C. R. Geoscience 344 (2012) 441–448

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Hydrology, environment

Measuring runoff by plots at different scales: Understanding and analysing the sources of variation

Mesure du ruissellement au moyen de parcelles à différentes échelles : compréhension et analyse des sources de variation

Lawani Adjadi Mounirou [a,*], Hamma Yacouba [a], Harouna Karambiri [a], Jean-Emmanuel Paturel [a,b], Gil Mahé [b]

[a] *Institut international d'ingénierie de l'eau et de l'environnement, laboratoire hydrologie et ressources en eau, rue de la Science, 01-BP-594, Ouagadougou 01, Burkina Faso*

[b] *Laboratoire hydrosciences Montpellier, maison des sciences de l'eau, université Montpellier II, place Eugène-Bataillon, CC MSE, 34095 Montpellier cedex 05, France*

A R T I C L E I N F O

Article history:
Received 15 May 2012
Accepted after revision 22 August 2012
Available online 5 October 2012

Presented by Ghislain de Marsily

Keywords:
Plot
Runoff
Soil surface feature
Hydrologic process
Scale effect
Sahel

Mots clés :
Parcelles
Ruissellement
État de surface des sols
Processus hydrologiques
Effet d'échelle
Sahel

A B S T R A C T

The decrease of runoff with the increase in area is not a new fact. The scale effect depends on the spatial and temporal variability of different factors, including the surface characteristics and hydrodynamic properties of the soil and the vegetation development. The purpose of our work is to study the relative influence of the sources of variation of runoff from a small Sahelian catchment on several types of soil surfaces features. Plots of different sizes (1, 50 and 150 m^2) on cultivated soils and degraded soils (non-cultivated with three different types of crusts) were monitored for two consecutive years. The results show that the runoff coefficients of rainfall events range from 4 to 65% on cultivated soils and 16 to 96% on uncultivated bare and degraded soils. A statistical and dimensionless analysis shows that in degraded environments, the processes generating runoff on plots of 50 and 150 m^2 are identical and significantly different from the unit plot (1 m^2). The decrease in runoff with increasing scale becomes more pronounced when rainfall duration decreases. In cultivated areas, this result is not observed. Additional measurements are needed to better understand the differences in functioning at various scales of observations.

R É S U M É

La diminution de la lame d'eau ruisselée avec l'accroissement de la superficie n'est pas un fait nouveau. L'effet d'échelle dépend de la variabilité spatiotemporelle de différents facteurs, y compris les états de surface, les propriétés hydrodynamiques des sols et la croissance de la végétation. L'objectif de notre travail est d'étudier le rôle relatif des sources de variation du ruissellement d'un petit bassin sahélien, sur plusieurs types d'états de surface. Des parcelles de différentes tailles (1, 50 et 150 m^2) sur sols cultivés et sur sols dégradés (non cultivés avec trois différents types de croûtes) ont été suivies pendant deux années consécutives. Les résultats montrent que les coefficients de ruissellement par événements varient entre 4 et 65 % sur les sols cultivés et 16 et 96 % sur les sols non cultivés dégradés. Des analyses statistiques et dimensionnelles montrent qu'en milieu dégradé, les

* Corresponding author.
E-mail address: adjadi.mounirou@2ie-edu.org (L.A. Mounirou).

1631-0713/$ – see front matter © 2012 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.crte.2012.08.004

processus de génération de ruissellement sur les parcelles de 50 et 150 m^2 sont identiques et significativement différents de la parcelle unitaire (1 m^2). La diminution du ruissellement avec l'augmentation de l'échelle devient plus prononcée avec la décroissance de la durée de pluie. En milieu cultivé, ce résultat n'est pas observé. Des mesures complémentaires sont nécessaires pour mieux appréhender les différences de fonctionnement aux différentes échelles d'observations.

1. Introduction

In the Sahel, surface runoff constitutes the main source of water resources available for human, agricultural and pastoral activities. The mobilization and management of this resource in this region are very sensitive to the variability of climate (Mahé and Paturel, 2009) and require tools to quantify the runoff aptitude of the different types of soils of a catchment. However, the complexity of hydrological processes, their large variability in space and time, raise a number of basic questions on watershed hydrology (Beven, 1995; Blöschl and Sivapalan, 1995): at which scales do the major runoff physical processes occur? Which scales have to be selected for measurements and observations?

