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Multi-scale analysis of runoff from a statistical perspective in a small Sahelian catchment under semiarid climate --Manuscript Draft--

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Abstract:	<p>Runoff measurements were carried on soils with different surface features types from 2010 to 2015 at various homogeneous unit scales and land use types in the Tougou watershed (in northern Burkina Faso) under semiarid climate. Statistical and dimensional analysis were used to investigate significant differences in runoff response behaviour on plots of 1 m², 50 m² and 150 m², hydrologic units of 6 and 34 ha and the catchment of 37 km². Results show that on both cultivated and bare soils, the runoff excess decreases as the area increases, under similar rainfall pattern and prior antecedent soil moisture conditions. Statistical analysis revealed that on degraded soils, the processes of runoff generation on the plots of 50 and 150 m² are identical and significantly different from those observed on the unit plot (1 m²). A minimum plot length of 10 m was found to be optimal to accurately estimate runoff on degraded soils. On cultivated soils, runoff is significantly different from one site to another because of the spatial variability of hydrodynamic properties of the soil. Moreover, the decrease in runoff is induced by the microrelief and the slope. Such results show that the scale effect on the runoff is related to the spatial heterogeneity of soils and furthermore intensified by the rainfall intensity. Such results highlight the value of separate measurements of runoff on homogeneous units in terms of land use prior to distributed hydrological modelling, hence allowing an innovative approach to the problem of scale transfer.</p>
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Prof. Dr. Abdullah M. Al-Amri
Editor-In-Chief
Arabian Journal of Geosciences

July 23, 2019

Prof. Dr. Abdullah M. Al-Amri,

We, the authors, are pleased to submit an original and full research paper entitled “***Multi-scale analysis of runoff from a statistical perspective in a small Sahelian catchment under semiarid climate***” for consideration for publication in the *Arabian Journal of Geosciences* journal. This paper is a contribution to the problem of spatial variability of runoff and the effect of scale of observation in hydrology. We monitored during six years runoff on different land use type and at various scales of observation on a small Sahelian basin of West Africa, under semiarid climate. The aim of our research was to understand the sources of surface runoff variation and to determine the optimal minimum area to accurately estimate runoff on plots as a function of the soil surface condition, hence contributing to the upscaling problem in hydrology.

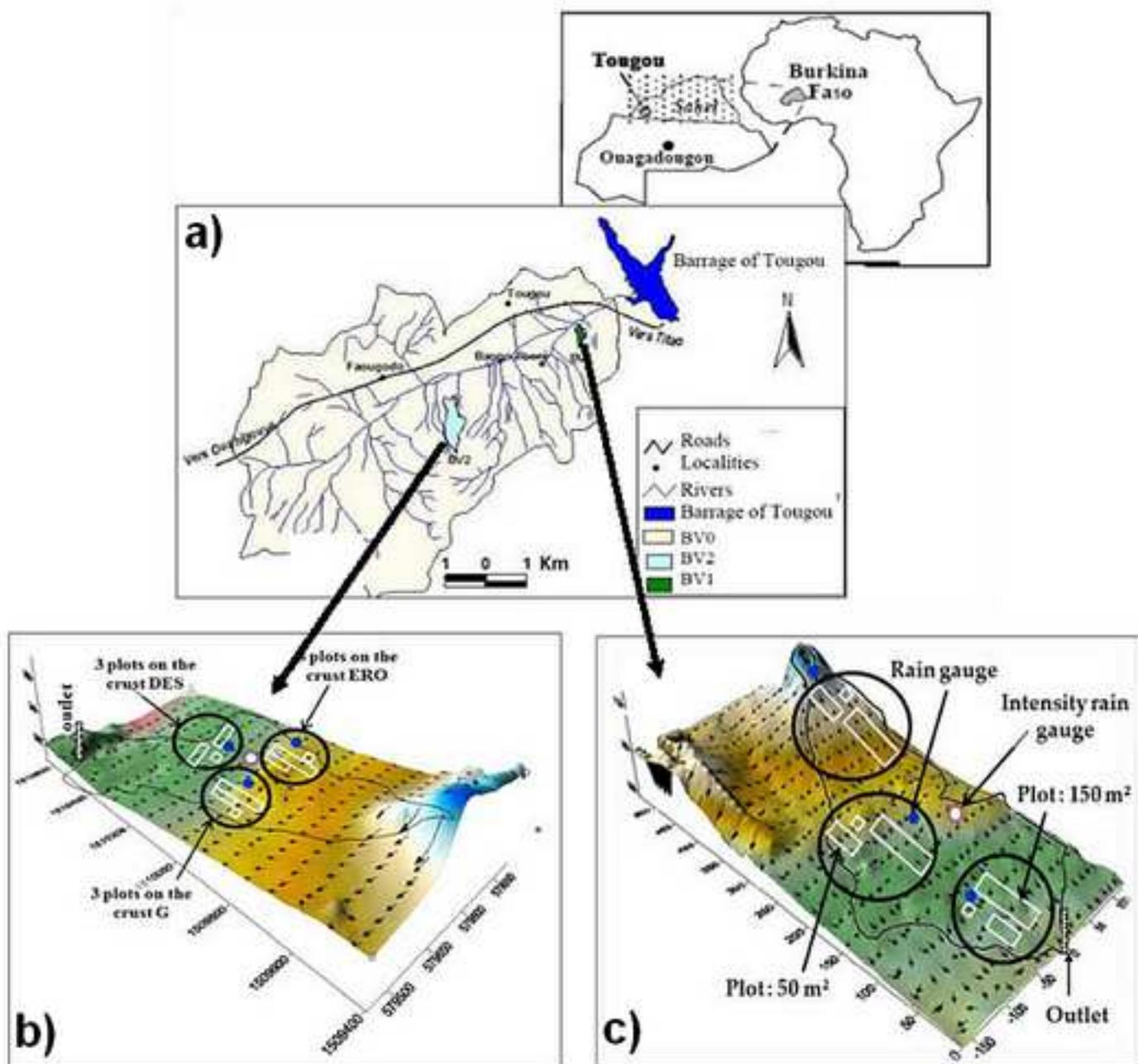
Our measurements were carried out on both degraded and cultivated soils. The results presented in this paper suggest that a minimum length of 10 m is sufficient to accurately measure runoff on degraded soils. On cultivated soils however, the elementary zone representative of the runoff is greater than 150m². Our findings illustrate that the issue of scale is critical when attempting to transpose processes discovered at the scale of a plot to higher spatial scales.

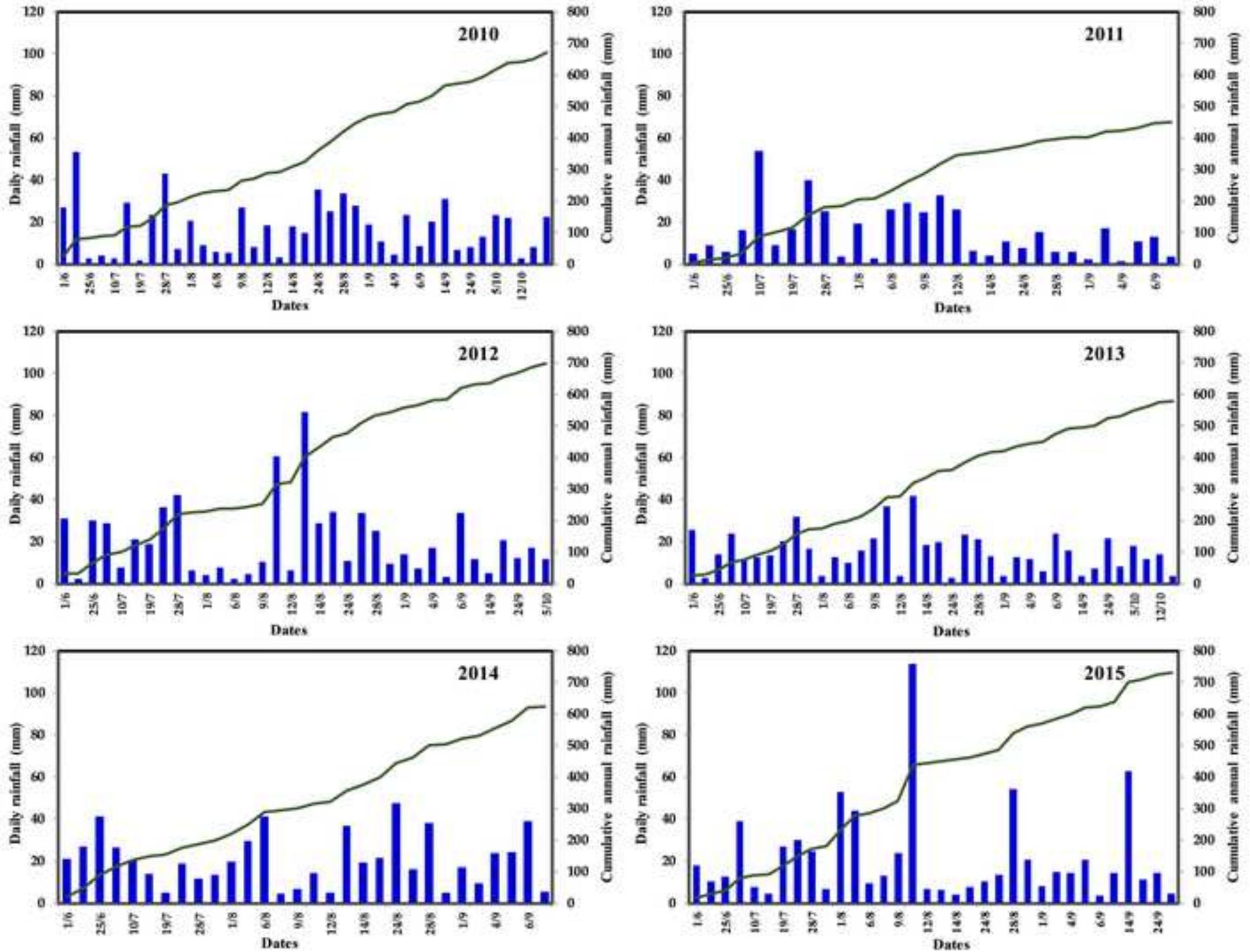
We believe that this manuscript is suitable for publication by *Arabian Journal of Geosciences*. This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose.

