Hillslope dynamics of on-farm generation of surface water flows: The case of rain-fed cultivation of pearl millet on sandy soil in the Sahel

J. Rockström a,*, C. Valentin b

a Natural Resources Management, Department of Systems Ecology, Stockholm University, S-10691 Stockholm, Sweden
b ORSTOM, BP 114 16, Niamey, Niger

Accepted 9 September 1996

Abstract

Results from on-farm measurements of surface overland flow of both runon (Ron) and runoff (Roff) are presented for a continuously cultivated pearl millet (Pennisetum glaucum (L.) R.Br.) field, along a characteristic catena, in the Sahel (Niger). Despite the deep sandy soil along the studied hillslope, classified as a Typic Haplustult, non-negligible depths of Roff were measured during two rainy seasons: 12–13% of total rainfall for the upslope position and 6–8% for the downslope position. This was explained by the presence of surface crusts with low infiltrability. Upslope, more than 30% of the soil surface was covered with erosion crusts (runoff coefficient (Kr) = 60–70% for moist soil conditions) during 40% of the rainy season. The mean coverage of erosion crust for two rainy seasons was 26% upslope, compared with 11% and 15% midslope and downslope, respectively.

Weeding, carried out manually with hand hoes, had a very positive effect on soil infiltrability. The destruction of surface crusts resulted in zero Roff (Kr = 0) for rainstorms directly following weeding operations. However, surface crusts were quickly re-established as a result of the erosive effect of the following storms.

Large volumes of runon (Ron) water were measured at the upslope limit of the field (14.4 m³ m⁻¹ in 1995, corresponding to a rainfall depth of 47.5 mm if redistributed over the 8.5 ha millet field). Small volumes were registered downslope (Ron = 0.75 m³ m⁻¹), indicating redistribution of Ron along the hillslope. The Ron originated from the upstream degraded fallow zone and the adjacent sparsely vegetated plateau, which in effect functioned as water-harvesting zones.

* Corresponding author. Tel: +46 (0)8 16 12 83. Fax: +46 (0)8 15 84 17. e-mail: jrock@system.ecology.su.se.

0378-3774/97/$17.00 © 1997 Published by Elsevier Science B.V. All rights reserved.

P11 S0378-3774(96)01282-6
184 J. Rockström, C. Valentin / Agricultural Water Management 33 (1997) 183–210

$R_{\text{off}}$ was modelled based on field observations of surface coverage of soil crusts, data on hydraulic characteristics for the observed crusts, rainfall data and estimates of antecedent soil moisture. Despite high variance in the observed $R_{\text{off}}$, the model provides a reasonable estimate of $R_{\text{off}}$, indicating the possibility of predicting $R_{\text{off}}$ on cultivated fields where crust coverage changes quickly over time.

The large volumes of measured overland flow suggest that $R_{\text{on}}$ and $R_{\text{off}}$ cannot be excluded from on-farm water-balance studies. The findings also indicate the potential of developing water-harvesting systems for protective irrigation during the frequent periods of water stress in the rain-fed Sahelian agriculture. © 1997 Published by Elsevier Science B.V.

Keywords: Rain-fed agriculture; Runoff; Sahel; Semi-arid; Surface crust; Water harvesting

1. Introduction

In sub-Saharan Africa, 97% of the agriculture is presently rain-fed (FAO, 1995). This agriculture will, for the foreseeable future, supply food for growing populations in the African drylands (Parr et al., 1990; FAO/UNDTCD/UNDP, 1991). Water is a major limiting factor in arid and semi-arid tropical agriculture (Lal, 1991). Maximizing rain-use efficiency (RUE) is therefore an important issue for dryland farmers (Le Houérou, 1984; Gregory, 1989). In the Sudano-Sahelian zone in West Africa, it is not necessarily the limited annual rainfall that is a constraint in crop production, but rather the proportion of rainfall that enters the rootzone and becomes plant-available soil moisture (Sivakumar and Wallace, 1991). At the same time soils are in general very poor in nutrients, especially phosphorous (Bationo and Mokwunye, 1991), which means that nutrients and moisture alternate in being the primary limiting factor for crop growth (Klaij and Vachaud, 1992; Brouwer et al., 1993).

One way to achieve higher RUE is to increase the infiltration capacity of the soil surface in order to diminish losses of water through overland flow. This is important in the Sahel region, where the combination of crust-sensitive sandy soils and erratic rainfall events result in a high risk of runoff generation (Casenave and Valentin, 1992; Serpantié et al., 1992). Runoff production is, apart from rainfall characteristics, largely governed by soil surface conditions such as soil crusts and vegetation cover (Hoogmoed and Stroosnijder, 1984; Wilcox et al., 1988; Alberge1 et al., 1992). These factors have been affected by the diminishing length of fallow periods in the region during the last few decades (World Bank, 1989; Matlon, 1990; Rockström, 1995).

Topography seems to have a minor influence on runoff production in semi-arid zones like the Sahel, compared with surface conditions such as vegetation cover and surface crusts (Dunne and Leopold, 1978). However, the landscape relief can have an important role in favouring overland flow from degraded and impermeable upstream zones in a watershed.

Crop water balance studies in the Sahel, in general carried out on-station in experimental plots, often either assume runoff ($R_{\text{off}}$) and runon ($R_{\text{on}}$) to be zero (Lal, 1991; Klaij and Vachaud, 1992), or ensure that no overland flow will affect the experiments conducted (see, for example, Payne et al., 1990). Measured $R_{\text{off}}$ in cultivated experimental fields has been reported to be very low, not exceeding 1.5% of
the rainfall depth (Hoogmoed et al., 1991). Low \( R_{\text{off}} \) production despite high-intensity rains has been explained by the high hydraulic conductivity (> 100 mm h\(^{-1}\)) of the predominantly deep sandy soils in cultivated fields. In the above cases, the following water balance is valid for dryland agriculture (Klaij and Vachaud, 1992):

\[
P = E_T + D + \Delta S
\]

(1)

where \( P \) is rainfall, \( E_T \) is evapotranspiration, \( D \) is drainage and \( \Delta S \) is the change in soil moisture storage in the rootzone.

The assumption of zero or very low \( R_{\text{off}} \) is rarely valid under on-farm conditions. In these cases input and output terms for overland flow are added to the water balance.

\[
P + R_{\text{on}} = R_{\text{out}} + R_{\text{off}} + E_T + D + \Delta S
\]

(2)

\( R_{\text{on}} \) and \( R_{\text{off}} \) reflect the dynamics of inflow of water from upstream zones \( (R_{\text{on}}) \) and the partitioning of rainfall between infiltration and overland flow \( (R_{\text{off}}) \) due to soil surface conditions. \( R_{\text{out}} \) is the throughflow of \( R_{\text{on}} \) that does not infiltrate within the studied system.

This paper presents the results from measurements of \( R_{\text{off}} \) and \( R_{\text{on}} \) production in a farmer's field in the Sahelian zone of Niger. The field measurements of \( R_{\text{off}} \) are used to validate a model for predicting \( R_{\text{off}} \) based on observations of soil surface features. The objective is to present a tool for predicting \( R_{\text{off}} \), and to present data on the spatial redistribution and the production of overland flow in a field continuously cultivated with pearl millet \( (\text{Pennisetum glaucum (L.) R.Br.}) \) on sandy soil in the Sahel.