In recent decades, the evaluation of runoff has referred to experimental plots from 1 m^2 to several tens of m^2. These studies have shown and justified that runoff decreases with increasing plot surfaces. However, the causes of the identified scale effect are related to the characteristics of the plots, their localization on the hillslope and the objectives of each study. Thus, Cerdan et al., 2004, Gomi et al., 2008, and Mayor et al., 2011 justify the scale effect on plots by the spatial variability of soil infiltration capacity. Others indicate the dynamics of the intensity of precipitation (Stomph et al., 2002; Van de Giesen et al., 2005, 2011) and threshold effects for some processes (Le Bissonnais et al., 2006) or the development of emergent properties of soils at certain scales (Reaney et al., 2007).

In the Sahel regions, several "soil surface features units" have been identified (Casenave and Valentin, 1992) and their hydrodynamic and morphological characteristics play a significant role in the formation of runoff and the subsequent transfer within the hydrographic network. Consequently, variability in surface conditions, soil surface crusting, vegetation, and roughness can all produce different hydrologic regimes at different spatial scales.

In this study, we propose to analyze the scale effect on two types of surfaces:

- cultivated soils;
- degraded uncultivated soils, and we make an attempt to identify the factors explaining this observed scale effect.

2. Materials and methods

2.1. Study site, experimental design and measurements protocol

Runoff measurements were performed for 2 years (2010–2011) on the Tougou watershed (37 km^2) located in the Sahel zone of Burkina Faso (Fig. 1). The geographical coordinates of its outlet are: 13° 40′ 56″ N and 2° 13′ 39″ E. It is characterized by a unimodal annual rainfall regime, and the average annual rainfall varies between 400 and 650 mm. Rainfall shows an irregular distribution over the year: large storms occurring from early or mid-May to mid- or late October provide 95% of the annual rainfall, while the other 7 months are dry. Rainfall from July to September is about 80% of annual rainfall. There has been, on average over 2 years, respectively nine, 13 and eight rainfall events (rainfall $\geq$ 1 mm) during these 3 months. In the high rainy season, rainstorms are recorded mainly in August and September, with maximum intensities that can reach 130 mm/h during 5 min and 70 mm/h during 30 min. The watershed, like other Sahelian watersheds, is characterized by Hortonian runoff because soils have little vegetation cover and encrusted surfaces, and a relatively deep aquifer with as main recharge points the bottom of the beds of the river network (Favreau et al., 2002).

In the catchment, two homogeneous hydrological units in terms of land use were identified on the basis of a thematic mapping of soils and cropping systems: the first hydrologic unit is a cultivated sub-basin (6.1 ha) and the second is a degraded uncultivated sub-basin (33.8 ha). These two units represent the main soil surface feature of the catchment area according to Casenave and Valentin (1992).

Inside each of these hydrological units, three sites were identified. On each site, a block of three plots (1 m^2 (1 × 1), 50 m^2 (10 × 5) and 150 m^2 (25 × 6)) was installed. A network of 12 rain gauges (one per site) and five tipping bucket rain gauges (one per hydrological unit) were placed across the watershed to monitor the spatial variability of the rainfall. Each year, except for a few rainy episodes which were localised only on portions of the watershed, the entire rainfall network has always recorded some rain but with amounts varying between stations.

An overview of the experimental setup is shown in Fig. 1. The experimental design by soil surface types is presented in Table 1. Tillage, crop type and soil physical properties are described in Table 2. The hydrodynamic properties of the soil are strongly heterogeneous in cultivated areas, as evidenced by the magnitude of the parameter changes in this sub-basin. However, within the same site, the variations are much weaker. Thus, on each site, the hydrodynamic properties of the soil are assumed to be homogeneous. Only the micro-relief (slope and storage capacity) is different from one plot to another. Although the crop types are almost identical on the three sites, we observe a difference in the tillage type although we cannot tell if it is significant.