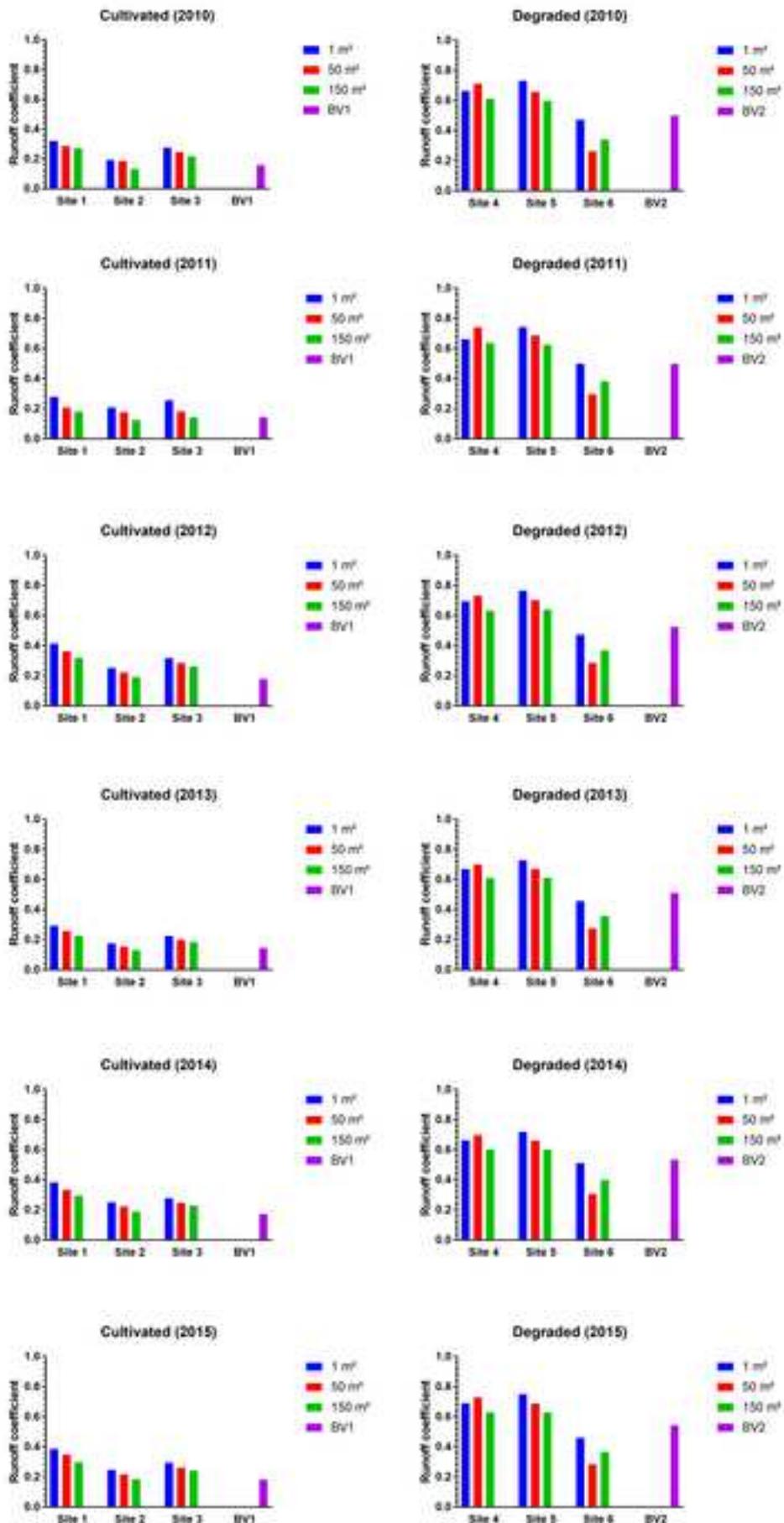
Thank you for your consideration. Sincerely,



Lawani Adjadi **MOUNIROU**







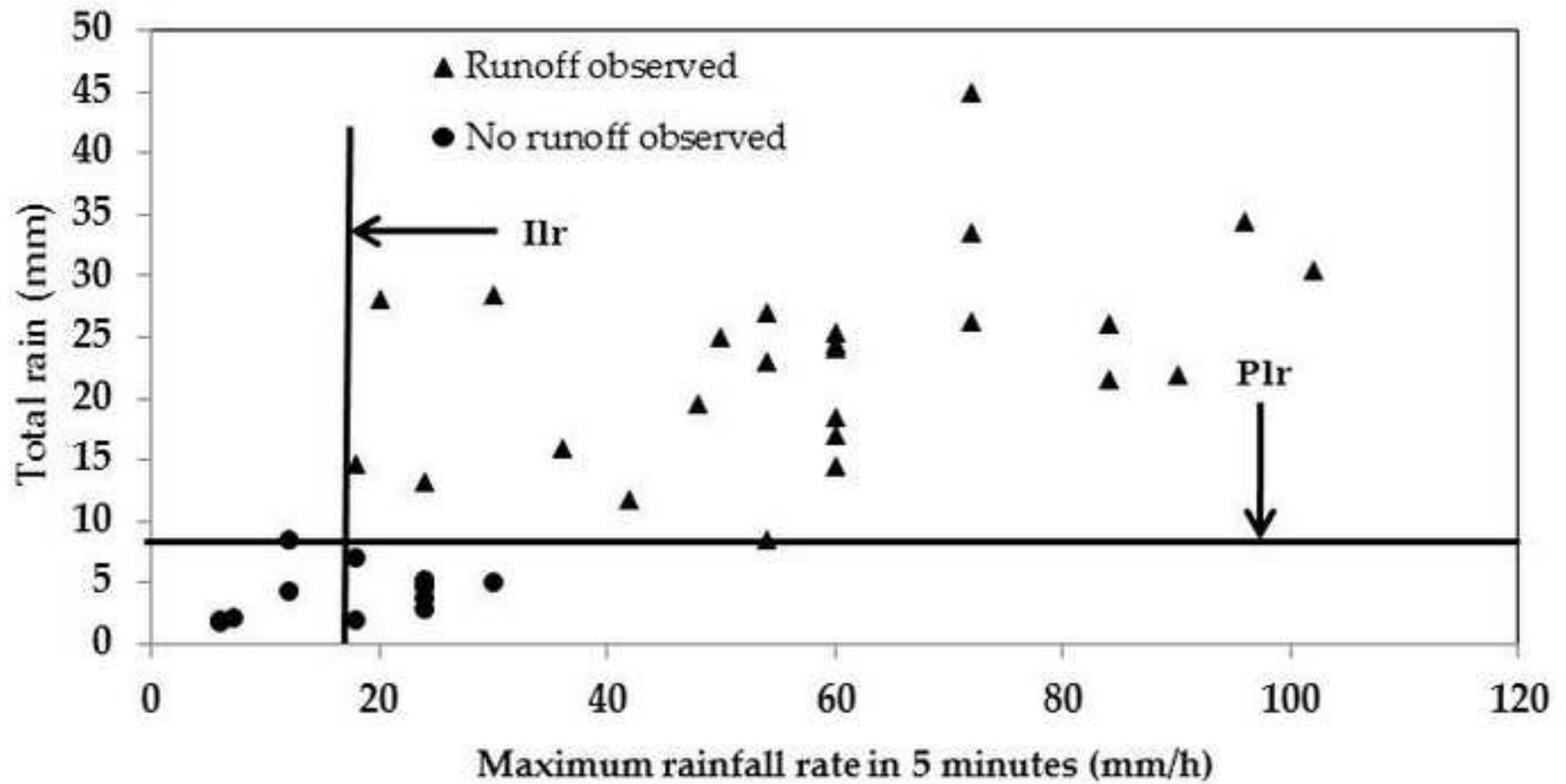


Table 1 Experimental arrangement of the study, description and geometric characteristics of measurement plots

Site name	Unit name	Hydrological unit type	Size	Average slope (%)	Surface feature type	Land use			
Site S ₁	S ₁₋₁	Plot	1 m ² (1x1)	1.60	Cultural (C)	Cultivated soils			
	S ₁₋₅₀	Plot	50 m ² (5x10)	1.80					
	S ₁₋₁₅₀	Plot	150 m ² (6x25)	1.35					
Site S ₂	S ₂₋₁	Plot	1 m ² (1x1)	1.70					
	S ₂₋₅₀	Plot	50 m ² (5x10)	1.40					
	S ₂₋₁₅₀	Plot	150 m ² (6x25)	1.60					
Site S ₃	S ₃₋₁	Plot	1 m ² (1x1)	4.00			Erosion (ERO)	Degraded and uncultivated soils	
	S ₃₋₅₀	Plot	50 m ² (5x10)	4.20					
	S ₃₋₁₅₀	Plot	150 m ² (6x25)	2.85					
Site S ₄	S ₄₋₁	Plot	1 m ² (1x1)	0.75					
	S ₄₋₅₀	Plot	50 m ² (5x10)	1.25					
	S ₄₋₁₅₀	Plot	150 m ² (6x25)	0.93					
Site S ₅	S ₅₋₁	Plot	1 m ² (1x1)	0.90	Gravelly (G)	Degraded and uncultivated soils			
	S ₅₋₅₀	Plot	50 m ² (5x10)	0.96					
	S ₅₋₁₅₀	Plot	150 m ² (6x25)	0.80					
Site S ₆	S ₆₋₁	Plot	1 m ² (1x1)	2.30			Dessication (DES)	Degraded and uncultivated soils	
	S ₆₋₅₀	Plot	50 m ² (5x10)	2.10					
	S ₆₋₅₀	Plot	50 m ² (5x10)	3.55					
BV ₁	Sub-catchment	6.1 ha	1.91	Cultural (C)					Cultivated soils
BV ₂	Sub-catchment	33.8 ha	1.18	ERO, G, DES					Degraded and uncultivated soils
BV ₀	Catchment	37 km ²	0.68	C, ERO, G, DES					