2. Materials and methods

2.1. Crust types

Because we will refer throughout this paper to a classification system of surface conditions (Valentin and Bresson, 1992) based on the typology proposed by Casenave and Valentin (1992), we present the main characteristics of the types encountered on our site in Table 1. The structural crusts ST2 and ST3, also called sieving crusts, develop in

<table>
<thead>
<tr>
<th>Surface type (unit surface)</th>
<th>Structure</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivated surface 1 (C1)</td>
<td>Surface with no crust, vesicular porosity &lt; 5%</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>Drying crust (DRY)</td>
<td>Massive single sandy microhorizon</td>
<td>5–10</td>
</tr>
<tr>
<td>Structural crust No. 2 (ST2)</td>
<td>Laminated, a sandy microlayer over a thin seal of finer particles</td>
<td>1–3</td>
</tr>
<tr>
<td>Structural crust No. 3 (ST3)</td>
<td>Laminated, coarse sandy layer at the top, followed by a vesicular fine sandy layer, and a seal of finer particles at the bottom</td>
<td>1–3</td>
</tr>
<tr>
<td>Erosion crust (ERO)</td>
<td>Smooth surface made of a single seal of fine cemented particles</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Adapted from Casenave and Valentin, 1992.
sandy soils (Valentin, 1986; Greene and Ringrose-Voase, 1994; Bielders and Baveye, 1995a). They are made up of two contrasting layers. The uppermost layer, 1–5 mm thick, consists of loosely packed sand with the coarser particles usually concentrated at the surface (more pronounced in ST3 than in ST2). Vesicles are common. The underlying layer is 0.1–1 mm thick. It contains a high amount of fine particles, with a very low porosity. The upper and lower boundaries of this clayey layer are sharp. The impact of raindrops on sandy soils results in a winnowing process which leads to an inverse sorting of soil particles in relation to sedimentation crusts; the finer the particles,

Fig. 1. (A) A bird’s-eye view of the landscape catena. [1], plateau; [2], degraded fallow zone; [3], farmers millet field; [4], lowland depression zone; [5], principle gullies; [6], experimental site (the broken line corresponds to the topographic map in (C)); [7], the well (located at the bottom of the watershed). Adapted from aerial photographs taken in 1992 during the HAPEX-Sahel project. Converted to a 1:5000 scale map by Timouk (1994). (B) Schematic illustration of the toposequence. Numbers correspond to those in (A). (C) Topographic map over the farmers' pearl millet fields, including the experimental plots.
the deeper they are concentrated. Filtration of the fine particles can enhance this initial sorting (Valentin, 1986; Valentin, 1991; Bielders and Baveye, 1995b). The erosion crust consists of only one thin, 0.1–1 mm thick, plasmic layer which is very dense and coherent. It results from the erosion of a sieving crust. When the loose coarse-textured upper layer is removed by overland flow and/or by wind, the underlying clayey layer
outcrops (Valentin, 1986; Valentin, 1991). This exposed thin clayey layer progressively becomes denser with increased erosion.

2.2. Field site

The field site is located in the Samadey watershed (approximately 10 km²) situated about 70 km east of Niamey, the capital of Niger. This watershed constituted a part of the East Central Supersite during the HAPEX-Sahel experiment in 1992 (Goutorbe et al., 1994). The research was carried out in the small endorheic watershed surrounding the village of Samadey in the northern part of the watershed (02°41'50E, 13°35'5N). The experimental site, illustrated in Fig. 1, consists of a 315 m x 270 m millet field located on a hillslope. The relatively uniform slope along the field varies between 2 and 3% with a slightly higher slope at the top (2.9%) than at the bottom (2.0%). The site forms part of a typical catena of the Sahelian landscape (Fig. 1(B)) (d'Herbès and Valentin, 1997).

Upstream (Zone 1 in Fig. 1(A) and (B)) we find a dissected laterite-capped plateau dominated by soils with low infiltrability. Here the saturated conductivity (Ksat) for structural and sedimentary crusts (Valentin and Bresson, 1992) has been measured as 0.18–0.31 cm h⁻¹ (Peugeot et al., 1997). The vegetation on the plateau is sparse and organised in alternating bands of bush vegetation, mainly *Guiera senegalensis* (L.), in tiger bush formations. These plateaux, covering 28.2% of the geographical area (1 x 1°) surrounding the Niamey region (d'Herbès and Valentin, 1997), function as water harvesting zones, producing surface water that flows down the primarily sandy hillslopes in water-eroded gullies and rills (between Zones 1 and 4 in Fig. 1(A) and (B)).

The gullies (Index 5 in Fig. 1(A)) transport water to the bottom of the watershed, eventually saturating the more clayey soils of the lowland depression zone (Index 4 in Fig. 1(A) and (B)). There is no baseflow, i.e. all gullies are ephemeral, producing R_on only during rainfall events.

Pearl millet is cultivated in the deep, sandy mantled hillslopes. A millet field is often delimited by two gullies. The zone between the plateau and the upstream limit of the cultivated field (Index 2 in Fig. 1(A) and (B)) consists of a degraded fallow with a steep edge slope up to the plateau. This uncultivated zone generates R_on, due to low infiltrating erosion crusts and rills, which flows into the millet field, and eventually spreads into flat, sandy zones and infiltrates.

The experimental field is used for subsistence cultivation of pearl millet, and has been under continuous cultivation for at least 20 years. The pearl millet is cultivated manually using traditional Sahelian practices (McIntire and Fussell, 1989), including sparse sowing (millet pockets 1–1.5 m apart) after the onset of the first real rain (in May/June, generally exceeding 15 mm), followed by thinning and two series of weeding operations during the growing season (90–120 days).

There is spatial variability in soil characteristics along the field (Table 2) with a more distinct diagnostic horizon and a redder hue upslope compared with a more yellow and cation-rich downslope. However, classification resulted in a Typic Haplustult (USDA Soil Taxonomy) for the whole field. The content of organic matter is low (on average 0.25%), as is the base saturation (BSU) in the subsoil (32%) and the effective cation
Table 2
Soil characteristics for the upslope and downslope positions along the hillslope

<table>
<thead>
<tr>
<th>Horizons</th>
<th>Depth</th>
<th>Texture (%)</th>
<th>Class</th>
<th>Bulk density</th>
<th>ECEC</th>
<th>BSU</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Clay (&lt;2 μm)</td>
<td>Silt (2-50 μm)</td>
<td>Sand (50 μm-2 mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>g cm⁻³</td>
<td></td>
<td>(%)</td>
</tr>
<tr>
<td>Upslope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0-15</td>
<td>3.1</td>
<td>5.7</td>
<td>91.2</td>
<td>Sand</td>
<td>1.65</td>
<td>17.9</td>
</tr>
<tr>
<td>Bt</td>
<td>15-40</td>
<td>10.1</td>
<td>4.0</td>
<td>85.9</td>
<td>Loamy sand</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>40-130</td>
<td>8.9</td>
<td>3.9</td>
<td>87.2</td>
<td>Loamy sand</td>
<td>1.52</td>
<td>8.0</td>
</tr>
<tr>
<td>C2</td>
<td>130-(225)</td>
<td>16.3</td>
<td>5.5</td>
<td>78.2</td>
<td>Sandy loam</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>Downslope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0-30</td>
<td>3.8</td>
<td>5.8</td>
<td>90.4</td>
<td>Sand</td>
<td>1.63</td>
<td>24.6</td>
</tr>
<tr>
<td>Bt</td>
<td>30-100</td>
<td>10.2</td>
<td>4.9</td>
<td>84.9</td>
<td>Loamy sand</td>
<td>1.56</td>
<td>8.3</td>
</tr>
<tr>
<td>C1</td>
<td>100-125</td>
<td>7.5</td>
<td>5.1</td>
<td>87.4</td>
<td>Loamy sand</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>125-(225)</td>
<td>7.3</td>
<td>5.2</td>
<td>87.5</td>
<td>Loamy sand</td>
<td>1.55</td>
<td></td>
</tr>
</tbody>
</table>

a Effective cation exchange capacity (meq per 100 g clay).
b Bas saturation.
c Organic matter.

exchange capacity (ECEC, 8.2 meq 100 g⁻¹ clay in the subsoil). The texture of the soil, with an average of 91% sand, 6% silt and 3% clay in the A horizon, corresponds well with the composition presented by Casenave and Valentin (1992) as being especially sensitive to crust formation (90% sand, 10% clay and silt).

