NUMERICAL ANALYSIS OF THE IMPACT OF CHARCOAL PRODUCTION ON SOIL HYDROLOGICAL BEHAVIOR, RUNOFF RESPONSE AND EROSION SUSCEPTIBILITY[1]

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ABSTRACT

The impact of charcoal production on soil hydraulic properties, runoff response and erosion susceptibility were studied in both field and simulation experiments. Core and composite samples, from 12 randomly selected sites within the catchment of *Kotokosu* were taken from the 0–10 cm layer of a charcoal site soil (CSS) and adjacent field soils (AFS). These samples were used to determine saturated hydraulic conductivity (Ksat), bulk density, total porosity, soil texture and color. Infiltration, surface albedo and soil surface temperature were also measured in both CSS and AFS. Measured properties were used as entries in a rainfall runoff simulation experiment on a smooth (5 % slope) plot of 25 x 25 m grids with 10 cm resolutions. Typical rainfall intensities of the study watershed (high, moderate and low) were applied to five different combinations of *Ks* distributions that could be expected in this landscape. The results showed significantly ($p < 0.01$) higher flow characteristics of the soil under charcoal kilns (increase of 88 %). Infiltration was enhanced and runoff volume reduced significantly. The results showed runoff reduction of about 37 and 18 %, and runoff coefficient ranging from 0.47–0.75 and 0.04–0.39 or simulation based on high (200 mm h^{-1}) and moderate (100 mm h^{-1}) rainfall events over the CSS and AFS areas, respectively. Other potential impacts of charcoal production on watershed hydrology were described. The results presented, together with watershed measurements, when available, are expected to enhance understanding of the hydrological responses of ecosystems to indiscriminate charcoal production and related activities in this region.

Index terms: hydro-physical properties, infiltration, simulated runoff, watershed hydrology.

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(1) Recebido para publicação em junho de 2007 e aprovado em novembro de 2008.

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RESUMO: *INVESTIGAÇÃO NUMÉRICA/QUANTITATIVA SOBRE O IMPACTO DO PROCESSO DE PRODUÇÃO DE CARVÃO NAS PROPRIEDADES HIDRÁULICAS, RESPOSTA AO DEFLÚVIO E SUSCETIBILIDADE DO SOLO À EROSÃO*

O impacto do processo de produção de carvão nas propriedades hidráulicas, a resposta ao deflúvio e a suscetibilidade do solo à erosão foram estudados em experimentos de campo e de simulação. Amostras indeformadas e compostas de 12 locais aleatoriamente selecionados dentro do reservatório de Kotokosu foram coletadas na camada de 0–10 cm no solo sob carvão (CSS) e no solo adjacente (AFS). Essas amostras foram usadas para determinar a condutividade hidráuli7ca saturada (Ksat), densidade do solo, porosidade total, textura e cor do solo. A infiltração, o albedo de superfície e a temperatura de superfície do solo também foram medidos no CSS e AFS. Os parâmetros medidos foram usados como entrada nos experimentos de simulação de deflúvio em uma parcela uniforme (5 % de declividade) de 25 x 25 m, com grides de 10 cm de resolução. Altas, moderadas e baixas intensidades de chuva, típicas da bacia em estudo, foram aplicadas em cinco diferentes combinações de Ksat, que poderiam ser esperadas nessa paisagem. Os resultados mostraram que as características do fluxo do solo sob carvão aumentaram significativamente ($p < 0,01$) em 88 %. A infiltração foi aumentada e o volume de deflúvio reduzido significativamente. Houve redução no deflúvio em torno de 37 e 18 %, e o coeficiente de deflúvio variou de 0,47–0,75 e 0,04 a 0,39 para a simulação de chuvas de alta (200 mm h^{-1}) e moderada (100 mm h^{-1}) intensidades nas condições CSS e AFS, respectivamente. Outros impactos em potencial da produção de carvão na bacia hidrológica foram observados. Espera-se que, com os resultados aqui apresentados, além dos determinados na bacia, quando disponíveis, haja uma compreensão melhor das respostas hidrológicas do ecossistema de fabricação indiscriminada de carvão e de outras atividades relacionadas nessa região.

Termos de indexação: propriedades hidrofísicas, infiltração, deflúvio simulado, bacia hidrológica.

INTRODUCTION

Charcoal production by pyrolysis procedures, bushfires (land clearing fire) and forest fires are expanding in scope and magnitude in many tropical catchments, especially in sub Saharan African countries. This is attributed to a sharp population increase which results in a higher demand for food, fiber and energy, along with the low level of agricultural mechanization, instability of power supply and unstable rainfall patterns, culminating in drought, among other factors (Ajayi, 2004). It is documented that the magnitude of heat released during these soil heating processes are similar depending on the period or wood load in the piles, and could influence soil properties (Oguntunde et al., 2004; Glaser et al., 2002; Mataix-Solera et al., 2002). In the study of a tropical watershed in Indonesia, Ketterings et al. (2000, 2002) reported that severe burning associated with these processes have a drastic effect on soil texture, color, mineralogy and other soil properties. Oguntunde et al. (2004) observed a significant decrease in clay fraction and corresponding increase in sand content in severely burnt soils, which could result in poor water holding capacity (Ulery & Graham, 1993).