Table 2 Characteristics of rainfall in Tougou catchment from 2010 to 2015

Month	Rainfall				% Monthly	Intensity				Frequency
	Maximum Pj (mm)		Monthly rainfall (mm)			I _{max-5mn} (mm/h)		I _{max-30mn} (mm/h)		Average number of events
	Avg	σ	Avg	σ		Avg	σ	Avg	σ	
June	41.6	10.8	101.8	35.2	16%	81.6	7.5	42.2	6.2	5
July	43.3	12.1	146.5	42.7	23%	82.5	10.9	42.8	8.5	8
August	57.8	32.8	218.0	43.0	35%	95.9	16.7	58.8	9.4	11
September	35.9	16.6	119.6	41.8	19%	78.5	29.0	42.7	12.5	8
October	21.6	9.6	41.5	26.3	7%	37.6	14.9	26.7	11.5	3

Pj = daily rainfall; *Iavg* and *I_{max}* = average and maximum intensity; *Avg* = average; σ = standard deviation

Table 3 Soil type, and soil physical properties of the 6 sites on the Tougou watershed

Site	Soil type	Ksat (mm/h)	Ksat (Casenave and Valentin 1989)	Bulk Density Da (g/cm ³)	Porosity (%)	Manning roughness (n)
Site S ₁	Loam	21 – 25		1.40 – 1.46	45 – 47	0.050
Site S ₂	Sandy	27 – 33	15 - 35	1.36 – 1.44	46 – 49	0.060
Site S ₃	Sandy gravelly	16 – 19		1.46 – 1.48	44 – 45	0.065
Site S ₄	dry clay	2 – 2.5	2 – 4	1.58 – 1.61	39 – 40	0.015
Site S ₅	Gravelly	3 – 3.5	3 – 5	1.88 – 1.94	27 – 29	0.020
Site S ₆	Sand	12 – 15	10 – 20	1.66 – 1.70	36 – 37	0.025

Number of infiltration tests by site: 12 - Number of porosity tests by site: 9

Table 4 Results of statistical analysis of the land use type on runoff for similar observation scales

Test name		Kruskal-Wallis			Mann-Whitney			
		Results						
Scale	Type of plot	Hypothesis H_0	p - value	Power of the test	Hypothesis H_0	Decision	p - value	Power of the test
1 m ²	S _{1-1m²}	Rej	< 0.01 %	96%	$\mu(S_{1-1m^2}) = \mu(S_{2-1m^2})$	Rej	< 0.01 %	95%
	S _{2-1m²}				$\mu(S_{1-1m^2}) = \mu(S_{3-1m^2})$	Rej	0.0038	89%
	S _{3-1m²}				$\mu(S_{2-1m^2}) = \mu(S_{3-1m^2})$	Rej	0.0034	81%
50 m ²	S _{1-50m²}	Rej	< 0.01 %	96%	$\mu(S_{1-50m^2}) = \mu(S_{2-50m^2})$	Rej	< 0.01 %	95%
	S _{2-50m²}				$\mu(S_{1-50m^2}) = \mu(S_{3-50m^2})$	Rej	0.0079	86%
	S _{3-50m²}				$\mu(S_{2-50m^2}) = \mu(S_{3-50m^2})$	Rej	0.0077	77%
150 m ²	S _{1-150m²}	Rej	< 0.01 %	96%	$\mu(S_{1-150m^2}) = \mu(S_{2-150m^2})$	Rej	< 0.01 %	95%
	S _{2-150m²}				$\mu(S_{1-150m^2}) = \mu(S_{3-150m^2})$	Rej	0.0153	79%
	S _{3-150m²}				$\mu(S_{2-150m^2}) = \mu(S_{3-150m^2})$	Rej	< 0.01 %	93%

H_0 = equality of the ranks of mean runoff potential - Rej = Rejected

Table 5 Results of statistical analysis of the plot size effect on runoff for different land use types

Tests name		Kruskal-Wallis			Mann-Whitney			
Site name	Type of plot	Hypothesis H_0	Results		Hypothesis H_0	Decision	p - value	Power of the test
			p - value	Power of the test				
Site S1: cultivated	1 m ²	Rej	0.71%	80%	$\mu(1m^2) = \mu(50m^2)$	Rej	0.44%	81%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	1.02%	73%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	72.19%	< 10%
Site S2: cultivated	1 m ²	Rej	0.15%	90%	$\mu(1m^2) = \mu(50m^2)$	Acc	88.54%	< 10%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	0.25%	89%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Rej	0.20%	86%
Site S3: cultivated	1 m ²	Acc	10.71%	34%	$\mu(1m^2) = \mu(50m^2)$	Acc	6.65%	23%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Acc	29.04%	< 10%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	20.22%	21%
Site S4: Erosion	1 m ²	Rej	< 0.01%	96%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	< 0.01%	95%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	81.25%	82%
Site S5: Gravelly	1 m ²	Rej	< 0.01%	95%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	94%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	< 0.01%	94%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	95.78%	85%
Site S6: Desiccation	1 m ²	Rej	< 0.01%	96%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(50m^2) = \mu(50m^2)$	Acc	75.55%	76%

H_0 = equality of the ranks of mean runoff potential - Rej = Rejected - Acc = Accepted. Values in bold refers to tests runs where null hypothesis (H_0) were rejected, with a satisfactory power

Table 6 Runoff potential at different scales and measures of scale effect

Plot name	2010		2011		2012		2013		2014		2015	
	Rp	l/s										
S ₁₋₁	2.53		2.33		3.27		2.33		3.03		3.04	8.5
S ₁₋₅₀	2.13	0.84	1.68	0.72	2.7	0.83	1.92	0.82	2.48	0.82	2.58	0.85
S ₁₋₁₅₀	2.34	1.10	1.68	1.00	2.74	1.01	1.95	1.02	2.54	1.02	2.57	1.00
S ₂₋₁	1.49		1.59		1.94		1.34		1.93		1.89	
S ₂₋₅₀	1.57	1.05	1.5	0.94	1.89	0.97	1.3	0.97	1.87	0.97	1.84	0.97
S ₂₋₁₅₀	1.06	0.68	1.19	0.79	1.53	0.81	1.05	0.81	1.52	0.81	1.5	0.82
S ₃₋₁	1.38		1.28		1.59		1.12		1.39		1.47	
S ₃₋₅₀	1.20	0.87	0.97	0.76	1.39	0.87	0.98	0.88	1.21	0.87	1.28	0.87
S ₃₋₁₅₀	1.29	1.08	1.05	1.08	1.55	1.12	1.09	1.11	1.35	1.12	1.43	1.12
S ₄₋₁	7.67		7.64		8.03		7.72		7.65		7.97	
S ₄₋₅₀	6.36	0.83	6.63	0.87	6.55	0.82	6.27	0.81	6.23	0.81	6.52	0.82
S ₄₋₁₅₀	6.35	1.00	6.61	1.00	6.56	1.00	6.31	1.01	6.25	1.00	6.51	1.00
S ₅₋₁	7.73		7.84		8.07		7.67		7.58		7.9	
S ₅₋₅₀	6.72	0.87	7.00	0.89	7.16	0.89	6.84	0.89	6.74	0.89	7.02	0.89
S ₅₋₁₅₀	6.70	1.00	7.00	1.00	7.14	1.00	6.82	1.00	6.72	1.00	7.02	1.00
S ₆₋₁	3.11		3.29		3.13		3.01		3.37		3.04	
S ₆₋₅₀	1.82	0.59	2.04	0.62	1.97	0.63	1.9	0.63	2.12	0.63	1.96	0.64
S ₆₋₁₅₀	1.81	0.99	2.03	1.00	1.96	0.99	1.89	0.99	2.11	1.00	1.95	0.99

Rp = Runoff potential - l/s = larger / smaller. Values in bold refer to similar runoff potential values at different observation scales.

Multi-scale analysis of runoff from a statistical perspective in a small Sahelian catchment under semiarid climate

Lawani Adjadi Mounirou¹, Cheick Oumar Zouré¹, Roland Yonaba¹, Jean-Emmanuel Paturel², Gil Mahé², Dial Niang¹, Hamma Yacouba¹, Harouna Karambiri¹.

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Declarations of interest: none.

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Abstract

Runoff measurements were carried on soils with different surface features types from 2010 to 2015 at various homogeneous unit scales and land use types in the Tougou watershed (in northern Burkina Faso) under semiarid climate. Statistical and dimensional analysis were used to investigate significant differences in runoff response behaviour on plots of 1 m², 50 m² and 150 m², hydrologic units of 6 and 34 ha and the catchment of 37 km². Results show that on both cultivated and bare soils, the runoff excess decreases as the area increases, under similar rainfall pattern and prior antecedent soil moisture conditions. Statistical analysis revealed that on degraded soils, the processes of runoff generation on the plots of 50 and 150 m² are identical and significantly different from those observed on the unit plot (1 m²). A minimum plot length of 10 m was found to be optimal to accurately estimate runoff on degraded soils. On cultivated soils, runoff is significantly different from one site to another because of the spatial variability of hydrodynamic properties of the soil. Moreover, the decrease in runoff is induced by the microrelief and the slope. Such results show that the scale effect on the runoff is related to the spatial heterogeneity of soils and furthermore intensified by the rainfall intensity. Such results highlight the value of separate measurements of runoff on homogeneous units in terms of land use prior to distributed hydrological modelling, hence allowing an innovative approach to the problem of scale transfer.

Keywords Rainfall intensity, Runoff potential, Sahel, Soil spatial heterogeneity, Surface feature.

Introduction

Hydrological processes are complex and vary considerably in space and time. In the last decades, understanding the influence of scale on hydrological processes and mechanisms (soil wetness, runoff generation, infiltration, percolation, erosion) has been an active area of research and remains a major challenge for hydrologists (Yair and Raz-Yassif 2004; Soulsby et al. 2006; Van de Giesen et al. 2011; Chaplot and Poesen 2012; Guo et al. 2015; Anache et al. 2017). In particular, the analysis of variation of runoff on plots of different sizes has been recognized as a key step in modelling the hydrology of watersheds (Boardman 2006; Bracken and Croke 2007). However, many efforts have been directed to the theoretical aspects of upscaling (Blöschl 2001) and less have tackled experimental studies regarding the hydrology of watersheds (McGlynn et al. 2004). International research initiatives such as Hydrology, Environment, Life and Policy (HELP) and Prediction in Ungauged Basins (PUB) stressed the need for hydrologists to transfer to larger spatial scales, understanding the processes unveiled on small experimental catchments to facilitate management decisions of large hydrologic systems (Sivapalan et al. 2003; Bonell et al. 2006). Upscaling targets the unresolved issue of scale, based on a similarity of measurements (Lin and Wang 2010) and differs from the process of transferring the parameters of a given watershed to a neighbouring watershed referred to as regionalization (Blöschl and Sivapalan 1995).