2.3. Rainfall

The rainfall at the field site is characteristic for the Sahelian region, with an extremely high spatial and temporal variability (a coefficient of variation exceeding 25%) (FAO, 1987). Rainfall is erratic, with 35% of the events having an intensity exceeding 50 mm h⁻¹. The average intensity rate is 35 mm h⁻¹ (Lebel et al., in press). The average annual rainfall for the region is 560 mm, based on data from 1950 to 1989 (Le Barbé and Lebel, 1997). For the rainy seasons 1994 and 1995, total rainfall was 595.5 mm and 517 mm, respectively. Rainfall was measured with a recording rain gauge, located on the midslope position, using the tipping bucket technique and a 400 cm² cone diameter. Each tip corresponds to 0.5 mm rain depth, which was recorded to the nearest second on an EPROM cartridge (Erasable Programable Read Only Memory).

2.4. Experimental design

At three slope positions in the field (upslope, midslope and downslope), experimental pearl millet plots were set up in a randomized block design with two treatments (manure and fertiliser) and four repetitions (12 plots per slope position, including control plots) (see Fig. 1(C)). The upslope position corresponded to the natural upstream limit of the field (Fig. 1(A) and (B)). The downslope position corresponded to the natural transition
from the sandy soil to the more clay-rich soil in the lowland zone (i.e. the fringe area where the farmer starts cultivating sorghum (*Sorghum bicolor* (L.) Moench). The midslope position was placed halfway between the other two. The plots were 6 m × 16 m, with 5 × 14 (or 70) millet pockets in each plot. The farmer's practices for sowing and weeding were used in the experimental plots, and the farmer cultivated pearl millet all around the plots.

2.5. Soil moisture monitoring

In each of the experimental plots one neutron access tube was placed to a depth of 300–340 cm, giving a total of 12 tubes per slope position (in 1994 manured plots had no access tubes, resulting in eight tubes). Soil moisture was monitored after each rainfall event, and then 2 and 4 days after the rain, with a minimum of three measurements per week. Measurements were taken at depths of 10, 20, 30, 40, 50 and 60 cm, and then at 20-cm increments. Two neutron probes were used, calibrated from two series of gravimetric sampling (at the moment of installation of access tubes) (a SOLO 25S, Nardeux Company, and an IH II Probe, Didcot Instrument Company). A single combined calibration equation was calculated for the surface layers (0–20 cm). For the rest of the soil profile the same calibration equations were used for upslope and downslope tubes, while specific equations were calculated for midslope tubes, due to a deeper sandy profile (calibration equations were calculated for layers 30–120 cm, 140–220 cm and 240–340 cm).

2.6. Infiltration variability

The spatial variability of infiltration between slope positions was estimated by calculating rainfall concentration factors (RCF), i.e. the ratio of measured infiltration:recorded rainfall, from neutron probe data, following the procedure used by Gaze et al. (1997). RCFs were calculated only when neutron probe measurements were carried out the day before and immediately after a rainfall event. Compensation was made for soil evaporation between the measurements using a modified square-root time relationship (Pilbeam et al., 1995), which was calculated from 17 series of microlysimeter measurements from rainfall events during 1995, carried out following the procedure used by Daamen et al. (1993).

2.7. Runoff/runon plots

At each slope position, a runoff plot of the same size as the millet plots was set up to measure $R_{off}$. Next to these closed plots, open 6-m-wide (corresponding to the width of the millet plots) runon plots were set up with the outlet located at the same level as the upstream limit of the millet plots (see Fig. 1(C)). $R_{off}$ plots were thereby isolated from runon plots in order to permit $R_{off}$ modelling. This means that $R_{out}$ was not monitored.

These six plots (three runoff and three runon plots) consisted of 10-cm-high brick borders equipped with a collector system at the outlet made up of a series of 0.2-m³ tanks. The closed plots had two tanks with a divider mounted on the first tank which
reduced the volume of water reaching the second tank with a factor four (i.e., a by four divider). The open plots were equipped in the same way but with two–four tanks owing to larger volumes of captured water.

Each runoff plot was placed so that it represented the surface conditions in the control plots of each slope position (zero input of fertiliser or manure corresponding to the farmers’ normal practice). Runon plots were placed in representative locations for each slope position, with the specific objective of trying to avoid rills entering (upslope) or crossing the field. This was in order to guarantee a measurement of minimum \( R_{on} \) volumes of water for each slope position. \( R_{on} \) and \( R_{off} \) production was monitored for every rainfall event.

\( R_{on} \) observations from 1994 are not included in the analysis owing to flooding of the tank systems during 11 storms (the tank set-up in 1994 was not sufficiently dimensioned to capture the large volumes of \( R_{on} \)). Therefore these data are not included in the analysis. Before the 1995 rainy season a fourth tank was added to the upslope runon plot, and the midslope runon plot was moved (approximately 10 m) to avoid a developing rill, and a third tank was added.

2.8. Soil surface conditions

Parallel to direct observations of \( R_{off} \), soil surface conditions were monitored in all 36 millet plots and the runoff plots using the classification system presented above (see Table 1). This method has been extensively used for \( R_{off} \) calculations for fallow and plateau surfaces in the Sahelian region (e.g. Albergel et al., 1992; d’Herbès and Valentin, 1997; Peugeot et al., 1997). On these sites, soil surface features (a combination of ‘unit surfaces’: surface types including crusts with specific hydraulic and morphological properties) are relatively stable, i.e. they do not change rapidly over time, owing to lack of human manipulation.

In contrast to the description given above, the development of surface conditions in a farmer’s field is dynamic, especially as a result of weeding carried out once or twice during the growing season. This weeding, done manually with a hilaire (a type of hand hoe), cuts the soil some 2–3 cm below the surface, thereby destroying the surface crusts. After a weeding operation, the percentage of the soil covered with an erosion crust, which is the most impermeable crust, goes down to zero. Progressively, under the impact of rainfall and overland flow, i.e. with increased cumulative rainfall \( P_{cum} \), the erosion crust is re-established.

Field observations of surface conditions were carried out three times per rainy season. In each plot 32 observations were made, one every meter along two diagonal lines. For each plot, a relative crust coverage \( (C_i) \) (%) was then calculated for each surface crust type.

2.9. Hydraulic variables for runoff modelling

Experimental results have shown that runoff events do not occur under a certain critical rainfall intensity \( (I_c) \) (Lamachère, 1991; Casenave and Valentin, 1992). \( I_c \) is an empirical parameter related to the saturated hydraulic conductivity \( (K_{sat}) \) of the soil.
surface. For the purposes of this study, we used $I_c = 18$ mm h$^{-1}$, as proposed by Peugeot et al. (1997), which is derived from runoff measurements in pearl millet fields in the studied region.

Rainfall hyetographs were calculated based on 5-min interval data from the recording rain gauge. Rain depths not exceeding $I_c$ were subtracted, leaving only the effective rain depth ($P_u$, from the French *Pluie utile*), which is assumed to produce overland flow (Lamachère, 1994).

The runoff coefficient ($K_r$,) (%) for a specific surface crust ($i$) is given by

$$K_{ri} = \left( \frac{R_{off,i}}{P_u} \right) \times 100$$  \hspace{1cm} (3)

where $R_{off,i}$ is the cumulative depth of surface runoff (mm) for soil surface ($i$) during a rainstorm, and $P_u$ is the depth of effective rain (mm) for the storm.