The effects of the heating processes on soil are a result of the burning severity, which is determined by the peak temperatures and duration of a fire (Certini, 2005). Low to medium fire severity resulted in darkening of the topsoil while high-severity fires (> 600 °C) cause pronounced reddening of the topsoil, accompanied by an increase in both Munsell value and chroma (Ulery & Graham, 1993; Ketterings & Bigham, 2000). In a review on the effects of fire on forest soil properties, Certini (2005) concluded that low to moderate-severity fires result in a renovation of the dominant vegetation by the elimination of undesired species and a transient increase in pH and available nutrients in the forests, while severe fires (such as wildfires) generally lead to a significant loss of organic matter, deterioration of both structure and porosity, leaching and erosion, among other drawbacks.

Bushfires have been reported to cause increased runoff and erosion losses due to vegetation removal, enhancement of hydrophobicity (water repellency) resulting in reduced infiltration and greater sediment load in rivers (Certini, 2005; Inbar et al., 1998). Scott & van Wyk (1990) reported a 200 % increase in annual runoff and about 300 % in the peak discharges during the year after a forest fire in South Africa. However, Ueckert et al. (1978) found that soil bulk density, porosity and, consequently, rainfall infiltration, was not significantly affected by fire in a tobosagrass community.

A significant impact of bushfires on soil surface albedo and temperatures has also been reported. Compared with pre-fire sites, Scholes & Walker (1993) and Beringer et al. (2003) observed an albedo reduction of about 50 % in post-fire areas. This influences soil temperature, which in turn affects soil biophysical processes, such as seed germination, root growth, plant development and biomicrobial activity (Potter et al., 1987).

Charcoal may affect soil physical properties such as soil water retention and aggregate stability, leading to enhanced crop water availability and reduced erosion effects (Piccolo & Mbagwu, 1990; Piccolo et al., 1997). Tryon (1948) studied the effect of charcoal addition on the available moisture in soil of different textures. A positive effect of 18 % increase in soil water retention was observed upon addition of 45 % (by volume) charcoal to a sandy soil while a decrease of about 20 % was noted for a clay soil, whereas no change was recorded for a loamy soil, under the same charcoal treatment. Therefore, improvements of soil water retention by charcoal ameliorations may only be expected in coarse-textured soils or soils with large amounts of macropores (Glaser et al., 2002). The results of the numerous studies on the effect of fire and pyrolysis heat on soil properties vary widely; the purpose of this study was therefore to investigate the combined effects of charcoal production procedures on soil hydro-physical properties and the potential influence on infiltration behaviour, runoff response and erosion susceptibility in a combined field and simulation experiment in a tropical watershed.

Study area

The study watershed is located near the town of Ejura, a densely populated rural district about 90 km northeast of Kumasi, and lies in the forest–savannah transition zone of Ghana (lat 07 ° 20 ´ N, long 01 ° 16 ´ W, (Figure 1). The climate is wet semi-equatorial, with a long wet season between April and October, which alternates with a relatively short dry season between November and March. Mean total rainfall and temperature, from 1973-1993, are 1264 mm and 26.6 ^{o}C, respectively (Oguntunde et al., 2004). A survey was conducted to obtain information on the farmers' perception of bushfire, wildfire and charcoal making, their participation in these practices, and their observations concerning crops planted on soils of charcoal sites in comparison with the adjacent field soils, among other aspects.

MATERIALS AND METHODS

Experimental measurements and analyses

Within the study catchment, 12 charcoal production sites were randomly selected for sampling purposes (Figure 1). Information from farmers and villagers revealed that the selected sites had been cultivated between 2 to 14 months at the time of sampling. Samples were also collected at a distance of 10–15 m away from the edge of the charcoal sites to assess the effects of charcoal production on selected soil physical and hydrological properties: hydraulic conductivity, bulk density, hue, chroma and soil texture. At each sampling point, five undisturbed soil samples were carefully collected with sampling rings in the 2–10 cm layer. The soils were sampled so as to ensure similar soil properties for comparison (Oguntunde et al., 2004). For the bushfire sites, field sample were collected after the fire incident, shortly before the onset of the rainy season in February – March, 2002.