Many studies of the hydrodynamic behaviour of the soil at various spatial scales have successfully demonstrated that the production of runoff per unit area decreases with an increasing surface area of the plot. Such finding have been related to the downstream re-infiltration (Gomi et al. 2008; Mayor et al. 2011; Asadzadeh et al. 2012; Mounirou et al. 2012; Sadeghi et al. 2013; Lemma et al. 2018). Re-infiltration of runoff water was mainly attributed to the spatial variability of the soil infiltration capacity (Yair and Kossovsky 2002; Esteves and Lapetite 2003; Cerdan et al. 2004; Li and Sivapalan 2011). Other causes for the problem of scale on runoff have been identified such as the rainfall pattern and spatial variability (Reaney et al. 2007; Van de Giesen et al. 2011; Chen et al. 2016; Cristiano et al. 2019), the non-linearity of hydrological processes (Lesschen et al. 2009; Cerdan et al. 2010), the threshold effect regulating the occurrence of specific processes and the development of emergent properties of the soil at certain scales (Antoine et al. 2011; Mayor et al. 2011; Miyata et al. 2019). Thus, the variability of soil moisture conditions, the crusting and rainfall intensity patterns each produce different hydrologic regimes at different spatial scales.

In arid and semiarid environments, the hortonian runoff process, which is deemed to occur when rainfall intensity exceeds soil infiltration capacity, is often the main mechanism for runoff generation (Chen et al. 2016). As such, in these areas, understanding the runoff generation process at different spatial scales and on different surface features within a watershed is critical to provide accurate estimations of runoff and other hydrological processes

1 for modellers depending on the scale and to develop suitable management practices of water resources. Most
2 studies which quantified runoff in the Sahel up to date have addressed the plot-scale of 1 m², a few tens of square
3 meters or the scale of small catchments (Peugeot et al. 1997; Karambiri et al. 2003; Peugeot et al. 2003; Malam
4 Issa et al. 2009). Few studies have focused on the issue of scale transfer. The results obtained by Diallo (2000) on
5 the catchment of Djitiko in Mali, although measuring at nested scales, were analyzed in relation to the fate of the
6 materials removed from the plots along the catchment and drainage network. Moreover, the study focused on the
7 Sudanian area, as opposed to the Sahel. The investigation of scale effect on runoff production in Sahelian
8 landscape, under semiarid climate is the objective of this research. More specifically, this paper aims at
9 characterising runoff at various spatial scales and develop linking between measurements at the plot level with
10 those at the watershed scale.

11 **Materials and methods**

12 **Description of the experimental site**

13
14 The Tougou watershed, with an area of 37 km² is located in northern Burkina Faso (Fig. 1) in the Sahel zone. It
15 is characterized by a unimodal annual rainfall which varies between 400 and 650 mm per year, mainly between
16 June and October (Mounirou et al. 2012; Zouré et al. 2019). Hydrography of the watershed is characterized by a
17 weak and diffuse network, with channels and gullies draining streams to a non-perennial main river named
18 *Bilampoanga*, long of 8.5 km. Altitude on the basin varies between 320 m and 367 m, with slopes ranging from 2
19 to 10%. Three types of soil can be found within the area: (i) slightly evolved soils (25% of the area), with a sandy,
20 sandy-clay, sandy-gravel at the top; (ii) crude mineral soils (35% of the area) which tends to physical degradation
21 into glacis, called *zipelle* in local language (Sawadogo et al. 2008); (iii) hydromorphic soils (40% of the area)
22 located in alluvial terraces and peripheral depressions, very clayey, often highly silted. Vegetation is sparse, made
23 of savannas shrubs (Mounirou 2012). Land use types found within the watershed are cultivated areas, bare and
24 degraded soils and natural vegetation representing 73%, 22% and 5% of the area of the catchment (Diello 2007).
25 Hydrology of the watershed, as in most Sahelian watersheds, is characterized by hortonian runoff processes as the
26 soil has little vegetation cover and encrusted surfaces and a relatively deep aquifer with recharge occurring at the
27 bottom of the minor riverbeds (Koïta et al. 2017).
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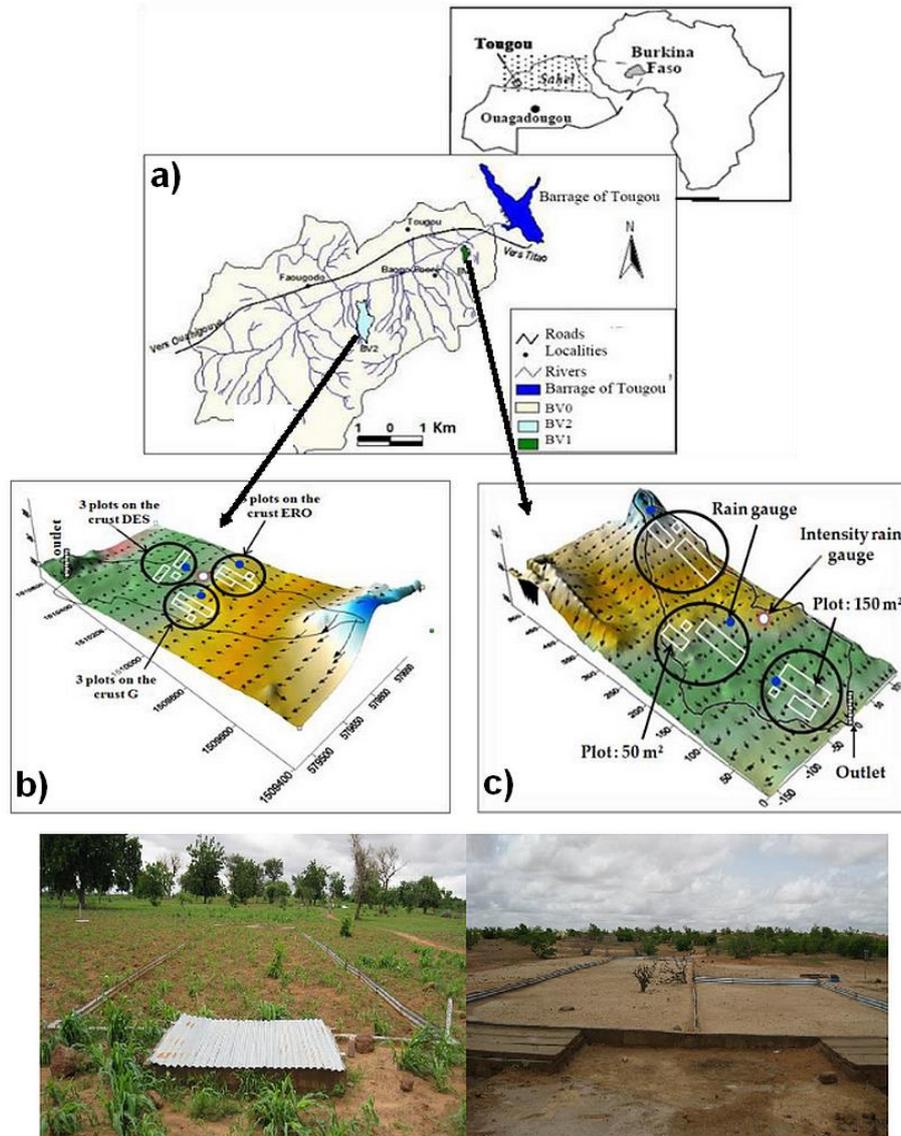


Fig. 1 Location of (a) Touguou and sub-catchments within the watershed, (b) cultivated sub-catchment and its experimental plots, (c) degraded sub-catchment and its experimental plots

Experimental setup and data collection

In this study, changes in hydrologic response and flow transfer through the hydrological network were assessed through the monitoring and analysis of dominant mechanisms observed on homogeneous units at different spatial scales. Sivapalan and Wood (1986) showed that even though runoff is highly correlated with rainfall early in the beginning of a storm, it is the properties of the soil which definitely determines runoff. In this study, runoff on four major soil surface features of the catchment was measured. The term “*soil surface feature*” refers to the soil crusting typology established by Casenave and Valentin (1989) for Sahelian soils. It consists of a system of elementary surfaces, homogeneous at any given time in terms of land cover, soil surface and superficial soil organization, transformed by the wind, rainfall, fauna and human activity. As such, each type of soil surface feature is likely to exhibit a specific behaviour in the partition of rainfall between runoff and infiltration, providing a key to understand and model runoff processes in this context. The experimental setup used in this study is presented in Table 1.

Table 1 Experimental arrangement of the study, description and geometric characteristics of measurement plots

Site name	Unit name	Hydrological unit type	Size	Average slope (%)	Surface feature type	Land use		
Site S ₁	S ₁₋₁	Plot	1 m ² (1x1)	1.60	Cultural (C)	Cultivated soils		
	S ₁₋₅₀	Plot	50 m ² (5x10)	1.80				
	S ₁₋₁₅₀	Plot	150 m ² (6x25)	1.35				
Site S ₂	S ₂₋₁	Plot	1 m ² (1x1)	1.70				
	S ₂₋₅₀	Plot	50 m ² (5x10)	1.40				
	S ₂₋₁₅₀	Plot	150 m ² (6x25)	1.60				
Site S ₃	S ₃₋₁	Plot	1 m ² (1x1)	4.00			Erosion (ERO)	Degraded and uncultivated soils
	S ₃₋₅₀	Plot	50 m ² (5x10)	4.20				
	S ₃₋₁₅₀	Plot	150 m ² (6x25)	2.85				
Site S ₄	S ₄₋₁	Plot	1 m ² (1x1)	0.75				
	S ₄₋₅₀	Plot	50 m ² (5x10)	1.25				
	S ₄₋₁₅₀	Plot	150 m ² (6x25)	0.93				
Site S ₅	S ₅₋₁	Plot	1 m ² (1x1)	0.90	Gravelly (G)	Degraded and uncultivated soils		
	S ₅₋₅₀	Plot	50 m ² (5x10)	0.96				
	S ₅₋₁₅₀	Plot	150 m ² (6x25)	0.80				
Site S ₆	S ₆₋₁	Plot	1 m ² (1x1)	2.30	Dessication (DES)			
	S ₆₋₅₀	Plot	50 m ² (5x10)	2.10				
	S ₆₋₁₅₀	Plot	50 m ² (5x10)	3.55				
	BV ₁	Sub-catchment	6.1 ha	1.91	Cultural (C)	Cultivated soils		
	BV ₂	Sub-catchment	33.8 ha	1.18	ERO, G, DES	Degraded and uncultivated soils		
	BV ₀	Catchment	37 km ²	0.68	C, ERO, G, DES			

Three sites were identified within the cultivated sub-catchment (BV_1). On each site, a block of three plots was established. The hydrodynamic properties of the soil of each site were assumed to be homogeneous as well as cropping practices. Microrelief (defining the slope and soil storage capacity) was considered different from one plot to another. In the degraded sub-catchment (BV_2), the plots were established in blocks of three (3) according to type of soil surface features. Each plot of 1 m² was isolated from the outside run-on by a metal frame fitted with a trap and connected to a buried 200 litres plastic barrel via a PVC pipe. Each plot of 50 and 150 m² was isolated by sheets driven into the ground over at least 10 cm to prevent the resurgence of sub-surface water from outside. Downstream, the plot was equipped with a collection system consisting of two or three concrete tanks. A gauge was installed in each tank to monitor changes in water level and derive volumetric flow rates. The BV_1 and BV_2 sub-catchments and the BV_0 watershed were each equipped with a level meter and water level logger for hydrometric gauging. A network of 10 rain gauges and 5 tipping bucket rain gauges spread throughout the catchment were used to monitor the spatial variability of the rainfall.