The initial soil moisture content in the soil surface at the time of a rainstorm influences the value of $K_r$. The method proposed by Kohler and Linsley (1951) was used to estimate soil moisture depletion considering an antecedent precipitation index (API):

$$IK_n = (IK_{n-1} + P_{u,n-1}) \exp^{-\alpha t}$$  \hspace{1cm} (4)

where $IK_n$ (mm) is the value of the API before rainfall event $n$, $IK_{n-1}$ is the value of the index for the preceding event $n - 1$, $P_{u,n-1}$ is the effective rainfall depth and $t$ is time (the fraction of days between $n$ and $n - 1$). The constant $\alpha$ was set at 0.5, as proposed by Casenave (1982).

From in-situ measurements of $R_{off}$ for different crusts under rainfall simulation experiments, Casenave and Valentin (1992) have estimated $K_r$ values for a rainfall event of $P_u = 50$ and two different $IK$ values, namely $IK = 0$ (corresponding to dry soil conditions, pF > 4.2) and $IK = 20$ (corresponding to an almost saturated soil, pF well below 3). $K_r$ at $IK = 0$ and $IK = 20$ could then be estimated according to

$$K_{ri} = \frac{R_{off,i}(P_uIK)}{P_u} \times 100$$  \hspace{1cm} (5)

$K_{ri}$ values (%) for dry ($IK = 0$) and wet ($IK = 20$) conditions for the surface crusts found in pearl millet fields at the site are presented in Table 3. These are only estimates for the hydraulic conductivity of crusts, which are difficult to infer from infiltration measurements owing to the poorly defined thickness and unknown hydraulic gradients.

### Table 3

<table>
<thead>
<tr>
<th>Surface type</th>
<th>$K_{r0}$ (%) dry soil</th>
<th>$K_{r20}$ (%) wet soil</th>
<th>$P_{r0}$ (mm) dry soil</th>
<th>$P_{r20}$ (mm) wet soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0–10</td>
<td>5–15</td>
<td>30–40</td>
<td>20–30</td>
</tr>
<tr>
<td>DRY</td>
<td>30–40</td>
<td>40–50</td>
<td>10–20</td>
<td>1–5</td>
</tr>
<tr>
<td>ST2</td>
<td>25–40</td>
<td>35–50</td>
<td>10–20</td>
<td>3–6</td>
</tr>
<tr>
<td>ST3</td>
<td>30–40</td>
<td>35–45</td>
<td>10–15</td>
<td>5–10</td>
</tr>
<tr>
<td>ERO</td>
<td>50–65</td>
<td>60–70</td>
<td>2–6</td>
<td>0–5</td>
</tr>
</tbody>
</table>

Adapted from Casenave and Valentin, 1992.
which would allow a more accurate assessment of the hydraulic resistance of the crusts (Falayi and Bouma, 1975). However, a more rigorous assessment of crust hydraulic conductivity, performed in the same region using a disk permeameter coupled with microtensiometers (Vandervaere et al., 1997), has shown very good consistency between the measured hydraulic conductivity of structural sieving crusts (ST3) and erosion crusts, and the estimations done by Casenave and Valentin (1992).

As shown by Alberge et al. (1986), for example, a linear relationship can be assumed between $K_{ri}$ and $IK$.

$$K_{ri} = a_i IK + m_i$$  (6)

The constants $a_i$ and $m_i$ were calculated from the values of $K_{ri0}$ and $K_{ri20}$ given in Table 3. $K_{ri}$ could then be calculated from Eq. (6) for each day during the rainy season. These values were used to calculate the average weighted $K_r$ value for the runoff plots at time $n - 1$ (just before the next rainstorm), using the crust coverage percentage ($C_i$) calculated from the field observations.

$$K_{r_{n-1}} = \sum_{i=1}^{m} K_{ri} C_i$$  (7)

where $K_{ri}$ and $C_i$ were given as fractions. $K_{r_{n-1}}$ can then be used to calculate $R_{off}$ (mm) for the rainfall event on Day $n$.

$$R_{off} = K_{r_{n-1}} P_{u_n}$$  (8)

However, even at high rainfall intensities there is a certain pre-runoff rainfall ($P_r$) before runoff production occurs. $P_r$ is the depth of rainfall infiltrated or stored in depressions on the surface of the soil during the infiltration phase preceding Horton overland flow when infiltrability ($I_p$) still exceeds rainfall intensity (Hillel, 1971). $P_r$ depends on the initial moisture storage ($IK$). For the purpose of this study we have taken the two $P_r$ values, which were estimated for each crust type by Casenave and Valentin (1992): $P_{r0}$ corresponding to a dry soil ($IK = 0$, pF $> 4.2$), and $P_{r20}$ corresponding to an almost saturated soil ($IK > 20$, pF well below 3). A linear relationship was assumed between $P_r$ and $IK$.

$$P_{r_i} = a_i IK + m_i$$  (9)

where the constants $a_i$ and $m_i$ were calculated from the data in Table 3 (defining $P_{r20}$ at $IK = 20$). $P_{r_{n-1}}$ was then calculated in the same way as $K_{r_{n-1}}$ from the crust coverage ($C_i$) to give a weighted average $P_{r_{n-1}}$ for each rainfall event.

$$P_{r_{n-1}} = \sum_{i=1}^{m} P_{r_i} C_i$$  (10)

$P_{r_{n-1}}$ was then subtracted from $P_u$ to give the net runoff-producing rainfall $P_{n}$. Eq. (8) was thereby modified.

$$R_{off} = K_{r_{n-1}} P_{n}$$  (11)

$R_{off}$ depths were then calculated from Eq. (11) ($R_{calc}$) and compared with the observed $R_{off}$ values ($R_{obs}$).
3. Results and discussion

3.1. Rainfall

Cumulative $P_u$ ($P_{\text{cum}}$) was similar for the two rainy seasons (1994, 359 mm; 1995, 355.5 mm) despite the difference in cumulative rainfall ($P_{\text{cum}}$) (1994, 595.5 mm; 1995, 517 mm). Substantial differences in the distribution of $P$ and $P_u$ between the 2 years were observed, as shown in Fig. 2. Table 4 shows the distribution of $P_u$ in different size classes as proposed by Hoogmoed and Stroosnijder (1984). Worth noting is the high contribution to total $P_u$ of events with $P_u > 20$ mm, especially in 1994 (60.1%).

3.2. Runoff plots

Measured $R_{\text{off}}$ depths for the two rainy seasons are presented in Fig. 3(A) and (B). The figures indicate a gradient of diminishing $R_{\text{off}}$ moving down the slope (cumulative $R_{\text{off}} = 78$ mm upslope compared with 37 mm downslope in 1994). Statistically significant differences were calculated between the slope positions (upslope–downslope, significance $F=0.001$ (* * *); upslope–midslope, significance $F=0.041$ (*); midslope–downslope, significance $F=0.005$ (* *)) (using repeated measures analysis of variance with 1994 and 1995 data, analyzed together, including only events that produced $R_{\text{off}}$). These differences can be attributed to numerous factors: slope, vegetation cover, microtopography and surface crusting. As shown in Table 5, the coverage (%) of the erosion crust, calculated as a mean from the observations in the experimental millet plots for each slope position (excluding manured plots), was higher at the upslope position than at either the midslope or the downslope position, which contributes to higher $R_{\text{off}}$ depths upslope. Mean coverage of erosion crust in the runoff plots was 26%, 11% and 15% at upslope, midslope and downslope, respectively, for the 2 years.