The hydraulic conductivity (*Ks*) of the samples was determined in the laboratory using the falling head method (Klute & Dirksen, 1986); bulk density was determined by the core method (Blake & Hartge, 1986); total porosity was estimated based on particle and bulk densities (Danielson & Sutherland, 1986); soil color (hue, value and chroma components) was

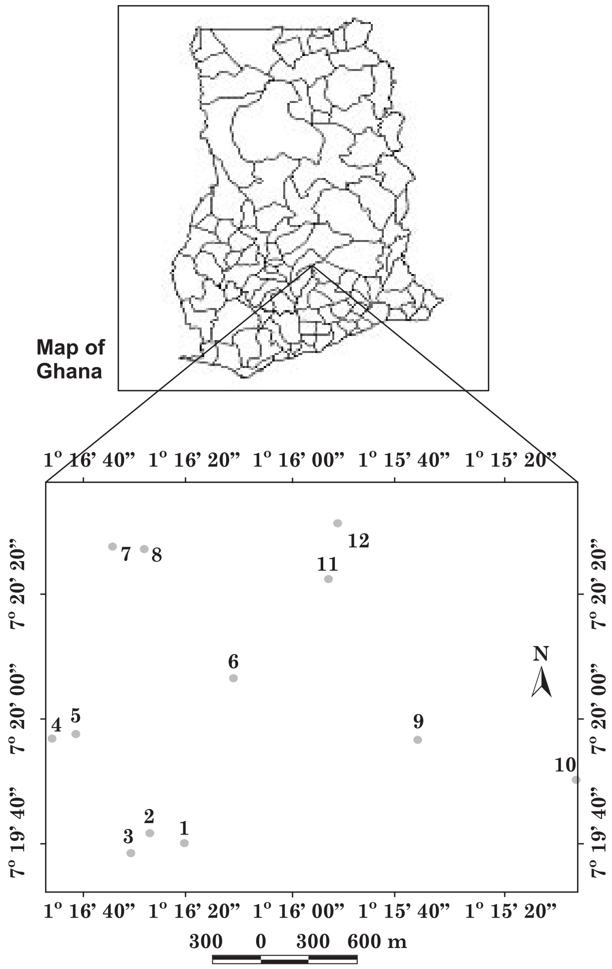

Figure 1. Map of the study area showing sampling points across the small watershed.

evaluated based on the Munsell color chart (Munsell color Company, 2000). Composite samples were air-dried, sieved (< 2 mm) and analyzed for percent sand, silt and clay by the hydrometer method (Bouyoucos, 1962). Field infiltration to determine field *Ks* for the bushfire field was measured using 0.5 cm suction mini-disk infiltrometers (Decagon Devices, Pullman, USA). A simple relationship expressed in equation (1) was used to compute the relative change of the soil properties between AFS and CSS:

$$RC(\%) = \frac{P_C - P_A}{P_A} X100 \qquad (1)$$

where RC is the relative change in percent, P_C is the soil property of soils under charcoal kilns and P_A is the soil property measured in the adjacent field soils. The mean properties of soils within and outside the charcoal sites were compared using the student t-test, following coding of the soil hues as 2.5 *YR* = 1; 5*YR* = 2; 7.5 *YR* = 3 and 10 *YR* = 4.

Simulation experiments and scenarios

For a more in-depth study of the effects of charcoal production on infiltration and runoff processes, a series of simulation experiments was implemented with an event-based, two dimensional hydrodynamic model, incorporating an infiltrating soil surface with spatially varied soil physical, hydraulic and microtopographic characteristics. The interactive infiltration process was modelled with the Philip Two-Term (PTT) infiltration equation and the time before ponding was approximated with the time compression algorithm. The model equations were resolved with a modified Leap-frog explicit finite difference scheme of second order with center time and space derivatives (Ajayi et al., 2008; Ajayi, 2004). The model successfully reproduced the runoff process in the catchment. The relative error in the performance of the model within the same watershed was based on a runoff volume of < 12 % and the runoff hydrograph predicted with an efficiency coefficient of 0.89.

The *Ks* and sorptivity values needed for the simulations under CSS and AFS were computed as geometric mean values of samples collected at a site based on the recommendation of Intsiful (2004). The simulations ware carried out on smooth 25 x 25 m plots with a prevailing slope of 5 %. The model domain consisted of 25 x 25 grid points with 1 m resolutions. The integration time step used was 0.01 second. Data sets of three typical rainfall intensities (high, moderate, and low, with 200, 100 and 30 mm h^{-1}, respectively) were selected from the data collected by a network of tipping-bucket rainfall gauges, fitted with HOBO-event logger data during the field campaign in the rainfall season of year 2002 Five experiments were performed at a high rainfall intensity with various percentages of effective CSS hydraulic parameters (i.e. 0, 25, 50, 75, and 100 %) distributed over the domain. Note that 0 and 100 % distributions correspond to values of AFS and CSS, respectively. A random distribution method was adopted to distribute the parameters over the domain as shown in figure 2. The five experiments were repeated for moderate and low rainfall, amounting to a total of 15 simulation experiments.