Data Analysis

A statistical analysis was conducted in this study on data acquired on plots from 2010 to 2015. The aim was: (i) to assess whether or not the plot location influences the runoff measurements; (ii) to assess the variations in runoff processes at different observation scales. In order to remove the effect of microrelief (explicitly slope), the runoff potential parameter (R_p), given by Eq. 1, was considered. It accounts for the soil type (for plots of the same scale) or the runoff length (for plots on the same site). Runoff potential is defined as the ratio of the runoff coefficient of the plot to the square root of its slope. This expression is a consequence of a physically-based modelling of runoff as defined in Chézy (1775) and Manning (1891) flow equations:

$$R_p = \frac{K_r}{\sqrt{I}} \quad (1)$$

where K_r is the runoff coefficient and I is the slope of the plot. A statistical analysis was carried out to determine, for each soil surface feature, the minimum representative area of runoff production. To that end, the non-parametric Kruskal-Wallis test, at the level of 5% was applied for two cases: (i) Null hypothesis H_0 defined as equality of the ranks of mean runoff potential for the three plots of the same scale; (ii) Null hypothesis H_0 defined as equality of the ranks of mean runoff potential for the three plots of the same site. The Kruskal-Wallis test is a generalization of the Mann-Whitney test, which aims to determine if two samples come from the same population (same statistical distribution). The statistic KW of Kruskal-Wallis test is given by Eq. 2.

$$KW = \frac{12}{N(N+1)} \sum_{j=1}^K \frac{R_j^2}{n_j} - 3(N+1) \quad (2)$$

where K is number of samples, N is the total number of observations = $\sum_{j=1}^K n_j$, R_j is the sum of the ranks in the j -th sample. Similarly, to assess the homogeneity in the variance of samples, the Levene test was applied at the 5% level. Null hypothesis H_0 was defined as equality of variance. The statistic L of Levene test is given by Eq. 3:

$$L = \frac{(N-K) \sum_{j=1}^K n_j (\bar{z}_j - \bar{z})^2}{(K-1) \sum_{j=1}^K \sum_{i=1}^{n_j} (z_{ij} - \bar{z}_j)^2} \quad (3)$$

The power of each test was calculated to allow confidence in the result obtained, especially when the test signals not significant. The power of a test $(1 - \beta)$ is the probability of rejecting the null hypothesis H_0 when it is indeed false (Howell et al. 2008; Bouyer 2009). It is the complement of the Type II error β (not reject the null hypothesis when it is false). The power of the Kruskal-Wallis test is given by Eq. 4:

$$1 - \beta = P(FS(df_1, df_2, \lambda) > qf(1 - \alpha, df_1, df_2)) \quad (4)$$

The statistic FS of quantile qf follows a Fisher-Snedecor law at $df_1 = K - 1$ and $df_2 = N - K$ (where df relates to the degrees of freedom). Its non-centrality parameter is illustrated by Eq. 5 where f is the effect size (Cohen 2013):

$$\lambda = N f^2 \quad f = \sqrt{\frac{\eta^2}{1 - \eta^2}} \quad (5)$$

where η^2 is the proportion of the total variance explained by the treatments. In this study, the power of a test was considered to be satisfactory for $(1 - \beta)$ is $\geq 95\%$ when the null hypothesis H_0 was accepted, and $(1 - \beta) \geq 80\%$ in the case where it was rejected, as suggested by Cohen (2013).

The runoff potential parameter helped in assessing whether the behaviour of the processes at various levels obey the same dimensionless relations. To measure the scale effect of the plot, the ratio (l/s) was introduced, where l stands for the runoff potential for a larger scale and s for the runoff potential at a smaller scale. When the ratio equals 1, the similar runoff generating processes occur at both scales. If the ratio is less than 1, there is an emergence of new processes at a higher scale. These new processes reduce runoff potential at the larger scale, are dominant and masked by the manifestation of the processes observed at a smaller scale. If the ratio is higher than 1, there is an increased runoff potential at larger scale and thus, an increase at the higher scale of the manifestation of the same processes observed at the smaller scale. A similar ratio have been used in previous research by directly using the runoff coefficient, allowing to overcome the effect of the slope on runoff production (van De Giesen et al. 2000).

Results

In this section, rainfall characteristics as well as key hydrodynamical properties of the soil in the study site are presented. Further, the results of measurements carried out on cultivated areas for a series of rainfall events which resulted in runoff at all scales of observation are presented. These results illustrate seasonal dynamics and effect of vegetation cover, microrelief and tillage on runoff. Also, runoff measurements on degraded and uncultivated

environments are presented, which highlight the influence of soil surface feature type and rainfall intensity on runoff production at various scales of observation. The results of statistical analysis are presented, allowing an analysis of differences in runoff potential across scales, before addressing the issue of scale effect on runoff.

Rainfall characteristics

Rainfall events observed from 2010 to 2015 are presented on Fig. 2. Table 2 presents the mean values of rainfall key parameters in the catchment during the period 2010-2015. Cumulative annual rainfall varies between 460 mm and 730 mm. Events duration varies from 12 to 245 minutes, but without any significant correlation to the amount of rainfall. Nearly 35% of event rainfall amount is between 10 and 20 mm; 7.5% are greater than 40 mm and represent on average 27% of cumulative annual rainfall. The rainfall in months of August and September represents about 54% of the annual rainfall. On average, there was respectively 11 and 8 effective rainfall events (greater than 1 mm) during these two months. Rainfall intensities of 120 mm/h at 5 minutes and 70 mm/h at 30 minutes are often exceeded. On the course of six years, there were nine daily rainfall events exceeding a threshold of 50 mm, the most important one being the extreme event which occurred on 05/08/2015 (114 mm).

Table 2 Characteristics of rainfall in Tougou catchment from 2010 to 2015

Month	Rainfall				% Monthly	Intensity				Frequency
	Maximum Pj (mm)		Monthly rainfall (mm)			I _{max-5mn} (mm/h)		I _{max-30mn} (mm/h)		Average number of events
	Avg	σ	Avg	σ		Avg	σ	Avg	σ	
June	41.6	10.8	101.8	35.2	16%	81.6	7.5	42.2	6.2	5
July	43.3	12.1	146.5	42.7	23%	82.5	10.9	42.8	8.5	8
August	57.8	32.8	218.0	43.0	35%	95.9	16.7	58.8	9.4	11
September	35.9	16.6	119.6	41.8	19%	78.5	29.0	42.7	12.5	8
October	21.6	9.6	41.5	26.3	7%	37.6	14.9	26.7	11.5	3

Pj = daily rainfall; Iavg and Imax = average and maximum intensity; Avg = average; σ = standard deviation

The observation period is characterized by a strong occurrence of intense rainfall events of 40 mm, which accounted for nearly 27% of annual rainfall. In comparison to the statistical analysis carried out on the maximum daily rainfall during the 1970-2012 period at Ouahigouya station, 25 km away from Tougou watershed (Mounirou 2012), the years 2010, 2012, 2014 and 2015 were found to be “wet years” while the years 2011 and 2013 were qualified as “dry years”. The total rainfall in August and September, which represents the middle and the end of the rainy season, averages at 385 mm for a wet year whereas it is close to 290 mm for a dry year, hence a relative difference of nearly 24%.

