 | 5–20 | 3–15 | 0–2 | 1.5–5 | 0–3 |
| G | 1 | 15–30 | 20–35 | 15–25 | 3–5 | 5–10 | 0–5 |
| G | 2 | 30–40 | 50–60 | 35–50 | 7–12 | 10–15 | 3–7 |
| G | 3 | 50–70 | 70–80 | 60–75 | 10–20 | 15–25 | 10–20 |
| G | 4 | 85–100 | 90–100 | 85–95 | 20–30 | 10–20 | 5–15 |

range of surface conditions, some criteria had to be included in the system as modifiers: vegetation cover, texture, surface roughness. These characteristics do not alter the definition of the unit surface, but they do influence the infiltration values. The definitions of the 11 main types of unit surfaces are given below and their hydrological characteristics are listed in Tables 1 and 3.

*Surface of cultural 1 type: C1*

Definition:

A cultivated surface where the vesicular porosity is less than 5%. This surface corresponds either to the absence of crust, or to a dominant structural crust — a single microlayer including the remains of slaked aggregates.

Modifiers:
(1) the vegetation cover exceeds 50% of the surface;
(2) coarse fragments cover more than 40% of the surface.

*Surface of cultural 2 type: C2*
Definition:
A cultivated surface with a vesicular porosity of between 5 and 30%. The runoff depositional crust usually covers less surface than with the structural ST1 or the erosion ERO types.
Modifiers:
(1) the magnitudes of either surface roughness or obstruction are high;
(2) the topsoil is clayey.

*Surface of cultural 3 type: C3*
Definition:
A cultivated surface with a vesicular porosity over 30%. This unit surface is usually associated with a dominant runoff depositional crust.
Modifier:
(1) the magnitudes of either surface roughness or obstruction are high.

*Surface of termite and earthworms type: TW*
Definition:
A non-cultivated surface with a minimum of 20% earthworm casts and a minimum of 30% termite harvesting constructions. This surface is always associated with an important vegetation cover (or residue cover) and is found only in areas where the mean annual rainfall exceeds 700 mm.

*Surface of worm type: W*
Definition:
A non-cultivated surface with a minimum of 20% earthworm casts and less than 30% termite harvesting constructions. It is found only in areas where the mean annual rainfall exceeds 700 mm.

*Surface of drying type: DRY*
Definition:
A non-cultivated surface with a maximum of 20% earthworm casts and a maximum of 40% coarse fragments without crust or with a drying crust. These surfaces are generally observed on sandy soils with a vegetation cover exceeding 50%.
Modifiers:
(1) the vegetation cover is less than 50%;

(2) the surface develops on layers of loose sands and is at least 30 cm deep (for example, a shifting microdune).

*Surface of structural 2 type: ST2*

Definition:

A non-cultivated surface with a maximum of 20% earthworm casts and a maximum of 40% coarse fragments, covered with a structural crust comprising two microlayers (Table 2).

Modifier:

(1) the vegetation cover exceeds 50%.

*Surface of structural 3 type: ST3*

Definition:

A non-cultivated surface with a maximum of 20% earthworm casts and a maximum of 40% coarse fragments covered with a structural crust comprising three microlayers (Table 2).

Modifier:

(1) the vegetation cover exceeds 50% or the topsoil is sandy (microdune, sand deposits).

*Surface of sedimentation type: SED*

Definition:

A non-cultivated surface with a maximum of 20% earthworm casts and a maximum of 40% coarse fragments covered with a sedimentation crust (Table 2), overlaying another crust or/and clayey topsoil.

Modifier:

(1) the sedimentation crust covers a non-crusted or a drying-crusted soil.

*Surface of erosion type: ERO*

Definition:

A non-cultivated surface with a maximum of 20% earthworm casts and a maximum of 40% coarse fragments, sealed with an erosion crust (Table 2).

Modifier:

(1) the erosion crust overlays a sandy soil.

*Surface of pavement type: G*

Definition:

A non-cultivated surface with a maximum of 20% earthworm casts and more than 40% coarse fragments, with the major part of the coarse fragments embedded in a three microlayered crust (Table 2).