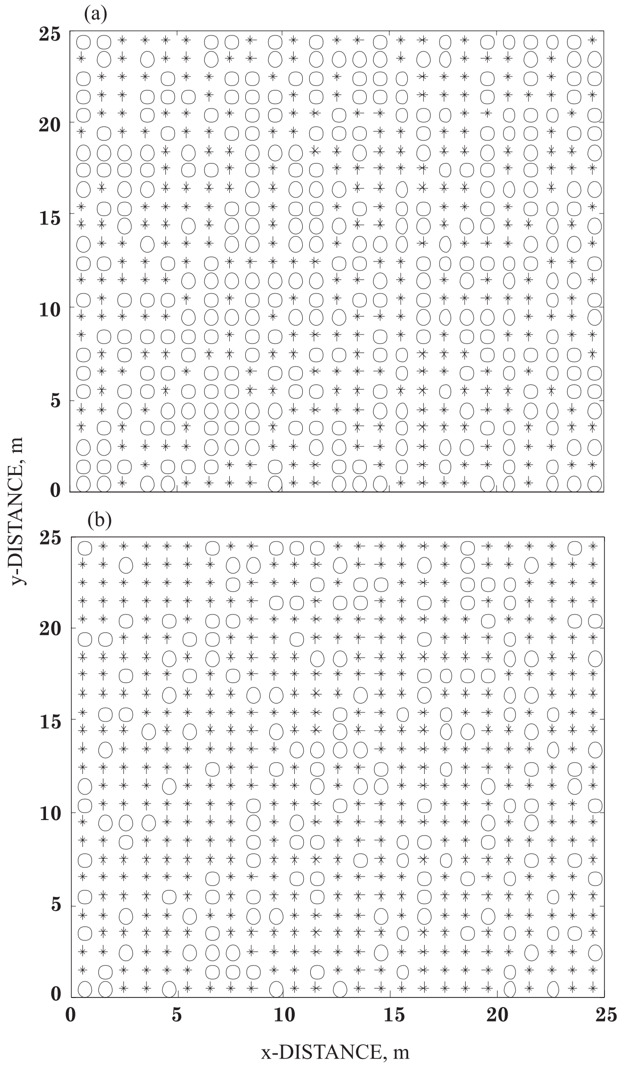

Figure 2. Samples of random distribution of effective Ks of both CSS and AFS over the plot: (a) 50 % and (b) 75 % distribution of CSS values, '*' represents point with CSS and 'o' point with AFS Ks values.

RESULTS AND DISCUSSION

Bushfire, charcoal burning drivers

The survey results from 40 randomly interviewed respondents from the villages and hamlets located within the watershed indicated that about 63 % of the respondents were involved in charcoal making and/ or fire wood selling, apart from farming. Almost all farmers (95 %) practice bush burning for land preparation. Subsistence arable crop production is predominant. About 70 % of the farmers work on less than 2.43 ha (6 acres) of land annually. Representative for the prevailing land tenure system in the area, 85 % of the farmers work on leased land. The majority of the villagers were found to be landless foreigners from near-by countries, especially Burkina Faso and the Republic of Togo. The study revealed that charcoal production was primarily motivated by the need for additional income, sometimes for farm inputs, as insurance in case of crop failure, and in some situations to meet other socio-cultural needs, while bush burning is influenced by the farmers' perception of increased fertility and relative low cost of land preparation. The survey also showed the trees most commonly used for this product: Shea butter (*Vitellaria paradoxa*), Mahogany (*Khaya grandifoliola*), Teak (*Tectona grandis*), Mango (*Mangifera indica*), Potrodum (*Erythrophleum africanum)* Kane (*Anogeissus leiocarpus*), Ongo (*Terminalia avicenioides*) and Papao (*Afzelia africana*).

Effects of charcoal making on soil hydro-physical properties

A summary of the dataset showing the coefficient of variation (CV) and relative change in selected hydro-physical properties, among other statistics, is shown in table 1. The soil hue (the dominant spectral color) in soil not subjected to heating process (control plots) were the reddest with a mean of 3.2, the highest value (lightness of color) with a mean of 3.1 and the highest chroma (strength of color) with a mean of 2.1. Among these soil color variables, the value differs significantly between AFS and CSS at 1 % and Chroma at 5 % levels properties, respectively. Although the mean difference of hue was not significantly different between the two soils, the higher CV in CSS (40 %) as compared to AFS (12 %) coupled with a highly significant ($p < 0.01$) variance difference test (Levene's test for equality of variance) showed that a considerable spatial variation in Munsell hues among the sampled plots was due to heating effects (Table 2). The observation was corroborated when the redness rating was calculated ((RR = (10–YR hue) x chroma)/ value) according to Ulery & Graham (1993). The mean difference of RR was not significantly different between AFS and CSS whereas the CV was 52 and 98 % in both soils, respectively. This result was similar to previous studies on a slash-and-burn site in Indonesia (Ketterings & Bigham, 2000, 2002). These authors reported a decrease in Munsell values and chromas of topsoil under temperatures of up to 600 °C and explain that the soil darkening could be due to charring of the organic matter, in agreement with Ulery & Graham (1993). Other studies also showed a relationship between a deep black soil color and the presence of charred organic matter (Schmidt & Noack, 2000).