Even though cumulative $R_{\text{off}}$ is higher during the rainfall-rich 1994 (78 versus 63 mm for the upslope position), the percentage of total rainfall lost as $R_{\text{off}}$ was similar, as seen in Table 6 (upslope 1994/1995, 13.1/12.2%; downslope 1994/1995, 6.2/8.1%). For the two rainy seasons, mean $K_r$ (calculated on the basis of $P$ and not $P_u$) was similar, and amounted to 8.9% upslope and 5.7% downslope. The range of $K_r$ was very high, with maximum values exceeding 35% for all slope positions (36.4–48.5%), and standard deviation (SD) varying from 9.5 to 14.5 (Table 6).

A reason behind relatively low mean $K_r$ and high SD is seen in Fig. 4, which shows $K_r$ for the events that produced $R_{\text{off}}$ for the different slope positions 1995. Only 12 of the total 25 rainfall events produced $R_{\text{off}}$, and there were only six with $K_r > 15$% (upslope). These six events contributed 57.2 mm, or 91% of total $R_{\text{off}}$ upslope (85% of the total $R_{\text{off}}$ for the three slope positions). This is a result of the erratic and intensive character of the rainfall, with a few, very intensive storms per year. Mean $K_r$ for rainfall events producing $R_{\text{off}}$ was 12.6% in 1994 and 15.7% in 1995 for all slope positions (16.3% upslope, 14.8% midslope and 15.9% downslope in 1995).

The effect of weeding on $K_r$ and thereby $R_{\text{off}}$ is clearly illustrated in Fig. 3. After weeding, the thin infiltration-impeding crusts are broken, resulting in a large increase in $K_{\text{sat}}$. $K_{\text{sat}}$ for erosion crusts has been measured as 0.68 cm h$^{-1}$ (Peugeot et al., 1997),
compared with $K_{sat}$ for undisturbed subsoil, which was estimated at 20.8 cm h$^{-1}$ at the site. The result is that virtually no $R_{off}$ occurs after weeding (rainfall intensities exceeding 200 mm h$^{-1}$ have been measured, but these are rare and their duration is very short) (Hoogmoed and Stroosnijder, 1984). This was particularly noticeable after the 2nd weeding in 1994 (Fig. 3(A)). The large rainstorm ($P = 58.5$ mm, with $P_u = 49$ mm)
Table 4
Distribution of effective rainfall ($P_u$) in different size classes

<table>
<thead>
<tr>
<th>Size classes (mm)</th>
<th>Number of events</th>
<th>Total rainfall depth (mm)</th>
<th>Percentage of total rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu &lt; 10</td>
<td>17/16</td>
<td>76/53</td>
<td>21.2/14.9</td>
</tr>
<tr>
<td>Pu 10–20</td>
<td>5/9</td>
<td>67/132.5</td>
<td>18.7/37.3</td>
</tr>
<tr>
<td>Pu &gt; 20</td>
<td>6/4</td>
<td>216/170</td>
<td>60.1/47.8</td>
</tr>
<tr>
<td>Pu &gt; 30</td>
<td>3/3</td>
<td>128.5/148</td>
<td>35.8/41.6</td>
</tr>
<tr>
<td>Pu &gt; 40</td>
<td>2/2</td>
<td>96/148</td>
<td>26.7/41.6</td>
</tr>
<tr>
<td>Pu &gt; 50</td>
<td>0/1</td>
<td>0/58.5</td>
<td>0/16.5</td>
</tr>
</tbody>
</table>

Fig. 3. Measured cumulative $R_{off}$ production as a function of cumulative rainfall ($P_u$) for the rainy seasons (A) 1994 and (B) 1995. Weeding operations are indicated with arrows and tagged for $P_{cum}$ (cumulative $P_u$) and DAS (days after sowing).
Table 5
Observed coverage (%) of erosion crust at each slope position. The time of observation is given as cumulative 
$P_u$ ($P_{cum}$).

<table>
<thead>
<tr>
<th>Slope</th>
<th>$P_{cum}$ (mm) in 1994</th>
<th>$P_{cum}$ (mm) in 1995</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>42 157 223</td>
<td>29 181 316</td>
</tr>
<tr>
<td>Upslope</td>
<td>23 13 44</td>
<td>15 4 40</td>
</tr>
<tr>
<td>Midslope</td>
<td>21 4 29</td>
<td>12 3 25</td>
</tr>
<tr>
<td>Downslope</td>
<td>18 11 18</td>
<td>8 5 34</td>
</tr>
</tbody>
</table>

following the weeding produced zero $R_{off}$. Four days later, at $P_{cum} = 49$ mm after 
weeding, a $P_u = 47$ mm event produced substantial volumes of $R_{off}$ (11.1 mm upslope, 
11.2 mm midslope and 5.4 mm downslope). This illustrates the rapid formation of initial 
structural crusts as a result of raindrop impact, followed by the development of erosion 
crusts (Valentin and Bresson, 1992). Lamachère (1991) presents similar results for a 
sandy soil in Burkina Faso, where three soil-related factors governing $R_{off}$ production, 
$K_r$, $I$, and soil moisture storage ($S$), were shown to develop higher $R_{off}$ potential, as a 
function of $P_{cum}$ after weeding. At $P_{cum} = 100$ mm after weeding, the infiltration 
capacity of the soil was reduced by a factor 2, and at $P_{cum} = 200$ mm the $R_{off}$-reducing 
effect of weeding had ceased.

The development of surface crusts was calculated as a function of $P_{cum}$ from the 
field observations of crust coverage ($C_i$), assuming a linear relationship between 
$P_u$ and crust development (Fig. 5). Owing to similar $K_r$ and $P_r$ values, ST2 and DRY crusts 
were calculated together (ST2DRY). Antecedent soil moisture also contributes to 
increasing $K_r$ values as $P_{cum}$ increases. For the two rainfall events described above, 
the antecedent $IK$ index increased from 1.1 (indicating dry soil) for the 100% 
infiltrating storm after weeding, to an $IK$ value of 8.5 for the event producing $R_{off}$ with 
$K_r \approx 20\%$.

The measured $R_{off}$ indicates non-negligible depths of overland flow despite the sandy 
soil. Slightly higher $R_{off}$ depths ($K_r = 16.6\%$) have been measured in a sorghum field 
with a similar slope (3%) receiving similar annual rainfall (450 mm) (Roose and 
Bertrand, 1971), but in this case soils were more clayey, resulting in lower $K_{sat}$. The

Table 6
Measured $R_{off}$ coefficients ($K_r$) (%) (mean, maximum and standard deviation) and cumulative $R_{off}$ (mm) for 
the three slope positions during the 1994 and 1995 rainy seasons

<table>
<thead>
<tr>
<th>Slope position</th>
<th>Runoff coefficient ($K_r$) (%)</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Maximum</td>
</tr>
<tr>
<td>Upslope</td>
<td>8.4</td>
<td>9.3</td>
</tr>
<tr>
<td>Midslope</td>
<td>7.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Downslope</td>
<td>4.9</td>
<td>6.5</td>
</tr>
</tbody>
</table>

a Mean $K_r$ calculated from $K_r$ values for each rainfall event ($n$) that produced $P_u$, taken as the ratio 
$R_{offn}/P_n$ (i.e. total rain depth and not $P_u$).
Fig. 4. Measured $R_{\text{off}}$ coefficients ($K_r$) (%) during the 1995 rainy season. The rainfall events are indicated by day-number and rainfall depth ($P_u$) (mm).

difference between these studies is the large coverage and rapid development of surface crusts in the sandy millet field.

3.3. Runon plots

Measured cumulative production of $R_{\text{on}}$ is shown in Fig. 6. There is a systematic production of large volumes of $R_{\text{on}}$ entering the upstream limit of the millet field (Table 7). This overland flow (86.2 m$^3$ in 1995) originates from the degraded upstream fallow.