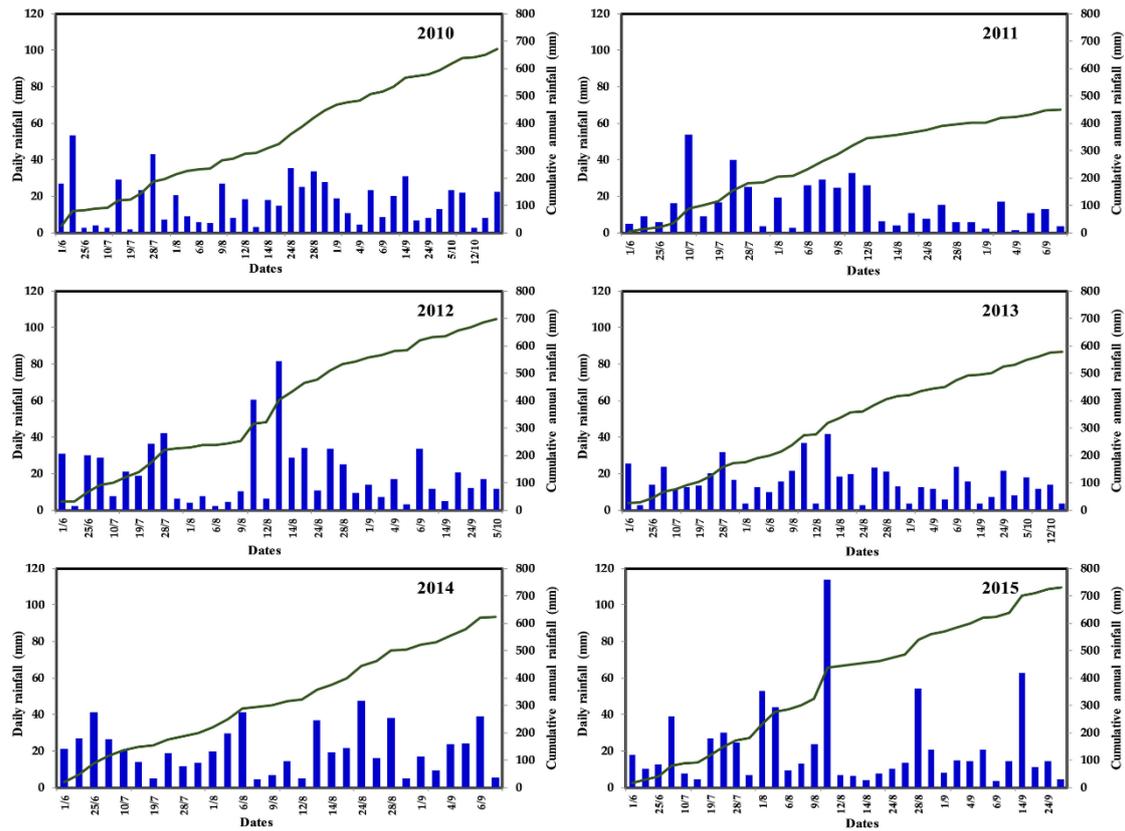


Fig. 2 Rainfall events observed in Tougou watershed from 2010 to 2015

Saturated hydraulic conductivity and bulk density at the local scale

The saturated hydraulic conductivity and bulk density of the main surface features in the watershed were measured in 2005, 2007, 2010 and 2012 and presented in Table 3. The results obtained are compared with the results of Casenave and Valentin (1992) on similar types of soil surface features in the Sahel and were found to be consistent. These results highlight the heterogeneity of the hydrodynamic properties of soils from one site to another, especially in cultivated soils. However, within the same site, there is a smoothing of this heterogeneity because of the lower amplitude of variation of each parameter. Hydrodynamic properties of the soils on each site were therefore assumed to be homogeneous and cultural practices almost identical. Measurements of bulk density at the first 15 cm of the topsoil on each plot revealed that the soil is significantly more compact in bare and degraded area than in cultivated area.

Table 3 Soil type, and soil physical properties of the 6 sites on the Tougou watershed

Site	Soil type	Ksat (mm/h)	Ksat (Casenave and Valentin 1989)	Bulk Density Da (g/cm ³)	Porosity (%)	Manning roughness (n)
Site S ₁	Loam	21 – 25		1.40 – 1.46	45 – 47	0.050
Site S ₂	Sandy	27 – 33	15 - 35	1.36 – 1.44	46 – 49	0.060
Site S ₃	Sandy gravelly	16 – 19		1.46 – 1.48	44 – 45	0.065
Site S ₄	dry clay	2 – 2.5	2 – 4	1.58 – 1.61	39 – 40	0.015
Site S ₅	Gravelly	3 – 3.5	3 – 5	1.88 – 1.94	27 – 29	0.020
Site S ₆	Sand	12 – 15	10 – 20	1.66 – 1.70	36 – 37	0.025

Number of infiltration tests by site: 12 - Number of porosity tests by site: 9

Spatial variability of the runoff

1 Fig. 3 shows the mean values of runoff coefficients for the main soil surface features in the watershed at various
2 scales from 2010 to 2015. Comparison of results shows that the runoff is significantly higher on bare and degraded
3 soils. In the cultivated area, the average value of runoff coefficient at each scale of observation varies from one
4 site to another. This variation in runoff for different plots at the same scale of observation is explained by the
5 differences in soil behaviour and associated farming practices. Lower runoff is produced when a rainfall event
6 occur after a dry spell or after tillage management operation on the plots. Tillage generally decreases the soil bulk
7 density, increases porosity and significant changes in the grain size distribution. In turn, it causes an increase in
8 soil surface storage (decrease in connectivity rate of furrows) and an increase in seepage potential of the soil
9 (Allmaras et al. 1966; Ahuja et al. 1998; Xu and Mermoud 2001). On the other hand, higher runoff takes place at
10 a time when the soil is already wet and in the case of exceptional rainfall events. Under these conditions the value
11 of the runoff coefficient might reach up to 60% at on the plots of 50 and 150 m².
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15 On cultivated soils, runoff usually begins after a cumulative rainfall amount of 14 mm if the soil is dry. This
16 threshold is reduced to 8.5 mm of cumulative rainfall when the soil becomes moist, crusted, or compact (Mounirou
17 2012). These thresholds depend partly on the rainfall pattern (intensity and rainfall volume fell after the topsoil
18 saturation) and especially on the condition of the topsoil surface (saturation deficit of the first centimetres of soil,
19 cracks and holes dug by earthworms, slaking crusts forming at the surface, litters, stones and residual clods).
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22 On degraded and uncultivated soils, runoff varies according to the nature of the crust. It is higher on erosion and
23 gravelly crusts and lower on desiccation crusts. Lower runoff values are generally caused by small amounts of
24 rainfall. On the other hand, higher runoff is observed during high-intensity rainfall events even if the cumulative
25 amount of rainfall is low. The maximum value of the runoff coefficient observed was 95% on erosion crusts
26 (ERO), 96% on gravelly crusts (G) and 56% on desiccation crusts (DES). These values on the plots of 50 m² were
27 observed for a rainfall event of 28 mm with a maximum intensity of 114 mm/h at 5 minutes (on 28/08/2010) and
28 a rainfall event of 99 mm with a maximum intensity of 90 mm/h at 5 minutes (on 03/08/2012). On bare and
29 degraded soil, the rainfall intensity is a more important factor than the amount of runoff volume. As such, for the
30 same soil surface feature, the values of the imbibition rainfall depend more on the intensity of the event than on
31 the moisture conditions. The minimum values of imbibition rainfall were found to be 4 mm for erosion and
32 gravelly crusts and 7 mm for desiccation crusts on plots 50 m² and 150 m² (Mounirou 2012).
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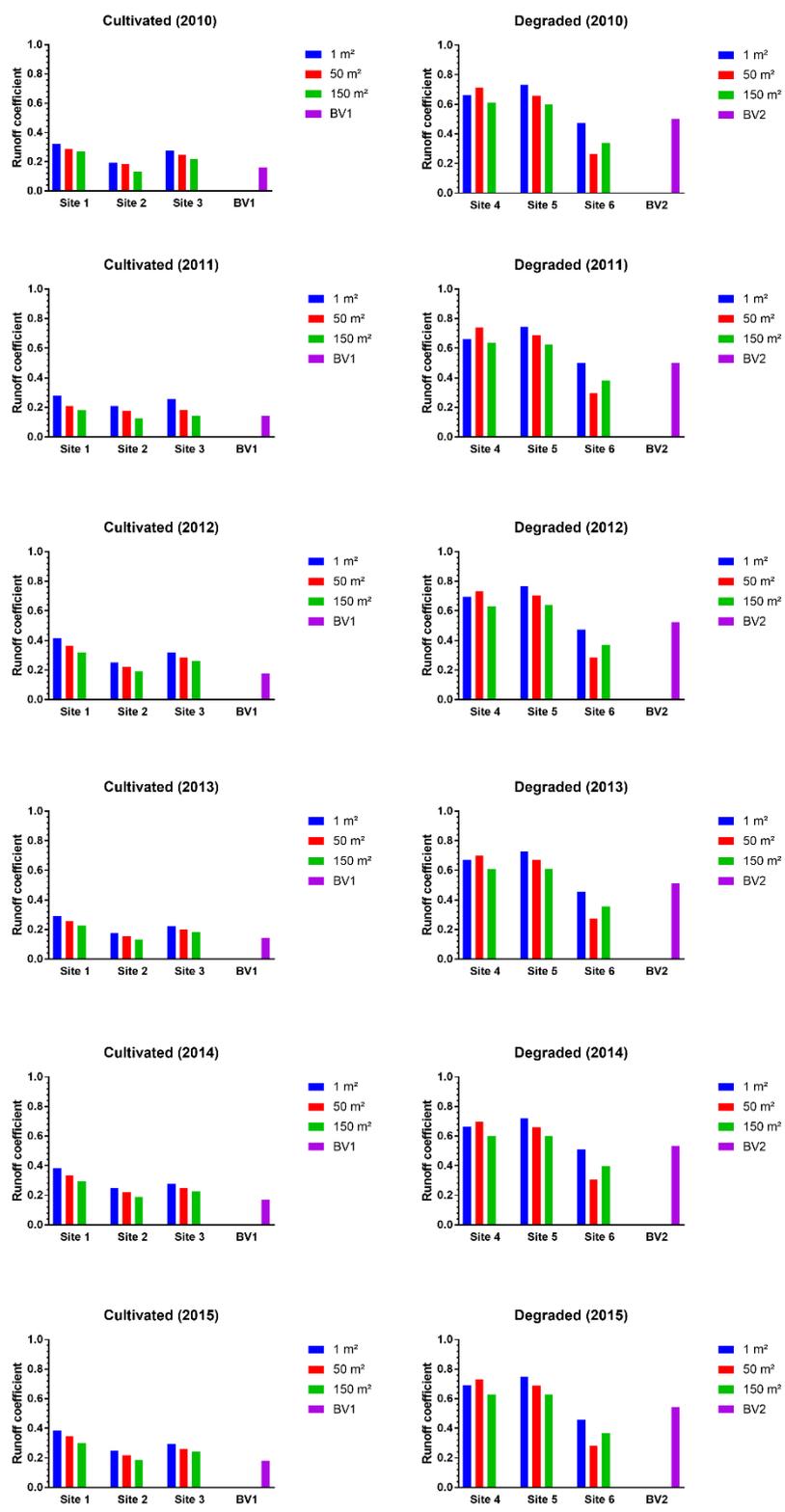


Fig. 3 Runoff coefficient at different scales of observations from 2010 to 2015

Fig. 4 illustrates the determination process of the imbibition rainfall amount (Plr) and the maximum rainfall intensity (Ilr) triggering runoff, below which runoff was never observed. With the exception of site 2, the value of the rainfall intensity threshold Ilr is higher than the corresponding saturated hydraulic conductivity. This result

confirms that in the Sahelian context, runoff is generally caused by the overflow of the infiltration capacity, namely, the hortonian process (Descroix et al. 2009; Chen et al. 2016).