Modifier:
(1) either the plasmic seal does not exist or is discontinuous;
(2) the plasmic seal does not exist and the amount of free gravel (not embedded in the crust) exceeds 50%;
(3) the surface is not crusted (presence of free gravel only);
(4) the soil is developed on dolerite or other 'green rock' (rare crust and important grass cover).

*Validation of the system*

To evaluate the applicability of the classification system, it was tested on 22 plots not included in the previous sample. These plots are scattered over a large region, three being located at Agassaghas (Fig. 1, No. 1) near Agadez (Niger), seven at Polaka (Fig. 1, No. 3) near Oursi, (northern Burkina Faso) and 12 at Mouda (Fig. 1, No. 10) near Maroua (northern Cameroon). The procedures and the simulated rainfall patterns differed considerably from those of the sample. This may account for certain discrepancies, especially in $P_r$ values which largely depend upon rainfall intensity. Therefore, the test mainly concerned the $K_i$ values. For 22 plots, 13 values of $K_i$ fell in the range of predicted values. For five other plots, the difference between the predicted and the measured $K_i$ remained below 5%. Thus, it can be inferred that the estimate was relatively accurate for 18 plots out of 22, i.e. 82% of the sample. For four values of poorly estimated $K_i$, the deviations were 8%, 14%, 14% and 17%, respectively.

For values of $I_l$, 14 fell in the predicted range or were close to it, totalling 64% of the sample. While $P_{rd}$ was correct for only 55% of the sample, $P_{rw}$ was correct for 73%, which shows that the influence of the rainfall intensity is less for a nearly saturated soil than for a dry soil.

This predictive model has also been tested on plots located in wetter regions:

(1) six on the watershed of Nadjoundi, in northern Togo where the mean annual rainfall is 1070 mm (Fig. 1, No. 8);

(2) eleven on the watershed of Hidenwou, in northern Togo where the mean annual rainfall is 1225 mm (Fig. 1, No. 9);

(3) eight on the watershed of Varale, in northern Ivory Coast where the mean annual rainfall is 1150 mm (Fig. 1, No. 11).

Of these 25 plots, 16 have values of $K_i$ within the predicted range whereas three are less than 5% beyond the limits. These represent 76% of the total sample. $I_l$ is correctly estimated for 53% of the sample, $P_{rd}$ for 36% and $P_{rw}$ for 76%.

*Hydrological application*

It was demonstrated that it was possible to subdivide the soil-surface type into a limited number of homogeneous hydraulical units, i.e. the 'unit surfaces'. Owing to the overwhelming number of possible combinations among these surfaces, a new concept, the 'surface features unit' had to be defined to characterize the environmental conditions at a higher level, i.e. that of the small watershed. This term can designate:

(1) one unit surface of important size, such as a 'reg' for example, made of the pavement type surface (G);

(2) the juxtaposition of many unit surfaces, for example a steppe with two unit surfaces: bare and crusted patches (ERO) surrounding grassy micromounds (DRY);

(3) a system of unit surfaces, i.e. a group within which interactions occur, as in the stippled tiger-bush pattern for example (including the unit surface type DRY in the thickets and ST3, ERO, G, and SED in the bare patches).

This concept was used to develop a new method of environmental mapping (Valentin, 1986). Mapping units facilitate modelling of the hydrological behaviour of the watershed as a whole, by combining the parameters of runoff production, namely the relations $L_r$ ($P_u$, $IK$) of the unit surfaces forming the units, in proportion to the surface area occupied (Albergel et al., 1986b).

This model was tested on 15 small watersheds in Africa. The results are reported in Table 4. The savannah watershed in Comba, Congo, was selected to illustrate the method as available data were most numerous (mean annual rainfall: 1400 mm).

The percentages of surface occupied by the various unit surfaces were defined after the surface conditions survey: 41% ST3, 27% G1, 23% TW, 5% ERO, and 4% C1.