Fig. 5. Crust development on the upslope position in 1995 as a function of $P_{\text{cum}}$. Based on field observations of crust distribution at $P_{\text{cum}} = 29, 181$ and 316 mm.
and plateau areas indicated in Fig. 1(A). Observed $R_{on}$ decreases moving down the hillslope (cumulative $R_{on} = 17.5$ m$^3$ (midslope); $R_{on} = 4.5$ m$^3$ (downslope) in 1995). $R_{on}$ was significantly higher at the upslope position compared with both lower positions (upslope–downslope, significance $F = 0.012$ (*); upslope–midslope, significance $F = 0.011$ (*); midslope–downslope, significance $F = 0.031$ (*)). These results are in line with observations in 1994 which, despite flooding of the midslope and upslope tank systems (leading to conservative data), resulted in cumulative $R_{on} = 55.3$ m$^3$ upslope, $R_{on} = 9.3$ m$^3$ midslope, and $R_{on} = 4.2$ m$^3$ downslope. As for the runoff plots, the effect of a few large and intensive storms producing large volumes of $R_{on}$ is manifested in high SD (mean $R_{on} = 4.1$ m$^3$ upslope for $P_u > 0$, $SD = 7.0$ m$^3$, and maximum $R_{on} = 22.2$ m$^3$, for 1995) (Table 7).

We lack observations on $R_{on}$ redistribution (i.e. $R_{out}$ measurements). If, for the sake of comparison, the recharge area for $R_{on}$ is considered as being the downstream millet plot (i.e. the runoff plot, thereby assuming $R_{out} = 0$), then cumulative $R_{on}$ for the upslope position in 1995 attains 958.2 mm (mean $R_{on} = 45.6$ mm, maximum registered

![Graph showing cumulative rainfall (Pu) and cumulative runon (m3).](image)

**Fig. 6.** Measured production of $R_{on}$ overland flow during 1995. The graph shows cumulative runon (m$^3$) as a function of $P_{cum}$ (mm).

Table 7

<table>
<thead>
<tr>
<th>Position</th>
<th>$R_{on}$ volume (m$^3$)</th>
<th>$R_{on}$ cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD $^a$</td>
</tr>
<tr>
<td>Upslope</td>
<td>4.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Midslope</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Downslope</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$^a$ Standard deviation.

$^b$ Cumulative $R_{on}$ (m$^3$) divided by the width of the open runon plots (6 m).
Table 8
Mean, maximum and cumulative $R_{on}$ depths (mm) and $R_{on}$ coefficients (ratio $R_{on}:P$) when considering a recharge area corresponding to a plot size of $6 \times 15$ m and for a theoretical estimation of the catchment area.

<table>
<thead>
<tr>
<th>Slope position</th>
<th>Mean $(mm)$</th>
<th>Maximum $(mm)$</th>
<th>Cumulative $(mm)$</th>
<th>$R_{on}$ coefficient mean (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plot Catch-</td>
<td>Plot Catch-</td>
<td>Plot Catch-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ment</td>
<td>ment</td>
<td>ment</td>
<td></td>
</tr>
<tr>
<td>Upslope</td>
<td>45.6</td>
<td>2.1</td>
<td>247.0</td>
<td>11.4</td>
</tr>
<tr>
<td>Midslope</td>
<td>8.8</td>
<td>0.9</td>
<td>50.1</td>
<td>5.0</td>
</tr>
<tr>
<td>Downslope</td>
<td>2.3</td>
<td>0.2</td>
<td>11.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

* Corresponding to a 6-m-wide corridor stretching from the entry of the plot up to the plateau (325 m) for the upslope plot, and a 150-m corridor for the midslope and downslope plots, corresponding to the distance between the plots along the hillslope.

$R_{on} = 247$ mm, mean $K_r = 122.4\%$ (Table 8). Even at the midslope, substantial $R_{on}$ was measured (cumulative $R_{on} = 194$ mm, mean $K_r = 24.7\%$). Downslope $R_{on}$ depths start to equal $R_{off}$ depths. Table 7 also includes $R_{on}$ produced per meter ($m^3 m^{-1}$), indicating the large volumes of water crossing the upstream border of the millet field (cumulative $R_{on} = 14.4 m^3 m^{-1}$ in 1995).

Table 8 also includes $R_{on}$ depths (mm) based on a theoretical estimation of the catchment area, which for the upslope plot was set to the 325-m-long degraded zone between the upstream limit of the field and the plateau. Midslope and downslope the catchment area was taken as the distance between the runon plots (150 m). The width was set to 6 m, corresponding to the plot width. Cumulative $R_{on}$ depths (mm) amounted to 44, 19 and 5 mm for upslope, midslope and downslope positions, respectively, for 1995 (or 8.5%, 3.8% and 1% of rainfall), which is approximately of the same order of magnitude as measured $R_{off}$.

Fig. 7 gives an indication of the redistribution of overland flow along the hillslope ($R_{on}$ given as positive values and $R_{off}$ as negative values for all rainfall events in 1995). Similar $R_{on}$ and $R_{off}$ depths are observed at the downslope position, which would suggest that practically all $R_{on}$ from the non-cultivated upstream zone is used to supply the upslope and the midslope with surface water. Despite the division of the measurements in closed runoff plots and open runon plots, both $R_{off}$ and $R_{on}$ diminishes moving down the slope.

The redistribution of overland flow along the slope should be possible to verify from neutron probe data on soil moisture storage for the different slope positions. Fig. 8(A) and 8(B) show the changes in soil moisture storage (0–300 cm) calculated as mean values for the grid of access tubes per slope position (storage set to zero at the onset of the rainy season). Despite high $R_{on}$ upslope, the figures indicate that soil moisture storage did not increase faster than the other slope positions. On the contrary, the data indicate a slower increase rate, which can be explained from higher $R_{off}$ compared to the downslope. This is also confirmed from RCF values calculated for six rainfall events (Table 9), where the upslope neutron access tubes have systematically lower mean infiltration than midslope and downslope tubes. Spatial variability between access tubes
Fig. 7. Comparison between the production of $R_{on}$ (positive values) and $R_{eff}$ (negative values) (mm) for the three hillslope positions. $R_{on}$ is calculated as the depth (mm) per plot area (corresponding to the runoff plot).

is high, with infiltration ranging from 0.3 to 1.75 times the rainfall for downslope tubes and from 0.09 to 1.16 times for upslope tubes. Similar values have been recorded in the same region by Gaze et al. (1997), who found an infiltration range of 0.6–1.2 times the rainfall for the majority of the locations studied (with a few cases of RCF exceeding 3). The lower infiltration observed here can probably be attributed to the slope and the relatively few local depressions. It should also be noted, however, that some of the RCF values (the August events) have been calculated when crop water use is significant, which would increase the RCF values. At the peak of moisture storage (1994), the upslope storage had increased, i.e. with 189 mm compared to 244 mm and 221 mm for the midslope and downslope, respectively.