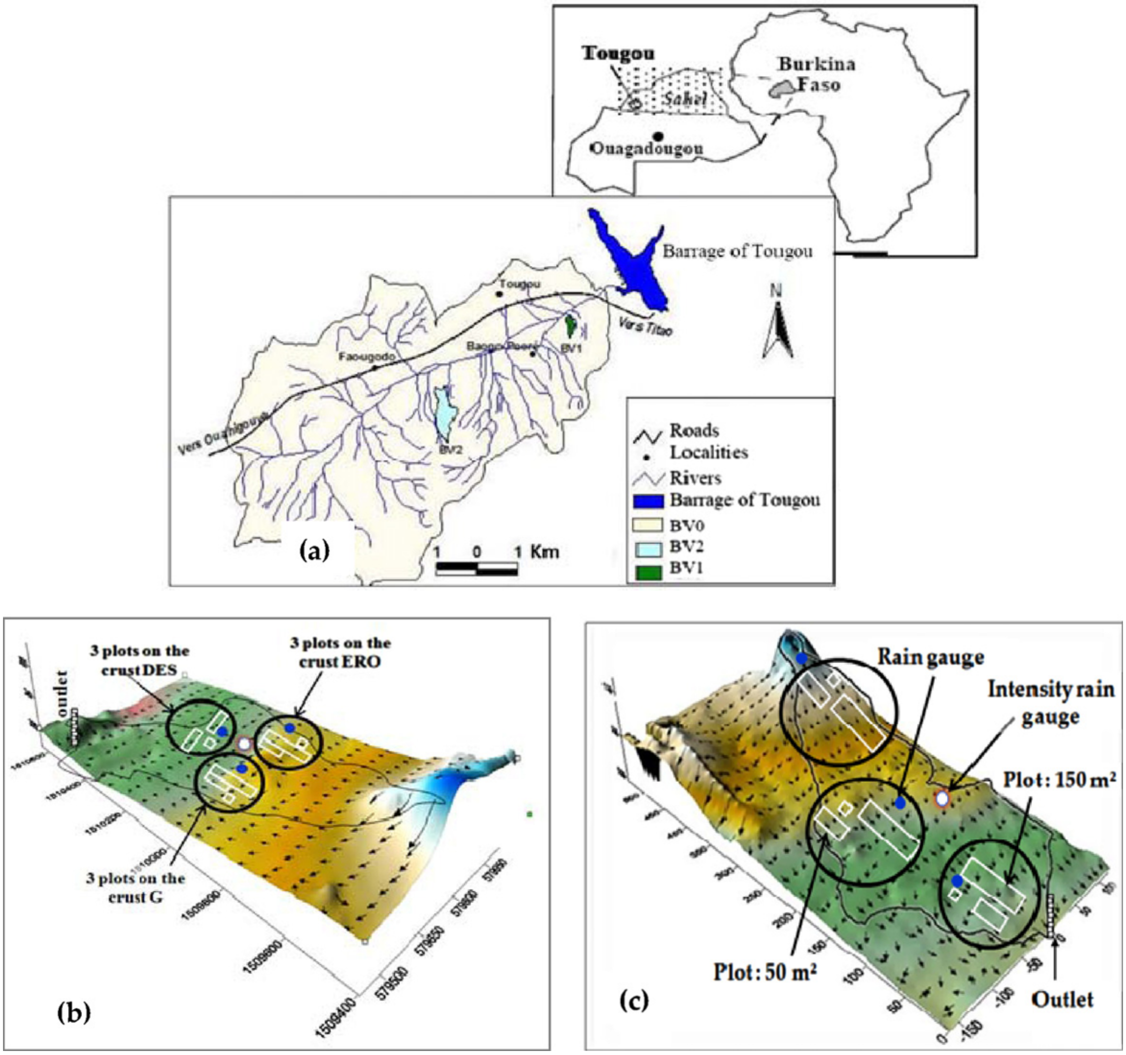

Fig. 1. (a) The Tougou watershed and location of sub-basins; (b) sub-basin in degraded soils and experimental plots; (c) sub-basin in cultivated soils and experimental plots.

Fig. 1. (a) Bassin versant de Tougou et localisation des sous-bassins ; (b) sous-bassin en sols dégradés et parcelles expérimentales ; (c) sous-bassin en sols cultivés et parcelles expérimentales.

2.2. Methodology of analysis

Statistical analysis was conducted on runoff coefficients to detect the scale effect for each type of soil surface. The aim was to investigate whether on each soil surface type, the mean of the runoff coefficient (arithmetic mean of the event values) was equal or significantly different on the three observation scales. The statistical analysis was made to determine, for each soil surface characteristics, the minimum representative area of the elementary processes causing the runoff.

To that end, we applied a nonparametric test, the Kruskall-Wallis test, at the threshold of 5% using the TANAGRA software (H_0 = equality of the mean values of the runoff coefficient of the three plots of the same site). The Kruskall-Wallis test is the generalization of the Mann-Whitney test, which compares two samples. The power of each test has been calculated to allow confidence in the obtained result, especially when it signals "not significant".

Then, the sources of variation were analysed on the same surface characteristics, then between them.