Soil bulk density in the control plots ranged from 1.1 to 1.5 g cm^{-3} while at the plot subjected to heat, it ranged from 1.2 to 1.6 g cm^{-3}. The coefficient of variation in both soils is about 9 % but the mean for CSS was found to decrease significantly ($p < 0.05$) by 9 %, compared to the AFS (control). Similarly, Ueckert et al. (1978) observed no change in bulk density due to soil heating. Generally, the soils were loamy sand textured. The sand fraction in AFS and CSS ranged from 71 % to 83 and 80 to 89 %, respectively. Both sand and clay components of the texture were significantly different in AFS compared to CSS. Both clay and silt particles, on exposure to high temperatures, fused to form sand-sized particles resulting in a loosely structured soil.

Total porosity was 45.7 % in AFS and 50.6 % in the CSS. Variations in porosity were low both in AFS (CV = 10 %) and CSS (CV = 9 %). Total porosity was

Table 1. Summary of statistics of selected soil hydro-physical properties

Soil properties	Minimum		Maximum		Mean		SD		CV		RC
	AFS	CSS	AFS	CSS	AFS	CSS	AFS	CSS	AFS	CSS	
									%		
Hydraulic conductivity (mm h^{-1})	27	47	96	206	61	114	20	50	33,3	43,9	87,9
Bulk density (g cm^{-3})	1,2	1,1	1,6	1,5	1,4	1,3	0,1	0,1	8,5	9,2	-9,0
Total porosity (%)	41,1	44,6	54,6	57,0	45,7	50,6	4,6	4,5	10,1	9,0	10,7
Hue	3,0	1,0	4,0	4,0	3,2	2,9	0,4	1,2	12,3	39,9	-7,9
Value	2,5	2,0	4,0	3,0	3,1	2,5	0,6	0,4	18,2	16,1	-21,3
Chroma	1,0	1,0	3,0	2,0	2,1	1,7	0,5	0,5	24,7	29,5	-20,0
Sand (%)	71,0	80,0	83,0	89,0	78,4	82,8	3,8	2,8	4,9	3,4	5,6
Silt (%)	12,1	10,1	20,1	17,1	15,9	14,2	2,9	2,2	18,0	15,7	-10,5
Clay (%)	2,9	0,9	10,9	4,9	5,7	3,0	2,6	1,3	45,9	44,3	-48,1

CSS: charcoal site soils; AFS: adjacent field soils; SD: standard deviation; CV: coefficient of variation; RC: relative change.

Table 2. Statistical tests for soil properties

Soil properties	Levene's test(1)		Student t-test(2)	
	F-statistic	V_d	t-statistic	M_d
Hydraulic conductivity (mm h^{-1})	79,1	***	3,42	***
Bulk density (g cm^{-3})	0, 08	NS	2,62	**
Total porosity (%)	0, 11	NS	2,61	**
Hue	11 , 84	***	0,71	NS
Value	1, 23	NS	3,33	***
Chroma	1, 22	NS	2,03	*
Sand (%)	2, 04	NS	3,23	***
Silt (%)	1, 53	NS	1,59	NS
Clay (%)	3, 35	*	3,25	***

(1) Levene's test for equality of variances. (2) Student´s t-test for equality of means. V_d: variance difference; M_d: mean difference; *, **, **: significant at 10, 5 and 1 % and NS: not significant.

significantly increased ($p < 0.01$) by charcoal production and the relative change was about 11 %. Additions of charcoal amendment have been reported to increase macroporosity and total porosity (Piccolo et al., 1996) whereas no significant effect from soil burning was observed (Ueckert et al., 1978). These observations may be responsible for the decrease in bulk density mentioned above. Bulk density is often used as a measure of soil structure or compaction as it varies with the soil structure condition related to packing (Black & Hartge, 1986). A higher sand fraction and total porosity may therefore reduce soil bulk density under earth kilns.

Saturated hydraulic conductivity values ranged from 27 to 96 mm h^{-1} (mean = 61 mm h^{-1}) in adjacent field soils (AFS) but varied between 47 and 206 mm h^{-1} (mean = 11.4 mm h^{-1}) under charcoal site soils (CSS). A highly spatially varied parameter, the CV of *Ks* in CSS and AFS was 44 and 33 %, respectively. Ks under AFS was significantly ($p < 0.01$) lower than under CSS. The relative change of this parameter was highest (88 %) of all soil properties reported here. According to the classification of Landon (1991), the flow characteristics of soils in AFS showed a moderate flow compared to the rapid flow observed in the soils under charcoal kilns. However, *Ks* values reported for both AFS and CSS are comparable to those reported in other studies (Ajayi, 2004; Agyare, 2004).