Both the 1994 and 1995 rainy seasons produced drainage flow, which complicates the interpretation of the soil moisture data. Another obstacle when trying to explain the redistribution of surface water in this landscape is that the measured overland flow only constitutes two out of five different modes of Horton overland flow (Table 10). The measured $R_{off}$, which is in-situ produced surface flow determined by soil surface conditions, moisture status and rainfall characteristics, has a low recharge range, normally infiltrating when reaching a zone with lower $K_r$. The measured $R_{on}$ is the sheet flow ‘harvested’ from crusted upstream zones with low infiltrability. To these should be added $R_{on}$ water flowing in small rills (rarely more than 10 cm deep and 50 cm wide). Rills transport water from the degraded upstream zone through the field, and supply water to the downslope zone. Along the 270-m-wide field, six such rills were identified; three passed through the field and infiltrated downstream of the downslope position, two infiltrated at the downslope position (between experimental blocks 3 and 4), and one infiltrated in a sandy fan between midslope and downslope positions (also between blocks 3 and 4).
Fig. 8. Development of soil moisture storage (0–300 cm) for the three slope positions during the two rainy seasons (A, 1994; B, 1995). Soil moisture storage was set to zero at the onset of the rainy season.
Table 9
Measured rainfall concentration factors (RCF) at different slope positions for six rainfall events

<table>
<thead>
<tr>
<th>Date</th>
<th>DAS</th>
<th>P</th>
<th>RCF at each slope position</th>
<th>Range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Down Mid Up</td>
<td>Down Mid Up</td>
<td></td>
</tr>
<tr>
<td>16 June 1994</td>
<td>0</td>
<td>33</td>
<td>0.84 0.62 0.58</td>
<td>0.30–1.23 0.35–0.71 0.09–0.86</td>
<td></td>
</tr>
<tr>
<td>3 August 1994</td>
<td>49</td>
<td>44.5</td>
<td>0.76 0.83 0.72</td>
<td>0.62–0.93 0.63–0.86 0.56–0.82</td>
<td></td>
</tr>
<tr>
<td>11 July 1995</td>
<td>21</td>
<td>50.5</td>
<td>0.71 0.82 0.67</td>
<td>0.54–0.98 0.48–1.14 0.22–0.99</td>
<td></td>
</tr>
<tr>
<td>1 August 1995</td>
<td>42</td>
<td>21</td>
<td>0.87 0.85 0.79</td>
<td>0.73–1.00 0.69–1.10 0.62–1.10</td>
<td></td>
</tr>
<tr>
<td>8 August 1995</td>
<td>49</td>
<td>56.5</td>
<td>nd 0.88 0.71</td>
<td>nd 0.54–1.30 0.35–1.16</td>
<td></td>
</tr>
<tr>
<td>11 August 1995</td>
<td>52</td>
<td>25</td>
<td>0.94 0.90 0.76</td>
<td>0.57–1.75 0.58–1.10 0.52–1.03</td>
<td></td>
</tr>
</tbody>
</table>

*a Each RCF is calculated as a mean of eight tubes per slope position in 1994 and 12 tubes per slope position in 1995.

The fourth form of overland flow is in-situ produced $R_{on}$, or long range $R_{off}$, produced from larger (often $>100$ m$^2$) degraded zones along the hillslope. Finally, the largest contributors of surface water flow are the gullies, which add to the frequent inundation in the lowland zone of the watershed. These different modes of overland flow indicate the complexity of interpreting soil moisture data.

Spatial variability of farmers' yields in the Sahel can be very large over short distances, as shown by Bouma et al. (1995), where pearl millet yields in a field

Table 10
Schematic features of different modes of surface overland flow present in cultivated hillslopes of the Samadey watershed

<table>
<thead>
<tr>
<th>Mode of surface overland flow</th>
<th>Scale</th>
<th>Recharge range</th>
<th>Catchment zone</th>
<th>Volumes produced (% of P)</th>
<th>Effect for agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>Crop field</td>
<td>Small</td>
<td>Very small</td>
<td>&lt; 50%</td>
<td>Dessicated crusted zones, supplying downstream zones</td>
</tr>
<tr>
<td>Runon sheetflow</td>
<td>Hillslope</td>
<td>Medium</td>
<td>Medium</td>
<td>&gt; 100%</td>
<td>Redistribution along hillside, within field</td>
</tr>
<tr>
<td>Runon rill</td>
<td>Hillslope</td>
<td>Medium-large</td>
<td>Medium</td>
<td>&gt; 100%</td>
<td>Redistribution along hillside, infiltration in sand fans, creates eroded rills</td>
</tr>
<tr>
<td>In-situ runon</td>
<td>Crop field</td>
<td>Small</td>
<td>Small</td>
<td>&lt; 50%</td>
<td>As above</td>
</tr>
<tr>
<td>Gully flow</td>
<td>Watershed</td>
<td>Large</td>
<td>Large</td>
<td>&gt; 100%</td>
<td>Recharge of watertable, inundation of lowland, large transport of sediments</td>
</tr>
</tbody>
</table>
experiment varied by a factor of 3.6 in a 0.3-ha field. Microtopography, with altering low and high zones, influences the distribution of surface overland flow. Low, relatively ‘wetter’ depressions, alternating with high, relatively ‘drier’ zones, have effects on spatial yield variability, as shown by Brouwer et al. (1993). We have not explicitly monitored microtopography. The microrelief has certainly had effects on both leaching, in line with results by Gaze et al. (1997), and moisture distribution (as shown from RCF values). No sedimentation crusts were observed along the slope (i.e., crusts formed in depressions with standing water), indicating that the slope in general had a stronger effect than microtopography on surface runoff distribution. Still the large observed volumes of $R_{cn}$ and $R_{off}$ presented here would suggest that leaching of nutrients and spatial variability in moisture are important factors affecting crop yields.

### 3.4. Runoff modelling

The prediction of $R_{off}$ in the model ($R_{calc}$) follows the procedure described in Eqs. (6)-(11). A rainfall event (14 August 1995 on Day 226) is taken as an example to illustrate the procedure. At the onset of the rain $IK = 10.75$ (Eq. (4)). The storm amounted to $P = 71$ mm, with $P_u = 58.5$ mm and $P_r = 5.7$ (Eqs. (9) and (10)). The constants $a_i$ and $m_i$ for each crust type, calculated from the crust data in Table 3, are presented in Table 11. Values for $C_i$, derived from the field observations (Fig. 5), were then used to calculate the mean weighted $K_{rn-1}$ for the runoff plot according to Eq. (7) ($C_i$ given in Table 11):

$$K_{rn-1} = 0.05K_{c1} + 0.74K_{st2dry} + 0.05K_{st3} + 0.16K_{ero}$$

$K_{rn-1}$ (equal to 0.27 in this special case) was then used in Eq. (11) to calculate $R_{calc}$ ($R_{calc} = 14.3$ mm compared with the measured $R_{obs} = 11.3$ mm).

A comparison between observed runoff ($R_{obs}$) and predicted runoff ($R_{calc}$) is presented in Fig. 9. A linear regression analysis was performed assuming the intercept to be equal to zero, and excluding all zero-$R_{off}$ events (no support was found for rejecting the $H_0$ hypothesis of intercept $= 0$ in Students $t$-test: $t = 0.43$, significance $t = 0.67$). Despite the high standard deviation for $R_{obs}$ (SD = 3.81 mm with a mean $R_{off} = 3.35$ mm for all rainfall events producing $R_{off}$), the model accounted for 86% of the variation in the data, indicating a reasonable correlation with the field observations (coefficient of
Fig. 9. Validation of \( R_{\text{off}} \) modelling. Comparison of predicted \( (R_{\text{calc}}) \) and observed \( (R_{\text{obs}}) \) \( R_{\text{off}} \) depths for the rainy seasons 1994 and 1995. The lines indicate the regression line and the 95% confidence limits.

\[
R_{\text{calc}} \text{ (mm)}
\]

determination \( R^2 = 0.86 \), 95% confidence interval 0.91–1.08, \( n = 88 \). The regression equation between observed and predicted \( R_{\text{off}} \) in Fig. 10 is

\[
R_{\text{obs}} = 0.99R_{\text{calc}} \quad (13)
\]

The regressions for the different slope positions and the cumulative predicted and observed \( R_{\text{off}} \) depths are presented in Table 12, and illustrated for the upslope position (1995) in Fig. 10.
The analysis above indicates the possibility of estimating \( R_{\text{off}} \) depth from knowledge of (i) the hydraulic characteristics of the soil surface, (ii) a simple moisture index \((IK)\) and (iii) rainfall data \((P_u)\). The model tends to exaggerate \( R_{\text{off}} \) for low rainfall depths, despite the effort of compensating for \( P_r \). This could be explained by the difficulty of combining ‘unit surfaces’ with specific hydraulic parameters into surface features on a larger scale (plot scale in this case). \( K_r \) values for each ‘unit surface’ were measured on 1-m\(^2\) plots under high-intensity rainfall (Casenave and Valentin, 1992). The effect is that the model does not take into account the spatial redistribution of surface water from one ‘unit surface’ with high \( K_r \) to another with lower \( K_r \). This water infiltrates before reaching the tank system where \( R_{\text{obs}} \) was measured. \( R_{\text{obs}} \) is systematically higher than \( R_{\text{calc}} \) for the upslope and midslope positions (with 5–6%), which would suggest that the microrelief has a low impact on \( R_{\text{off}} \) production compared with the slope, at least on a plot scale.