Since the measured hydrodynamic properties are homogeneous, the assumption that the source of variation was the slope, which differs from one plot to another, was tested. To better understand the scale effect, it is necessary to remove the influence of the slope on the runoff. For this, we defined a dimensionless number Pr, which is the ratio of the runoff coefficient of the plot by the square root of its slope. This dimensionless number Pr can be considered as the potential runoff of the plot thus overcoming the effect of the slope on runoff production. This formulation is similar to Manning's equation, which also uses the square root of the slope. Indeed, the storage surface on each plot is dependent on the runoff intensity, in steady-state regime, and on a parameter (Lafforgue, 2009) relying on the

Table 1
Experimental setup of the study.

Tableau 1
Dispositif expérimental de l'étude.

Name of site	Name of the units	Type of hydrological surface	Size	Average slope (%)	Type of surface feature	Type of land use
Site S_1	S_1-1	Plot	1 m^2	1.60		
	S_1-50	Plot	50 m^2	1.80		
	S_1-150	Plot	150 m^2	1.35		
Site S_2	S_2-l	Plot	1 m^2	1.70	Cultural (C)	Cultivated soils
	S_2-50	Plot	50 m^2	1.40		
	S_2-150	Plot	150 m^2	1.60		
Site S_3	S_3-1	Plot	1 m^2	4.00		
	S_3-50	Plot	50 m^2	4.20		
	S_3-150	Plot	150 m^2	2.85		
Site S_4	S_4-1	Plot	1 m^2	0.75	Erosion (ERO)	
	S_4-50	Plot	50 m^2	1.25		
	S_4-150	Plot	150 m^2	0.93		
Site S_5	S_5-1	Plot	1 m^2	0.90	Gravelly (G)	Degraded and uncultivated soils
	S_5-50	Plot	50 m^2	0.96		
	S_5-150	Plot	150 m^2	0.80		
Site S_6	S_6-1	Plot	1 m^2	2.30	Desiccation (DES)	
	S_6-501	Plot	50 m^2	2.10		
	S_6-502	Plot	50 m^2	3.55		
	BV1	Sub-catchment	6.1 ha	1.91	Cultural (C)	Cultivated soils
	BV2	Sub-catchment	33.8 ha	1.18	ERO, G, DES	Degraded and uncultivated soils

Table 2
Tillage, crop type and soil physical properties of the six sites.

Tableau 2
Labour, type de culture et propriétés physiques des sols des six sites.

Site	Soil type	Tillage type	Crop type	Ksat (mm/h)	Ksat (Casenave and Valentin, 1992)	Bulk density Da (g/cm^3)	Porosity (%)
S_1	Loam	Light tillage + weeding + mounding	Millet, sorghum and cowpea	21–25		1.40–1.46	45–47
S_2	Sandy	Means tillage + weeding + mounding	Millet, sorghum and cowpea	27–33	15–35	1.36–1.44	46–49
S_3	Sandy gravelly	Light tillage	Millet, sorghum and groundnut	16–19		1.46–1.48	44–45
S_4	Dry clay	No tillage	No crop	2–2.5	2–4	1.58–1.61	39–40
S_5	Gravelly			3–3.5	3–5	1.88–1.94	27–29
S_6	Sand			12–15	10–20	1.66–1.70	36–37

Number of infiltration tests by site: 12; number of porosity tests by site: 9.

characteristics of the plot (roughness and slope). An increase of the slope causes a decrease of the storage surface, and this effect is all the more significant since the slope is weak.

To approach the scale effect between two samples, we used a scale factor defined as the ratio between the dimensionless number Pr of the largest scale (Prl) and of the smallest scale (Prs). Van de Giesen et al. (2000) defined a similar ratio by directly using the runoff coefficients of the plots.

The heterogeneity of soil hydraulic properties was tested as a source of variation in runoff on soils with different surface characteristics. For this, we compared the runoff potential of plots of equal size.

In both cases, the observed scale effect was analysed by taking into account the rainfall characteristics.

3. Results and discussion

3.1. Spatial variability of runoff

Table 3 shows at various scales the mean runoff coefficient of the main soil surface characteristics of the

Table 3
Observed rainfall and runoff for the years 2010 and 2011 and for different scales.

Tableau 3
Pluviométrie et ruissellement observés pour les années 2010 et 2011 et pour différentes échelles.