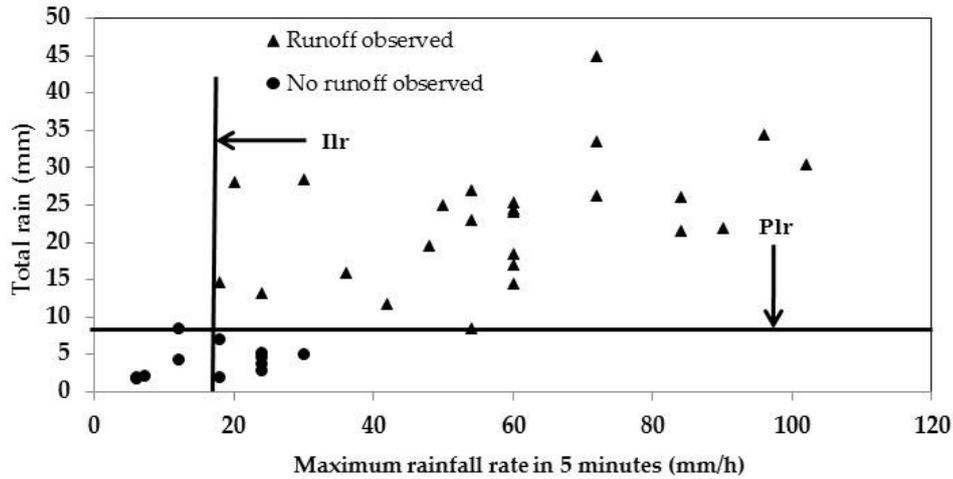


Fig. 4 Example of determination of the rain (*Plr*) and threshold intensity (*Iir*) of runoff on the plot $S_{1-150\text{ m}^2}$ for the year 2010

Statistical analysis of the runoff at various spatial scales

Table 4 shows the results of statistical tests runs applied of runoff data series at the same observation scale on cultivated soils. There were 133 observations in each series. According to the Kruskal-Wallis test (at the 5% level), the null hypothesis H_0 (equality of the ranks of mean runoff potential for the three plots of the same scale) was rejected (p -value $> 5\%$) at the three scales of observation that are 1 m^2 , 50 m^2 and 150 m^2 . Similarly, according to Levene's test, the heterogeneity between the variances was found to be significant at 5%-level (p -value $< 5\%$). For each test, the risk of rejecting the null hypothesis H_0 when it is true was found to be less than 0.01% (p -value < 0.0001). The power of each test is deemed to be acceptable at the critical threshold value of 80%, appropriate for a first type risk (Cohen 2013). The Mann-Whitney U-test application, at 5% level shows that at the same observation scale, the runoff potential is significantly different for the three sites. Although sites S_1 , S_2 and S_3 are installed on cultivated soils, at the same observation scale, the runoff potential significantly differs from one site to another. This suggests that the location of the plot influences the results because of the spatial variability of hydrodynamic properties of the soils.

Table 4 Results of statistical analysis of the land use type on runoff for similar observation scales

Test name		Kruskal-Wallis			Mann-Whitney			
		Results			Hypothesis H_0	Decision	p - value	Power of the test
Scale	Type of plot	Hypothesis H_0	p - value	Power of the test				
1 m ²	S _{1-1m²}	Rej	< 0.01 %	96%	$\mu(S_{1-1m^2}) = \mu(S_{2-1m^2})$	Rej	< 0.01 %	95%
	S _{2-1m²}				$\mu(S_{1-1m^2}) = \mu(S_{3-1m^2})$	Rej	0.0038	89%
	S _{3-1m²}				$\mu(S_{2-1m^2}) = \mu(S_{3-1m^2})$	Rej	0.0034	81%
50 m ²	S _{1-50m²}	Rej	< 0.01 %	96%	$\mu(S_{1-50m^2}) = \mu(S_{2-50m^2})$	Rej	< 0.01 %	95%
	S _{2-50m²}				$\mu(S_{1-50m^2}) = \mu(S_{3-50m^2})$	Rej	0.0079	86%
	S _{3-50m²}				$\mu(S_{2-50m^2}) = \mu(S_{3-50m^2})$	Rej	0.0077	77%
150 m ²	S _{1-150m²}	Rej	< 0.01 %	96%	$\mu(S_{1-150m^2}) = \mu(S_{2-150m^2})$	Rej	< 0.01 %	95%
	S _{2-150m²}				$\mu(S_{1-150m^2}) = \mu(S_{3-150m^2})$	Rej	0.0153	79%
	S _{3-150m²}				$\mu(S_{2-150m^2}) = \mu(S_{3-150m^2})$	Rej	< 0.01 %	93%

H_0 = equality of the ranks of mean runoff potential - Rej = Rejected

For each site, hydrodynamic properties were assumed to be constant, with only the microrelief differing from one plot to another. Analysis on the runoff potential (and not on the runoff coefficient) was useful in removing the effect of the slope inclination on runoff. The results of this statistical analysis are presented in Table 5.

Table 5 Results of statistical analysis of the plot size effect on runoff for different land use types

Tests name		Kruskal-Wallis			Mann-Whitney			
		Results			Hypothesis H_0	Decision	p - value	Power of the test
Site name	Type of plot	Hypothesis H_0	p - value	Power of the test				
Site S ₁ : cultivated	1 m ²	Rej	0.71%	80%	$\mu(1m^2) = \mu(50m^2)$	Rej	0.44%	81%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	1.02%	73%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	72.19%	< 10%
Site S ₂ : cultivated	1 m ²	Rej	0.15%	90%	$\mu(1m^2) = \mu(50m^2)$	Acc	88.54%	< 10%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	0.25%	89%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Rej	0.20%	86%
Site S ₃ : cultivated	1 m ²	Acc	10.71%	34%	$\mu(1m^2) = \mu(50m^2)$	Acc	6.65%	23%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Acc	29.04%	< 10%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	20.22%	21%
Site S ₄ : Erosion	1 m ²	Rej	< 0.01%	96%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	< 0.01%	95%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	81.25%	82%
Site S ₅ : Gravelly	1 m ²	Rej	< 0.01%	95%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	94%
	50 m ²				$\mu(1m^2) = \mu(150m^2)$	Rej	< 0.01%	94%
	150 m ²				$\mu(50m^2) = \mu(150m^2)$	Acc	95.78%	85%
Site S ₆ : Desiccation	1 m ²	Rej	< 0.01%	96%	$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(1m^2) = \mu(50m^2)$	Rej	< 0.01%	95%
	50 m ²				$\mu(50m^2) = \mu(50m^2)$	Acc	75.55%	76%

H_0 = equality of the ranks of mean runoff potential - Rej = Rejected - Acc = Accepted. Values in bold refers to tests runs where null hypothesis (H_0) were rejected, with a satisfactory power

1 On cultivated soils, the null hypothesis H_0 of the Kruskal-Wallis test (equality of the ranks of mean runoff potential
2 for the three plots of the same site) was rejected for S_1 and S_2 with a power test greater than 80%. It was accepted
3 on the site S_3 with a power of 44%. In other words, there is 66% chance to wrongly accept the null hypothesis H_0
4 when it is false (Champely 2006). The Mann-Whitney U-test confirmed this result (at the 5% level) with a p-value
5 of 23%. The power of the test is less than 23% in the case of acceptance of the null hypothesis H_0 . It can therefore
6 be concluded that there is a difference in runoff potential between the three plots of each site in the cultivated
7 area, which is probably due to the breakdown of hydrologic connectivity induced by tillage. Tillage increases the
8 porosity of the soil and leads to an increase in soil surface storage. The overall infiltration on the plot is therefore
9 statistically greater for a longer plot. In the same way, tillage disrupts the microtopography of the plot with a
10 consequent reduction of runoff at the outlet.
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12 On degraded sites, the number of observations in each series was 176. According to the Kruskal-Wallis test, the
13 null hypothesis H_0 (equality of runoff potential of the three plots at the same site) was rejected at 5% level for the
14 three site that are S_4 , S_5 and S_6 (p-value < 0.0001). Similarly, the heterogeneity between the variances was found
15 to be significant at 5% level (p-value = 0.0245). For each test, the risk of rejecting the null hypothesis H_0 when it
16 is true is less than 0.01% (p-value < 0.0001). Higher values of the power test confirm the alternative hypothesis:
17 the runoff potential is significantly different for the three plots. According to the Mann-Whitney U-test, the runoff
18 potential of the plots of 50 and 150 m² are equal but significantly different from the 1 m² plot at the level of 5%.
19 It can therefore be concluded that the same dominant processes are manifested at both scales. This also means that
20 beyond a 10 m long runway representing the length of the 50 m² plot, sufficient runoff energy is formed so that
21 the entire stream coming from upstream reaches the downstream of the plot. From these results, it can be inferred
22 that on degraded sites, a plot of 50 m² is optimal to study the elementary processes of runoff generation.
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26 **Scale effect**

27 As a measurement of the scale effect, the ratio l/s was introduced, defined as the runoff potential at a larger scale
28 ($Rp-l$) divided by the runoff potential at a smaller scale ($Rp-s$). At each site, during the six years of measurement,
29 the runoff potential was calculated for each plot to assess the scale effect. The results obtained are shown in Table
30 6. A trend is observed on degraded uncultivated soils over the six years of measurements. At each scale, the runoff
31 potential of the erosion crust is lesser than that of the gravel crust, but remains above the runoff potential from the
32 desiccation crust. The average ratio of runoff potential between plots of 50 m² and 1 m² is 0.83, 0.89 and 0.62 for
33 erosion, gravel and desiccation crusts respectively. It means that for a slope length ratio equal to 1/10th, an isolated
34 plot of 1 m² generates respectively 1.21, 1.13 and 1.60 times more runoff than an area of 50 m² installed on erosion,
35 gravel and desiccation crusts respectively. Moreover, the ratio of runoff potential between the plots of 150 and 50 m² is equal
36 to 1 for the three crusts types. This also confirms the results of the statistical analysis of the functioning of the
37 plots in degraded areas. It can be concluded that similar dominant processes occur at both scales and that beyond
38 a length of 10 m (which equals the length of the plot of 50 m²), a sufficient runoff energy for the entire flow from
39 upstream to reach the downstream of the plot.
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Table 6 Runoff potential at different scales and measures of scale effect