The runoff depth was then calculated as:

$$L_{rc} = 0.41\,L_{r_1}\,\mathrm{ST3} + 0.27\,L_{r_2}\,\mathrm{G} + 0.23\,L_{r_3}\,\mathrm{TW} + 0.05\,L_{r_4}\,\mathrm{ERO} + 0.04\,L_{r_5}\,\mathrm{C1} \quad (6)$$

where the associated equations given in Table 2 can be substituted for $L_{r_i}$. Hence:

$$L_{rc} = 0.61\,P_u + 0.026\,IK + 0.002\,P_u IK - 6.24 \quad (7)$$

The values of $P_u$ were those recorded by the rain-gauge in the centre of the watershed. $IK$ was derived from $P_u$. Regression equations between calculated

TABLE 4

Calculated ($L_{rc}$) and observed ($L_{ro}$) runoff depths on 15 small African catchments

| Catchment name | No. on Fig. 1 | Size ($km^2$) | Regression of $L_{ro}$ on $L_{rc}$ | Period of record | $R^2$ | Number of events |
|---|---|---|---|---|---|---|
| Agassaghas | 1 | 5.8 | $L_{ro} = 0.81\,L_{rc} - 4.3$ | 1978–85 | 0.83 | 40 |
| Kountkouzout | 2 | 16.6 | $L_{ro} = 0.52\,L_{rc} - 1.7$ | 1964–67 | 0.92 | 67 |
| Jalafanka | 3 | 0.81 | $L_{ro} = 0.69\,L_{rc}$ | 1976–82 | 0.84 | 63 |
| Polaka | 3 | 9.1 | $L_{ro} = 0.48\,L_{rc}$ | 1976–80 | 0.77 | 77 |
| Gagara E. | 4 | 35.0 | $L_{ro} = 0.66\,L_{rc}$ | 1985 | 0.91 | 15 |
| Gagara W. | 4 | 24.3 | $L_{ro} = 0.80\,L_{rc}$ | 1985 | 0.85 | 15 |
| Kognere | 5 | 19.8 | $L_{ro} = 0.60\,L_{rc} - 2.3$ | 1984 | 0.91 | 9 |
| Binnde | 6 | 9.7 | $L_{ro} = 1.39\,L_{rc}$ | 1982–83 | 0.88 | 38 |
| Kazanga | 6 | 54.8 | $L_{ro} = 1.10\,L_{rc}$ | 1982 | 0.89 | 16 |
| Kuo | 7 | 67.8 | $L_{ro} = 0.44\,L_{rc} - 5.51$ | 1974–76 | 0.93 | 17 |
| Nadjoundi | 8 | 19.0 | $L_{ro} = 0.74\,L_{rc} - 1.8$ | 1962–63 | 0.94 | 44 |
| Hidenwou | 9 | 23.2 | $L_{ro} = 1.7\,L_{rc} - 3.8$ | 1962–64 | 0.95 | 33 |
| Mouda 1 | 10 | 18.1 | $L_{ro} = 1.2\,L_{rc}$ | 1984–85 | 0.96 | 84 |
| Mouda 2 | 10 | $3.10^{-3}$ | $L_{ro} = L_{rc}$ | 1984–85 | 0.96 | 83 |
| Comba | – | 1.18 | $L_{ro} = 1.10\,L_{rc} - 1.5$ | 1972–76 | 0.91 | 109 |

($L_{rc}$) and observed ($L_{ro}$) runoff depths from the watershed were:

$$L_{rc} = 0.855\,L_{ro} + 2.52 \tag{8}$$

$$L_{ro} = 1.069\,L_{rc} - 1.51 \tag{9}$$

with

$$R^2 = 0.914, \qquad \text{for } n = 109 \tag{10}$$

The standard deviation on $L_{ro}$ (4.4 mm) reflected reasonable predictions of the floods (Fig. 4). This example shows that the simple proposed model can be applied in a wetter zone, provided surface features are similar to those of a semi-arid zone and promote heavy runoff.

## CONCLUSIONS

The results clearly illustrate the dominant role of surface conditions in runoff production in the semi-arid zone of West Africa. In particular, it was shown that various types of crusts can occur and thus induce different types of hydrological behaviour. Besides the well-known effect of vegetation as a runoff limiting factor, the favourable influence of faunal activity upon infiltration was also evidenced by our results.