Location	Name of the plot	Year 2010				Year 2011			
		Total rainfall (mm)	Runoff coefficient			Total rainfall (mm)	Runoff coefficient		
			Average	Standard deviation	Coefficient of variation		Average	Standard deviation	Coefficient of variation
Site S_1: cultivated	S_1-1	645	0.320	0.213	0.665	460	0.279	0.123	0.441
	S_1-50		0.285	0.190	0.666		0.209	0.120	0.575
	S_1-150		0.272	0.158	0.580		0.181	0.134	0.744
Site S_2: cultivated	S_2-1	651	0.191	0.142	0.741	461	0.208	0.111	0.533
	S_2-50		0.186	0.109	0.588		0.177	0.115	0.650
	S_2-150		0.132	0.114	0.864		0.121	0.080	0.657
Site S_3: cultivated	S_3-1	652	0.276	0.171	0.621	459	0.256	0.133	0.520
	S_3-50		0.246	0.143	0.580		0.183	0.099	0.539
	S_3-150		0.218	0.140	0.644		0.142	0.103	0.724
Site S_4: erosion	S_4-1	654	0.654	0.206	0.315	468	0.696	0.151	0.217
	S_4-50		0.711	0.217	0.305		0.760	0.132	0.174
	S_4-150		0.613	0.209	0.341		0.657	0.145	0.222
Site S_5: gravelly	S_5-1	663	0.726	0.213	0.293	466	0.770	0.154	0.200
	S_5-50		0.658	0.229	0.348		0.700	0.146	0.209
	S_5-150		0.599	0.221	0.369		0.640	0.152	0.238
Site S_6: desiccation	S_6-l	659	0.473	0.233	0.492	466	0.499	0.156	0.313
	S_6-50_1		0.264	0.126	0.480		0.296	0.087	0.293
	S_6-50_2		0.342	0.172	0.504		0.382	0.101	0.265
BV1		649	0.159	0.076	0.478	460	0.142	0.073	0.518
BV2		664	0.484	0.153	0.316	473	0.497	0.093	0.188

watershed. A comparison of results obtained on units of different land use clearly shows that the runoff is significantly higher on bare and degraded soils than on cultivated ones. These results confirm those of Rey et al. (2004) and illustrate the role of vegetation in the protection against surface hydric erosion.

In cultivated areas, the event values of the runoff coefficient of plots of 50 m^2 vary from 4 to 58%. The average value of the runoff depth for each scale of observation varies from one site to another. The low values of runoff were measured on site S2 because of the hydrodynamic properties of the soil surface and the tillage type (Table 2). Low runoff occurs when rain falls after a dry period or after tillage of the plots. Tillage generally decreases the bulk density, increases the porosity and changes the granulometric distribution of the soil, which causes an increase in surface storage (decrease in the connectivity rate of furrows) and an increase in the soil seepage potential (Ahuja et al., 1998; Allmaras et al., 1966; Xu and Mermoud, 2001). On the other hand, the highest runoff takes place when the soil is already wet, and in the case of exceptional rainfall events and thunderstorms.

In bare and degraded environments, runoff varies according to the nature of the crust. It is much higher on erosion (ERO) and gravelly (G) crusts than on the desiccation (DES) crust. On the 50 m^2 plots, the event values of the runoff coefficient vary between 16 and 95% for the ERO and G crusts, and between 10 and 70% for the DES crust. The lowest runoffs are generally caused by small amounts of rain, which correspond to low-intensity rainfall events. On the other hand, the high runoff coefficients are recorded during high-intensity rainfall events even if the total amount of rainfall is not very large.

3.2. Statistical analysis of the runoff at various scales

The results of statistical tests applied to the obtained runoff coefficient series are shown in Table 4. The size of each series is 41 for the plots in cultivated areas and 52 in bare and degraded environments. According to the Kruskal-Wallis test, the H_0 hypothesis (equality of the mean values of the runoff coefficient of the three plots at the same site) is accepted for the two cultivated sites S_1 and S_3, and rejected for the four other sites. However, the power of the tests for these two sites is not satisfactory when we consider the low obtained values. For the last cultivated site S_2, the hypothesis H_0 is rejected and the values of the power of the tests are acceptable: there is a consensus to consider a power of 80% suitable for a first kind risk. Note that the larger the sample size, the higher the power. Additional measurements must be carried out on these three sites to conclude on the equality or not of the means of the runoff coefficients.

On the other hand, on bare and degraded sites, the high values of the power of the test confirm the alternative hypothesis: the average runoff coefficients at the tested

Table 4
Results of the statistical tests.

Tableau 4
Résultats des tests statistiques.