Impact on simulated infiltration and runoff

A plot of cumulative infiltration using field measurements from the disc infiltrometer for both CSS and AFS is shown in figure 3, while the corresponding simulated results are given in figure 4, and the model parameters are presented in table 3. The values of cumulative infiltration for CSS were higher than FS at all times. This could be attributed to changes in the soil structure: decreased bulk density, increased porosity, sand fraction and *Ks* of heated soils, as reported above. The results of five different *Ks* distribution scenarios at the highest rainfall intensity (200 mm h^{-1}) are shown as cumulative runoff plots in figure 5, while the down slope total runoff after 60 min of simulation for all scenarios and the three rainfall types is shown in figure 6. Cumulative runoff decreased with increasing burning effect (charcoal-type). No surface runoff was generated on either CSS or AFS at the lowest rainfall intensity of 30 mm h^{-1} for 60 min. Similarly, under the moderate rainfall event of 100 mm h^{-1}, the runoff was insignificantly small as flow characteristics tend to be similar to those observed in CSS over the model domain or landscape. The runoff was reduced by about 37 and 18 % on AFS and CSS during the application of high and moderate rainfall events (Figure 6). Furthermore, the runoff coefficient was estimated between 47–75 % and 4–39 % for simulation with high and moderate rainfall events on the CSS and AFS, respectively. The observed absence of runoff on both soils under low rainfall event was the result of higher infiltration rates compared to rainfall intensity such that all rain was infiltrated during the simulation period without overland flow. When the runoff plot was submitted to the highest rainfall intensity, surface runoff began 3 min after the beginning of simulation and reached an equilibrium runoff after 20 min of simulation. Reduction in runoff on AFS and CSS was about 50 % when rainfall intensity also changes 50 %. It is also noteworthy that rainfall was simulated on a smooth inclined surface, which explains the observed high runoff coefficient on both soils. There were no depression storage – that would have reduced the flow rates and increased infiltration opportunity in the plot. In addition, 4 % of the moderate rainfall became down slope runoff even though the Ks for CSS is 103 mm h^{-1} (> 100 mm h^{-1} rainfall event) because the model already integrates the infiltration process interactively by capturing the expected reduction of infiltration rates as long as the rain lasted. Rainfall, which is a main factor in the hydrology of a watershed, plays a significant role in the modeled response.

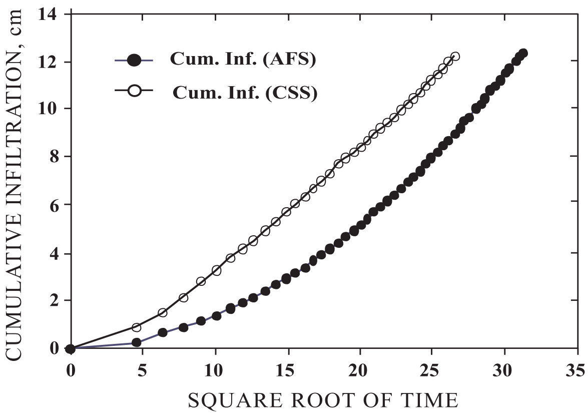

Figure 3. Typical cumulative infiltration curves of CSS and AFS measured with disc infiltrometer.

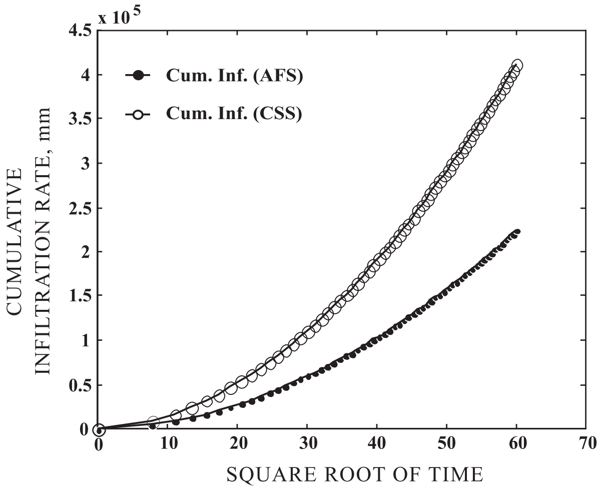

Figure 4. Simulated time variation of cumulative infiltration under high rainfall (200 mm h^{-1}) for AFS and CSS plot.