The change in soil surface coverage during the cultivation season, owing to the two weeding operations, is a further obstacle when modelling \( R_{\text{off}} \) based on surface features. In Fig. 3(A), it was shown that the \( P_u = 47.5 \) mm event following the 2nd weeding 1994

<table>
<thead>
<tr>
<th>Slope position</th>
<th>Cumulative ( R_{\text{off}} ) (mm)</th>
<th>Regression (^a)</th>
<th>Confidence intervals (95%)</th>
<th>( R^2 )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_{\text{obs}} )</td>
<td>( R_{\text{calc}} )</td>
<td>( R_{\text{obs}} )</td>
<td>( R_{\text{calc}} )</td>
<td>( R_{\text{obs}} = 1.05 R_{\text{calc}} )</td>
</tr>
<tr>
<td>Upslope</td>
<td>78</td>
<td>62</td>
<td>63</td>
<td>60</td>
<td>( R_{\text{obs}} = 1.06 R_{\text{calc}} )</td>
</tr>
<tr>
<td>Midslope</td>
<td>67</td>
<td>50</td>
<td>48</td>
<td>55</td>
<td>( R_{\text{obs}} = 0.83 R_{\text{calc}} )</td>
</tr>
<tr>
<td>Downslope</td>
<td>37</td>
<td>49</td>
<td>42</td>
<td>54</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Zero-\( R_{\text{off}} \) events are not included in the regression analysis. The intercept was assumed to be at 0 because \( H_0 \) (intercept = 0) in Student’s \( t \)-test could not be rejected (sign \( t = 0.63 \) upslope; \( t = 0.93 \) midslope; \( t = 0.68 \) downslope).
resulted in zero $R_{off}$. The model gave an $R_{calc}$ value of 8.2 mm for this rain (three points excluded from the graph in Fig. 9), indicating higher actual soil infiltrability after weeding than for the structural surface (ST2) used in the modelling ($I_p(ST2) = 70 - 75\%$ in dry soil and 50–55\% in wet soil). This could be changed by introducing a surface feature with $K_r$ values that correspond better to a weeded surface. However, as the surface crusts are very rapidly redeveloped after weeding, reasonable $R_{calc}$ values could be calculated for rainfall events following the weeding, using the basic ‘unit surfaces’ in Table 3. For example, the following rainfall event 4 days later, with a $P_u = 47$ mm gave a mean $R_{obs} = 9.2$ compared with $R_{calc} = 10.1$ for the three hillslope positions.

4. Conclusions

The Samadey experiment was conducted in a farmer’s field which was continuously cultivated along a gently sloping (2–3\%) catena, on a deep sandy soil (Typic Haplustult) with very high hydraulic conductivity in the subsoil ($K_{sat}$ estimated at 20.8 cm h$^{-1}$). Despite these conditions, which normally would favour rainfall infiltrability, measured $R_{off}$ from small plots was non-negligible (12–13\% of total rainfall for the upslope position) for 2 years (1994/1995) with above and slightly below average rainfall (1994, 595.5 mm; 1995, 517 mm; average $P = 560$ mm). This is explained by the large presence and rapid development of surface crusts with low infiltrability.

The measurements of $R_{on}$ indicate the large importation of water from the upstream degraded fallow zone and the plateau. Despite the problem of estimating the discharge area, the measured volumes of $R_{on}$ (86.2 m$^3$ for 1995 with below average rainfall), over a distance of 6 m (the plot width), are so large in relation to rainfall that a significant influence on the water balance, and most probably on crop yield development, is to be expected. Even with an assumption that the $R_{on}$ is redistributed over the whole field (270 m $\times$ 315 m), the annual recharge of 14.4 m$^3$ m$^{-1}$ would supply in total 45.7 mm of rainfall depth. This flow of $R_{on}$, which was shown to decrease rapidly moving down the slope and thus indicate redistribution in the field, probably contributes to the higher $R_{off}$ measured moving up the slope (cumulative $R_{off} = 78$ mm upslope compared with 37 mm downslope in 1995). The formation of surface crusts is governed by the impact of flowing water (i.e. water of high kinetic energy), and progressively moving up the hillslope, the soil is submitted to a larger volume of $R_{on}$, which is added to rainfall as crust-forming fuel.

Despite the dynamic feature of surface crusts in cultivated fields, the results presented here indicate the possibility of making reasonable predictions of $R_{off}$ based on knowledge of soil surface conditions, antecedent soil moisture in the upper soil profile, and rainfall data.

The results suggest that the parameters $R_{on}$ and $R_{off}$ are difficult to exclude from water-balance studies in the Sahel under on-farm conditions, even if they are conducted on sandy soils. Moreover, our measurements are not sufficient to let us understand the processes of overland flow on a field scale, which also include rill-flow and the spatial redistribution of $R_{on}$ ($R_{out}$).

The large volumes of observed $R_{on}$ indicate the problems that might arise when applying results from crop-water experiments conducted under controlled forms (i.e.
where $R_{on}$ and $R_{off}$ are assumed to be zero), in the agrohydrological reality of the farmer. It cannot be excluded that the dynamics of $R_{on}$ and $R_{off}$ form part of an intricate system of yield stabilisation, where the natural redistribution of harvested upstream water ($R_{on}$) in the field can be a factor ensuring a minimum crop yield during low-rainfall years.

The large volumes of $R_{on}$ indicate the potential of developing water harvesting systems, especially as the bulk of $R_{on}$ actually originates from a few large and intensive storms which result in a surplus of water. Upstream collection of water in reservoirs, in order to make possible protective irrigation during short periods of water stress, might be an interesting option in order to drought-proof crop production.

Weeding was shown to have a very positive effect on infiltrability, even though this was within only a short hydrological time span. $R_{off}$-reducing tillage can have an important effect on soil moisture availability and thereby on potential crop yields. However, more applied on-farm research is needed in order to increase the understanding of $R_{on}$ and $R_{off}$ dynamics, and to identify appropriate technologies for increased water-use efficiency in Sahelian rain-fed agriculture.

Acknowledgements

The Samadey research project was made possible by a grant from the Swedish Council for Planning and Coordination of Research (FRN) (grant 920716. A 8-5/218), and through the established research collaboration between the Natural Resources Management Institute at Stockholm University and ORSTOM. The experimental design of runoff and runon plots were done in collaboration with ORSTOM scientists Michel Esteve and Jean-Marc LaPetite. Sylvie Galle (ORSTOM) assisted with neutron probe calibration and access tube installation. The IH neutron probe was borrowed from George Dugdale at the University of Reading. Patrick Fox, Doulla Sindy and Mamane Alliko Effat assisted in the field work.

References


Hillslope dynamics of on-farm generation of surface water flows: The case of rain-fed cultivation of pearl millet on sandy soil in the Sahel

J. Rockström a,*, C. Valentin b

a Natural Resources Management, Department of Systems Ecology, Stockholm University, S-10691 Stockholm, Sweden
b ORSTOM, BP 114 16, Niamey, Niger

Accepted 9 September 1996