Name of the site	Type of plot	Name of the test				
		Kruskal-Wallis		Mann-Whitney		
		Results		Hypothesis H_0	Results	Power of the test (%)
		Hypothesis H_0	Power of the test (%)			
Site S_1: cultivated	1 m^2	Acc	31	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Acc	20
	50 m^2			$\mu_{(1m^2)} = \mu_{(150m^2)}$	Acc	38
	150 m^2			$\mu_{(50m^2)} = \mu_{(150m^2)}$	Acc	< 10
Site S_2: cultivated	1 m^2	Rej	67	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Acc	< 10
	50 m^2			$\mu_{(1m^2)} = \mu_{(150m^2)}$	Rej	64
	150 m^2			$\mu_{(50m^2)} = \mu_{(150m^2)}$	Rej	64
Site S_3: cultivated	1 m^2	Acc	54	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Acc	22
	50 m^2			$\mu_{(1m^2)} = \mu_{(150m^2)}$	Acc	54
	150 m^2			$\mu_{(50m^2)} = \mu_{(150m^2)}$	Acc	19
Site S_4: erosion	1 m^2	Rej	90	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Rej	85
	50 m^2			$\mu_{(1m^2)} = \mu_{(150m^2)}$	Rej	86
	150 m^2			$\mu_{(50m^2)} = \mu_{(150m^2)}$	Acc	54
Site S_5: gravelly	1 m^2	Rej	84	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Rej	82
	50 m^2			$\mu_{(1m^2)} = \mu_{(150m^2)}$	Rej	85
	150 m^2			$\mu_{(50m^2)} = \mu_{(150m^2)}$	Acc	62
Site S_6: desiccation	1 m^2	Rej	96	$\mu_{(1m^2)} = \mu_{(50m^2)}$	Rej	94
	50 m^2			$\mu_{(1m^2)} = \mu_{(50m^2)}$	Rej	95
	50 m^2			$\mu_{(50m^2)} = \mu_{(50m^2)}$	Acc	75

Acc: accepted; Rej: rejected; H_0: equality of the averages.

scales are significantly different. According to the Mann-Whitney test, the mean values of the plots of 50 and 150 m^2 are equal but significantly different from the 1 m^2 plots at the threshold of 5%. From these results, we can say that on degraded sites, a plot of 50 m^2 is sufficient to study the elementary processes of runoff generation.

3.3. Measure of the scale effect

Fig. 2 shows the average values of the scale factor of the plots. A trend is observed on degraded soils. The ratio of runoff potential between plots of 50 and 1 m^2 is about 0.86 for the erosion and gravelly crusts and 0.60 for the desiccation crust. This means that for a slope length ratio equal to 1/10, an isolated plot of 1 m^2 generates about 1.16 times more runoff per unit surface than an area of 50 m^2 for the erosion and gravelly crusts, and about 1.66 times more for the desiccation crust. Moreover, the ratio of potential runoff between the plots of 150 and 50 m^2 is equal to 1 for the three crusts. This also confirms the results of the statistical analysis of the functioning of the plots in degraded areas. We can confirm that it is the same dominant processes that occur at both scales. It can be assumed that beyond a length of 10 m (= length of the plot of 50 m^2), there is sufficient runoff energy for the entire flow from upstream to reach the downstream of the plot.

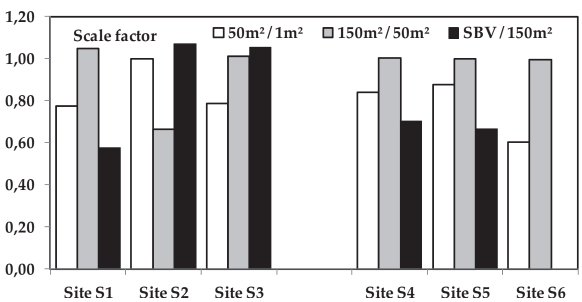

Fig. 2. Scaling factors for runoff at different scales of observation on six sites (S_1 to S_3: cultivated sites; S_4 to S_6: degraded sites).

Fig. 2. Facteurs d'échelle pour le ruissellement à différentes échelles d'observation pour les six sites (S_1 à S_3 : sites cultivés ; S_4 à S_6 : sites dégradés).

On cultivated soils, the values of the scale factor vary much more, depending on the site: this is due to the heterogeneity of the soil surface characteristics of the sub-basin. Sites S_1 and S_3 have a similar hydrological behaviour; the ratio between 50 and 1 m^2 plots is about 0.77. However, the same ratio between the plots of 150 and 50 m^2 is about 1.03. This means that the runoff-generating surfaces on the plots of 50 m^2 are fragmented whereas they are connected on the plots of 150 m^2. This phenomenon can be explained by the depressions caused by the tillage. This dimensionless analysis confirms that both in cultivated soils and bare and degraded soils, runoff decreases as the plot size increases.