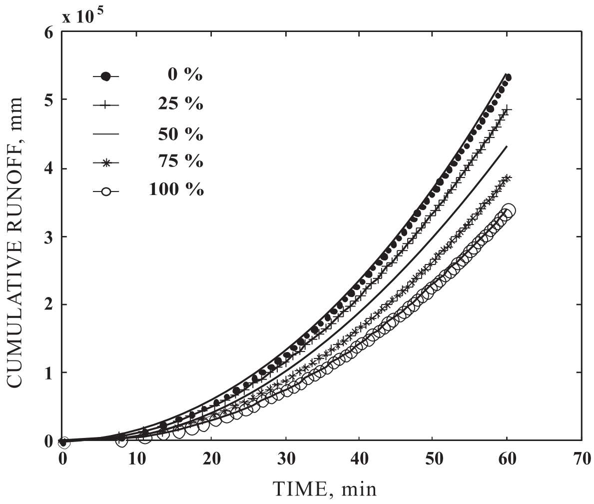

Figure 5. Simulated time variation of cumulative runoff under high rainfall (200 mm h^{-1}) for various CSS Ks distributions on the plot.

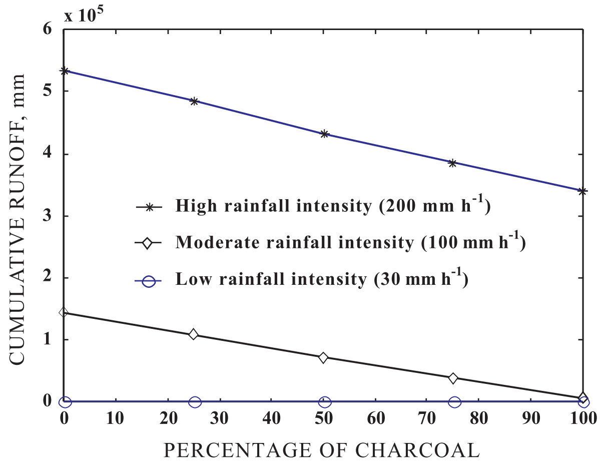

Figure 6. Variation of total runoff from the plots with the five different Ksat distributions and under High, Moderate and Low rainfall intensities. Results after 1 h of model simulation.

Reduction in generated surface runoff was a direct effect of enhanced water infiltration rates on CSS in comparison with AFS. Previous studies stated that charcoal addition to soil increases infiltration capacity and decreases erosion effects (Piccolo et al., 1997; Glaser et al., 2002). However, significantly increased runoff and erosion were observed in many studies, due to the loss of plant cover and development of water repellency by fire (Scott & van Wyk, 1990; Inbar, 1998). The combined effects on hydrological response of soils investigated here showed the dominance of charcoal amelioration over fire-induced effects. Care should be taken to draw conclusions from this plot-level study as the overall watershed response is likely to differ. A survey conducted among the charcoal producers showed that an average relation of 5:1 of un-covered area to area occupied by kiln is common. It is obvious that by the disappearance of the protective plant cover, especially the trees used for charcoal, the microclimate is influenced, soil flora and fauna are highly reduced, the hope of rebuilding the soil organic matter by falling leaves is dashed and a possible increase in runoff may exceed the reduction reported for CSS. A combination of these results and data at the watershed level would be required for a more detailed evaluation of the overall hydrological response

Table 3. Cumulative infiltration (I) model parameters ($I = C_1 t + C_2 t^{0.5}$)

Treatment	Model parameter		
	C_1	C_2	R^2
AFS	0.0123	0.0129	0.999
CSS	0.0076	0.2637	0.998

to charcoal production, which is currently practiced on a large scale in the study area.

CONCLUSIONS

Our study showed that some soil properties including color, bulk density, hue and chroma value and infiltration potential were affected by the heating process. Reduction in bulk density and increased sand fraction influenced total porosity, infiltration and flow characteristics of the soils under charcoal kilns. The simulated impact of the observed changes in soil hydraulic properties showed the potential effects of charcoal production on surface hydrology at the plot scale. Enhanced simulated rainfall infiltration and reduced surface runoff may be interpreted as increased water retention of CSS, which translates to reduced erosion susceptibility.

ACKNOWLEDGEMENTS

The first author acknowledges a grant from TWAS/CNPq when editing this paper. The research was partially supported by the GLOWA Volta project, funded by the German Federal Ministry of Education and Research (BMBF), grant no. 07GWK01, with additional support from the State of North Rhine Westphalia. The authors are indebted to the three anonymous reviewers, whose comments significantly improved the quality of the manuscript.

LITERATURE CITED

AGYARE, W.A. Soil characterization and modeling of spatial distribution of saturated hydraulic conductivity at two sites in the Volta Basin of Ghana. Boon, University of Boon, 2004. 194p. (Ecology and Development Series, 17)

AJAYI, A.E. Surface runoff and infiltration processes in the Volta Basin, West Africa: Observation and modeling. Boon, University of Boon, 2004. 160p. (Ecology and Development Series, 18)

AJAYI, A.E.; van de GIESEN, N. & VLEK, P. A numerical model for simulating Hortonian overland flow on tropical hillslope with vegetation elements. Hydrol. Proces., 22:1107-1118, 2008.

BERINGER, J.; HURTLEY, L.B.; TAPPER, N.J.; COUTTS, A.; KERLEY, A. & GRADY, P.O. Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in Northern Australia. Inter. J. Wildland Fire, 12:333-340, 2003.