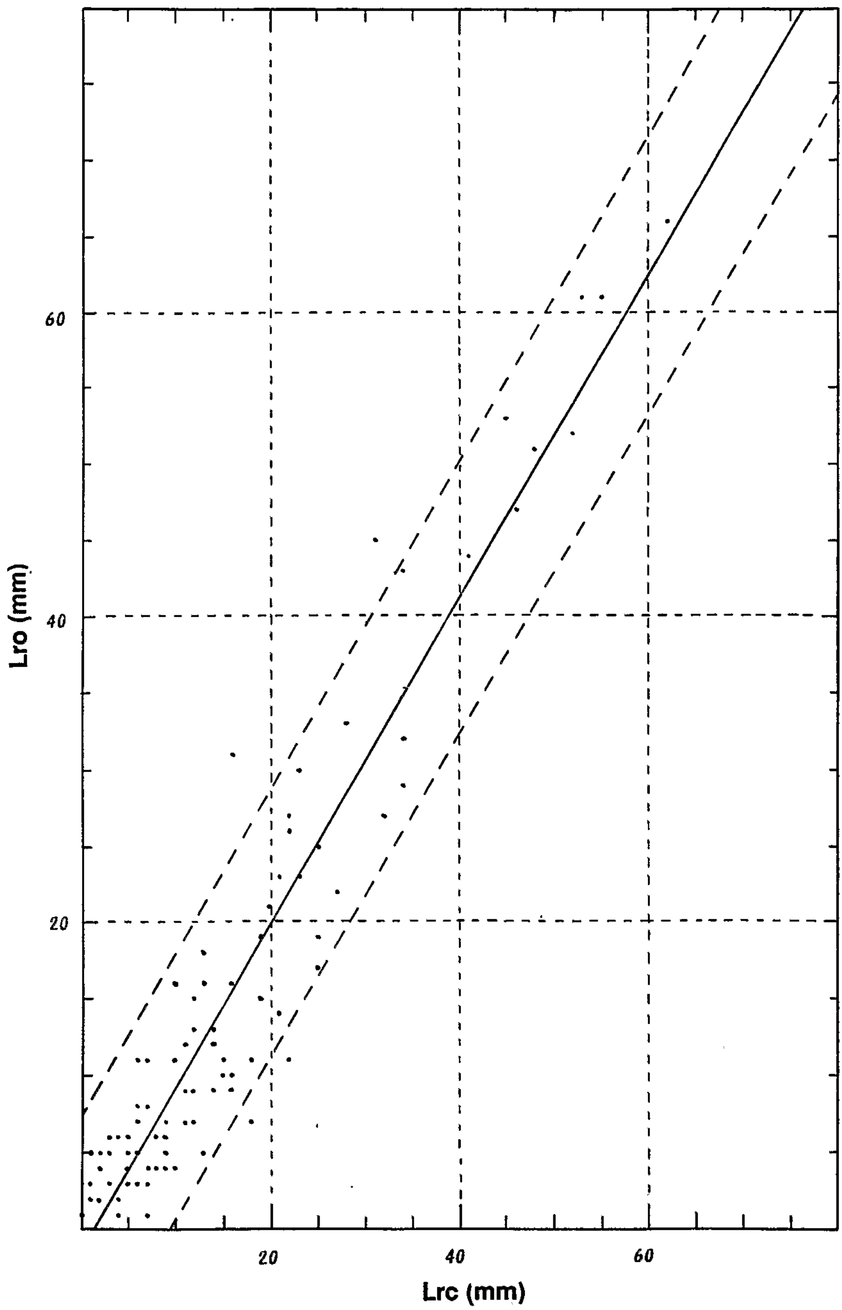


Fig. 4. Comparison of predicted ($L_{rc}$) and observed ($L_{ro}$) runoff depths from the Comba watershed. The dotted lines indicate the 95% confidence limits.

At the small watershed scale, the proposed method can give reliable results within the semi-arid zone where Horton overland flow is dominant. However, it would be unrealistic to apply this method for predicting runoff from ungauged catchments. At present, this approach permits an assessment of the parameters of the 10-year flood within 1 year while 3 to 5 years were usually necessary under these climatic conditions. It consists of collecting data from the outlet of the catchment over a period of 1 year and applying the simple proposed model. Inputs are climatic data and percentages of 'units surfaces' obtained from a surface conditions map.

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