3.4. Factors explaining the scale effect

In order to understand the causes of this scale effect, we compared the mean runoff coefficients per plot of the same

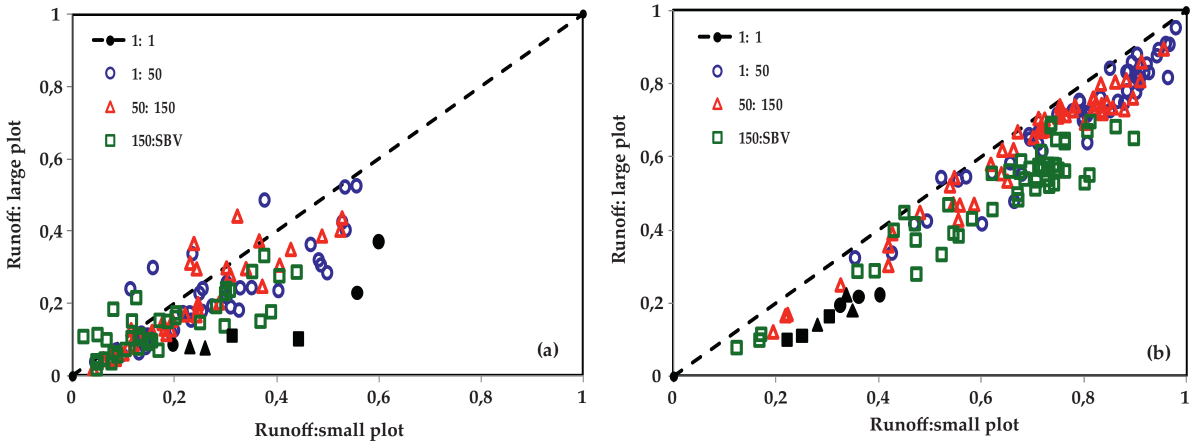

Fig. 3. Comparison by event of the runoff coefficients of three plots set up on each of the surface textures: (a) cultivated site S_3; (b) degraded site S_5.

Fig. 3. Comparaison, par évènement, des coefficients de ruissellement de trois parcelles installées sur chacune des textures de surface : (a) site cultivé S_3 ; (b) site dégradé S_5.

size, and the runoff coefficients by events of three plots on each of the soil surface types.

The comparison of plots of the same size showed that the mean runoff coefficient varies significantly from one site to another. These results concur with those of Cammeraat (2004) and show that the measurement site strongly influences the results. They are related to the variation of the hydrodynamic properties of soil surface characteristics: slope and in cultivated areas, tillage techniques (Table 2).

At the same scale of observation, the production of runoff depends more on the hydrodynamic properties of soils surface characteristics than on the rainfall parameters. Some results of the comparison between the runoff coefficients per rainfall event on the three plots within the same site are illustrated in Fig. 3. The coordinates of each point correspond: on the *x*-axis, to the event runoff coefficient of the smaller plot and on the y-axis, to the event runoff of the largest plot. The black dots in Figs. 3a,b correspond to rainfall events of short duration or low intensity.

On degraded and bare soils (Fig. 3b), we see that almost all dots in the cloud are below the diagonal. The surface characteristics have not changed, the slope of the plots and the dynamics of precipitation are the only sources of variation.

On the cultivated soils (Fig. 3a), the results are a little mixed due to the edaphic soil conditions (tilled or not) of the plots which are not the same before each rain event. Some dots on the three graphs are above the diagonal. They correspond to the points where the conditions of surface characteristics are different. For example, some (150: SBV) dots are above the diagonal because the plot of 150 m^2 is tilled while much of the sub-basin is not. If the soil moisture and surface characteristics are comparable, the runoff decreases with the increase in the plot size.

The analysis by class of rainfall events corroborates those of Stomph et al. (2002) who showed that the decrease in runoff with increasing slope length becomes more pronounced with shorter rain duration.

4. Conclusions

The results presented in this article illustrate the complexity of the hydrological processes and the number of parameters involved in the genesis of runoff. Through this study, we identified and analysed at different plot scales the causes of the well-known phenomenon of "decreasing runoff when the area of the plots increases". Our results show that the scale effect observed in the runoff is mainly due to the spatial heterogeneity of soil-surface characteristics. It becomes more pronounced when the duration of the rain decreases.

For both cultivated and bare and degraded soil surfaces, the scale effects are not the same and the position on the hill slopes of measurement plots strongly influences the results.

On the basis of statistical and dimensionless analyses, the results show that in degraded environments, the runoff generation processes on plots of 150 and 50 m^2 are identical and significantly different from those on the 1 m^2 plot. In cultivated areas, additional measures are needed to better understand the differences in functioning at various scales. In cultivated areas, the tillage increases soil infiltration, and reduces the connectivity of runoff areas.