BLACK, G.R. & HARTGE, K.H. Bulk density. In: KLUTE, A., ed. Methods of soil analysis. Physical and mineralogical methods. 2.ed. Madison, American Society of Agronomy, 1986. Part 1. p.363-375. (Agronomy Monograph, 9)

BOUYOUCOS, G.H. Hydrometer method improved for making particle size analysis of soils. Agron. J., 54:454-465, 1962.

CERTINI, G. Effects of fire on properties of forest soils: A review. Oecologia, 143:1-10, 2005.

DANIELSON, R.E. & SUTHERLAND, P.L. Porosity. In: KLUTE, A., ed. Methods of soil analysis. Physical and mineralogical methods. 2.ed. Madison, American Society of Agronomy, 1986. Part 1.p. 443-461 (Agronomy Monograph, 9)

GLASER, B.; LEHMANN, J. & ZECH, W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal-A review. Biol Fert. Soils, 35:219-230, 2002.

INBAR, M.; TAMIR, M. & WITTENBERG, L. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. Geomorphology, 24:17-33, 1998.

INTSIFUL, J.D. Upscaling of land surface parameters through inverse-SVAT modeling. Boon, University of Boon, 2004. 178p. (Ecology and Development Series, 20)

KETTERINGS, Q.M.; BIGHAM, J.M. & LAPERCHE, V. Changes in soil mineralogy and texture caused by slash-and-burn fires in Sumatra, Indonesia. Soil Sci. Soc. Am. J., 64:1108-1117, 2000.

KETTERINGS, Q.M.; BIGHAM, J.M. & van NOORDWIJK, M. Soil phosphorus availability after slash-and-burn fires of different intensities in rubber agroforests in Sumatra, Indonesia. Agric. Ecosyst. Environ., 92:37-48, 2002.

KETTERINGS, Q.M. & BIGHAM, J.M. Soil color as an Indicator of slash-and-burn fire severity and soil fertility in Sumatra, Indonesia. Soil Sci. Soc. Am. J., 64:1826-1833, 2000.

KLUTE, A. & DIRKSEN, C. Hydraulic conductivity and diffusivity. In: KLUTE, A., ed. Methods of soil analysis. Physical and mineralogical methods. 2.ed. Madison, American Society of Agronomy, 1986. Part 1. p.687-734. (Agronomy Monograph, 9)

LANDON, J.R. A booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. London, Booker Tate, 1991. p.58-125.

MATAIX-SOLERA, J.; GÓMEZ, I.; NAVARRO-PEDREÑO, J.; GUERRERO, C. & MORAL, R. Soil organic matter and aggregates affected by wildfire in a *Pinus halepensis* forest in a Mediterranean environment. Inter. J. Wildland Fire,11:107-114, 2002.

MUNSELL COLOR COMPANY. Munsell soil Color Charts, Rewashable Edition. GretagMacbeth, 617 New Windsor, Little Britain Road, 2000. NY12533.

OGUNTUNDE, P.G.; FOSU, M.; AJAYI, A.E. & van de GIESEN, N. Effects of charcoal production on maize yield, chemical properties and texture. Biol Fert. Soils, 39:295-299, 2004.

PICCOLO, A. & MBAGWU, J.S.C. Effects of different organic waste amendments on soil microaggregates stability and molecular sizes of humic substances. Plant Soil, 123:27-37, 1990.

PICCOLO, A.; PIETRAMELLARA, G. & MBAGWU, J.S.C. Effects of coal-derived humic substances on water retention and structural stability of Mediterranean soils. Soil Use Manag., 12:209-213, 1996.

PICCOLO, A.; PIETRAMELLARA, G. & MBAGWU, J.S.C. Use of humic substances as soil conditioners to increase aggregate stability. Geoderma, 75:267-277, 1997.

POTTER, K.N.; HORTON, R. & CRUSE, R.M. Soil surface roughness effects on radiation reflectance and soil heat flux. Soil Sci. Soc. Am. J., 51:855-860, 1987.

SCHMIDT, M.W.I. & NOACK, A.G. Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. Global Biogeochem. Cycles, 14:777-793, 2000.

SCHOLES, R.J. & WALTER, B.H. 'An African: Synthesis of Nylsvley Study.' Cambridge, University Press, 1993.

SCOTT, D.F. & van WYK, D.B. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. J. Hydrol., 121:239-256, 1990.

TRYON, E.H. Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol Monogr., 18:81-115, 1948.

UECKERT, D.N.; WHIGHAM, T.L. & SPEARS, B.M. Effect of burning on infiltration, sediment, and other soil properties in a mesquite-tobosagrass community. J. Range Manag., 31:420-425, 1978.

ULERY, A.L. & GRAHAM, R.C. Forest fire effects on soil color and texture. Soil Sci. Soc. Am. J., 57:135-140, 1993.