Plot name	2010		2011		2012		2013		2014		2015	
	Rp	l/s										
S ₁₋₁	2.53		2.33		3.27		2.33		3.03		3.04	8.5
S ₁₋₅₀	2.13	0.84	1.68	0.72	2.7	0.83	1.92	0.82	2.48	0.82	2.58	0.85
S ₁₋₁₅₀	2.34	1.10	1.68	1.00	2.74	1.01	1.95	1.02	2.54	1.02	2.57	1.00
S ₂₋₁	1.49		1.59		1.94		1.34		1.93		1.89	
S ₂₋₅₀	1.57	1.05	1.5	0.94	1.89	0.97	1.3	0.97	1.87	0.97	1.84	0.97
S ₂₋₁₅₀	1.06	0.68	1.19	0.79	1.53	0.81	1.05	0.81	1.52	0.81	1.5	0.82
S ₃₋₁	1.38		1.28		1.59		1.12		1.39		1.47	
S ₃₋₅₀	1.20	0.87	0.97	0.76	1.39	0.87	0.98	0.88	1.21	0.87	1.28	0.87
S ₃₋₁₅₀	1.29	1.08	1.05	1.08	1.55	1.12	1.09	1.11	1.35	1.12	1.43	1.12
S ₄₋₁	7.67		7.64		8.03		7.72		7.65		7.97	
S ₄₋₅₀	6.36	0.83	6.63	0.87	6.55	0.82	6.27	0.81	6.23	0.81	6.52	0.82
S ₄₋₁₅₀	6.35	1.00	6.61	1.00	6.56	1.00	6.31	1.01	6.25	1.00	6.51	1.00
S ₅₋₁	7.73		7.84		8.07		7.67		7.58		7.9	
S ₅₋₅₀	6.72	0.87	7.00	0.89	7.16	0.89	6.84	0.89	6.74	0.89	7.02	0.89
S ₅₋₁₅₀	6.70	1.00	7.00	1.00	7.14	1.00	6.82	1.00	6.72	1.00	7.02	1.00
S ₆₋₁	3.11		3.29		3.13		3.01		3.37		3.04	
S ₆₋₅₀	1.82	0.59	2.04	0.62	1.97	0.63	1.9	0.63	2.12	0.63	1.96	0.64
S ₆₋₁₅₀	1.81	0.99	2.03	1.00	1.96	0.99	1.89	0.99	2.11	1.00	1.95	0.99

Rp = Runoff potential - l/s = larger / smaller. Values in bold refer to similar runoff potential values at different observation scales.

On cultivated soils, surface roughness varies rapidly due to tillage management operation (seedling, weeding, ploughing). As such, the value of the runoff potential is a function of the cumulative annual rainfall but also its distribution as well as the soil permeability. At the same scale of observation, the runoff potential varies from one site to another. Hence, the scale factor between plots of 50 and 1 m² varies between 0.81 and 0.95 according to the soil type. Similarly, the scale factor between plots of 150 and 50 m² is between 0.79 and 1.10. The scale factor is higher on 150/50 m² than that of 50/1m² plots ratio. This suggests that the contributing zones on the plots of 50 m² are fragmented whereas they are connected on the plots of 150 m². The parameter that can explain these results is the spatial variation of the storage in the depressions caused by the tillage. The tillage creates a discontinuity between the smaller unit areas producing runoff. The connectivity of surface microtopography plays therefore an important role in the transfer of runoff. It can then be inferred that the plot of 50 m² (10 m of length) is not large enough to study the runoff processes on cultivated soils because of the shorter runoff length.

Discussion

In this study, runoff was analysed at several spatial scales and under various surface features in order to understand the change in the hydrological response as we move from unit to the watershed scale. Results obtained show that, both in cultivated soil and in bare soils, the runoff decrease with an increasing area. This decrease in runoff per unit area can be attributed to the non-linearity of processes, the spatial variability of the infiltration capacity of the soil and the rainfall pattern (Van de Giesen et al. 2005; Reaney et al. 2007; Gomi et al. 2008; Ribolzi et al. 2011; Van de Giesen et al. 2011; Langhans et al. 2019). When studying the generation process of runoff at different spatial scales on the Sahelian catchment of Banizoumbou (Niger), Esteves and Lapetite (2003) showed that the runoff coefficient is significantly irregular in space, due to the high spatial variability of infiltration and storage capacity of the soil and over time and the development of vegetation during the rainy season. They showed that at the local scale, infiltration and runoff are determined by the hydraulic properties of the topsoil crusts. However, at the scale of the field (100 m²), the microrelief and heterogeneity of the soil surface reduce the amount of runoff

1 water volumes. Likewise, Moreno et al. (2010) have studied the scale effect in relation with runoff and erosion
2 under the dry Mediterranean climate. In this study, runoff and sediment yield were monitored over a hydrological
3 year in 20 plots of various lengths (1-15m) in five sites of various slopes and exposed to varying levels of
4 vegetation cover. The results shown an overall decrease of runoff per unit area across all sites as the area of the
5 plot increases. They showed that at equal length, runoff is lower on the least degraded site. Van de Giesen et al.
6 (2011) evaluated the effect of scale on hortonian runoff on agricultural plots of various lengths in three countries
7 of West Africa (Burkina Faso, Côte d'Ivoire and Ghana). They observed that the longer plots generated lower
8 runoff coefficients than the shorter ones. Also, a greater variation in runoff coefficient was reported, but there was
9 an excellent correlation between the plots of equal length for each rainfall event. They concluded that the temporal
10 dynamics of rainfall is the primary cause of the scale effect observed on the plots. Asadzadeh et al. (2012)
11 evaluated the effect of plot size on runoff from seven plot sizes with varying lengths (2, 5, 10, 15, 22.1, 25 and 30
12 m) in northwestern Iran. Statistical analysis of runoff produced on each unit area showed that there were no
13 significant differences among the measurements at 15m and longer plots but in plots with 10m or lower, the results
14 were significantly different. They concluded that the 15m is the minimum optimal length for accurate estimation
15 of runoff at the plot scale.
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18 Our results confirm the decreasing trend in the average runoff coefficient as the size of the plot increases. In order
19 to understand the causes of this scale effect, average runoff coefficients for each plot of the same size were
20 compared in this study and then the runoff potential of three plots set up on each of the surface features. The
21 comparison of plots of the same size showed that the average value of the runoff coefficient varies significantly
22 from one site to another. These findings are consistent with those of Cammeraat (2004), Mathys et al. (2005), that
23 is the location (place) of measurements strongly influences the observations and are to be related to the spatial
24 variation in infiltration capacity (texture, structural stability) of the soil, microrelief and tillage management
25 operation in cultivated areas. Among all the aforementioned factors, spatial variability of soil hydraulic properties
26 seems to be one of the determinants of runoff in this area. As such, this parameter has been studied extensively
27 due to its crucial role in shaping the hydrologic responses of catchments (Assouline and Mualem 2002; Séguis et
28 al. 2002; Assouline and Mualem 2006). Field measurements showed large variability in the soil saturated
29 hydraulic conductivity, which often exhibits a log-normal distribution (Loague 1990; Corradini et al. 1998;
30 Morbidelli et al. 2006). Heterogeneity in soil hydraulic properties leads to spatial variability in infiltration rates.
31 As a result, the infiltration-runoff relationship becomes scale dependent.
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35 The results of the comparison for the runoff potential of the three plots within the same site are somewhat mixed
36 in cultivated soil due to the edaphic soil conditions of the plots (tilled or not) which are often not the same before
37 each rainfall event. Regardless, it has been noted in most cases and especially in degraded environment, the scale
38 effect is amplified in the case of low rainfall or average rainfall of low intensity. To conclude, our results show
39 that the scale effect observed in the runoff is mainly due to the spatial heterogeneity of the soil hydrodynamic
40 properties, furthermore amplified by the rainfall intensity.
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43 From the local plot to the watershed, the heterogeneity and variability of conditional key parameters of the runoff
44 increases with the area. Hence, additional processes emerge at higher scales such as water storage in depressions
45 or infiltration in more permeable areas. These permeable areas help absorb the flow of water, with particular
46 effects, when located downstream of a zone with high runoff potential. Wood et al. (1988) noticed that runoff
47 production changes with spatial scale while the variance of runoff reduces as the scale increases. They proposed
48 the concept of *Representative Elementary Area* (REA) for catchment hydrology to explore if scale-independent
49 hydrological responses exist at large scales beyond some characteristic REA. The concept of REA has been
50 applied to investigate scale effects on hydrologic processes. Wood (1998) found the characteristic length
51 relationship to the REA to be on the order of magnitude of $10^2 - 10^3$ m, while other studies reported that the size
52 of the REA might be event-dependent and controlled by initial conditions and rainfall intensity (Blöschl et al.
53 1995).
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Conclusions

Results presented in this paper illustrate the complexity of hydrological processes and the number of parameters involved in the runoff production. This study identified and analysed the most significant explanatory parameters of runoff in both cultivated and bare/degraded areas and showed that the scale effects are not the same depending on the types of surface features. The effectiveness of tillage on soil infiltration at reducing the rate of connectivity of runoff areas at plot scale has been observed. At the plot scale, soil surface roughness and bulk density were found to be the two key factors that determine the increase in connectivity of flow. Similarly, this research has shown that the location of plots on the slope influences the observed runoff quantity in the Sahel region. In addition, statistical analysis of the differences in functioning at various spatial scales of the landscape of Tougou watershed was carried out. The results obtained showed that that in a degraded environment, the runoff generation processes on plots of 150 and 50 m² are identical and significantly different from the unit scale. On cultivated soils, a plot of 50 m² or 150 m² is not sufficient to apprehend the main processes of runoff generation. At the plot level, hydrological processes are almost completely dependent on the hydrodynamic properties of the soil. The scale effect is mainly caused by run-on, which increases infiltration with spatial heterogeneity in soil properties and runoff travel distance. The issue of scale effect is critical when attempting to transpose the understanding of the processes discovered at the scale of a plot to larger spatial scales. Our results indicate the existence of important scale effect between the plot and the watershed. At the watershed scale, the spatial variability of the soil, the rainfall pattern, the topography, the relative position of runoff-producing areas are all factors which affect runoff.

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