Indeed, the scale effect issue is critical when attempting to transpose to larger spatial scales, the knowledge of the processes discovered at the scale of a plot. Our results are consistent with other studies that indicate the existence of a large-scale effect between the plot and the watershed.

Acknowledgments

The study received financial support from the European Union within the framework of the AMMA program (African Monsoon Multidisciplinary Analyses), the Swiss Cooperation (SDC) and IRD/HSM (HydoSciences Montpellier). The authors thank all field observers, technicians and trainees who contributed to data collection. They also thank the two reviewers Pierre Dubreuil and Bénédicte

Augeard, and an anonymous referee for constructive suggestions to improve this article.

References

Ahuja, L., Fieldler, F., Dunn, G., Benjamin, J., Garrison, A., 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci. Soc. Am. J. 62, 1228–1233.

Allmaras, P., Burwell, R., Larson, W., Holt, R., 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USDA, Washington, Report 7.

Beven, K., 1995. Linking parameters across scales: subgrid parametrizations and scale dependent hydrological models. Hydrol. Process 9, 507–527.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling. A review. Hydrol. Process 9, 251–290.

Cammeraat, L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in Southeast Spain. Agr. Ecosyst. Environ. 104, 317–332.

Casenave, A., 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.

Cerdan, O., Le Bissonnais, Y., Govers, G., Lecomte, V., Oost, K., Couturier, A., King, C., Dubreuil, N., 2004. Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. J. Hydrol. 299, 4–14.

Favreau, G., Leduc, C., Marlin, C., Guéro, A., 2002. Une dépression piézométrique naturelle en hausse au Sahel (Sud-Ouest du Niger). C. R. Geoscience 334, 395–401.

Gomi, T., Sidle, R.C., Miyata, S., Kosugi, K., Onda, Y., 2008. Dynamic runoff connectivity of overland flow on steep forested hillslopes: scale effects and runoff transfer. Water Resour. Res. 44, W08411 doi:10.1016/2007WR005894.

Lafforgue, A., 2009. Détermination des variations de la capacité d'absorption d'un sol en place sous averses simulées/Obtaining variations of field infiltration capacity from simulated rainstorm experiments. Hydrol. Sci. J. 23 (3), 355–372.

Le Bissonnais, Y., Raclot, D., Andrieux, P., Moussa, R., Louchart, X., Voltz, M., 2006. Effets d'échelle et variabilité de l'érosion entre parcelle et bassin versant en région de vignoble méditerranéen (France). In: Actes de la session VII organisée par le Réseau E-GCES de l'AUF au sein de la conférence ISCO de Marrakech (Maroc), pp. 325–330.

Mahé, G., Paturel, J.E., 2009. 1896–2006 Sahelian annual rainfall variability and runoff increase of Sahelian Rivers. C. R. Geoscience 34 (7), 538–546.

Mayor, A.G., Bautista, S., Bello, J., 2011. Scale-dependent variation in runoff and sediment yield in a semiarid Mediterranean catchment. J. Hydrol. 397, 128–135.

Reaney, S.M., Bracken, L.J., Kirkby, M.J., 2007. Use of the connectivity of runoff model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas. Hydrol. Process 21, 894–906.

Rey, F., Ballais, J.-L., Marre, A., Rovéra, G., 2004. Rôle de la végétation dans la protection contre l'érosion hydrique de surface. C. R. Geoscience 336, 991–998.

Stomph, T.J., De Ridder, N., Steenhuis, T.S., Van de Giesen, N.C., 2002. Scale effects of hortonian overland flow and rainfall-runoff dynamics: laboratory validation of a process-based model. Earth Surf. Proc. Land. 27, 847–855.

Van de Giesen, N.C., Stomph, T.J., de Ridder, N., 2000. Scale effects of Hortonian overland flow and rainfall runoff dynamics in a West African catena landscape. Hydrol. Process 14, 165–175.

Van de Giesen, N.C., Stomph, T.J., de Ridder, N., 2005. Surface runoff scale effects in West African watersheds: modelling and management options. Agr. Water Manage. 72, 109–130 doi:10.1016/j.agwat.2004.09.007.

Van de Giesen, N.C., Stomph, T.J., Ayaji, A.E., Bagayoko, F., 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: field data and models. Agr. Ecosyst. Environ. 142 (1–2), 95–101.

Xu, D., Mermoud, A., 2001. Topsoil properties affected by tillage practices in North China. Soil Till. Res. 60, 11–19.