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INFLUENCE OF SPATIAL STRUCTURE OF SOIL HYDRAULIC PROPERTIES ON SURFACE RUNOFF PROCESSES IN WEST AFRICA

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The effect of spatial variations of soil hydraulic properties on runoff response at plot scales was investigated in this study using a combination of results from field observation and numerical simulation experiments. Field observations were from two sets of scaled runoff plots during twenty-four (24) runoff events. Simulation experiments on four scenarios of hydraulic conductivity (K) distribution in a 2 m x 6 m runoff plot was implemented with a two dimensional hydrodynamic model developed and validated for tropical watersheds. In scenario A - "expanding", K values were increased linearly from 30 mm h^{-1} to 172 mm h^{-1} at regular grids downslope. In scenario B-"shrinking", K values were decreased downslope (inverse of scenario A). For scenario C - "measured" field measured K values were used on all the grid points; and in scenario D - "homogeneous" an average K value of the K distribution in scenarios A and B, 81.5 mm h^{-1}, was used on all the grids. Two typical rainfall events; high and low intensity, were selected from field data of 2002 for model simulations. The results clearly demonstrate the role of spatial variability of K in runoff processes during storm events. Scenario A produced lowest runoff volume, due to increasing infiltration opportunity, whereas the homogeneous distribution (scenario D) yielded the highest runoff volume for both low and high intensity events. Scenarios B and C showed similar results possibly due to their decreasing infiltration capacity downslope. For proper interpretations of runoff processes such as scale dependency, runoff coefficient, etc., this study showed that there is the need to consider temporal dynamics associated with surface runoff travel from point of initiation to discharge, spatial distribution and orientation, as well as the temporal pattern and intensity of rainfall events. Further discussions on the field observed runoff response to variability in hydraulic conductivity and plot sizes are included.

INTRODUCTION

There is a growing demand for accurate representation of surface runoff process in catchment (watershed) hydrology. However, quantifying surface runoff remains challenging due to the high variability (spatial and/or temporal) of rainfall, relief, vegetation, seasonal land-use practices, soil properties, and drainage network (Nunes et al., 2006; Herbst, 2006). Formulating a predictive model for surface runoff and erosion over large area is cumbersome (Léonard et al., 2006; Merz and Bárdossy, 1998). This is often the case, because measurement of infiltration, hydraulic conductivity, rainfall, surface features, etc., which are used as inputs in most rainfall-runoff models, are made at the point scale (Ajayi, 2004, van de Giesen et al., 2005), while the developed models are required to predict runoff response at catchment or even regional scales. Consequently discrepancies exist in results, as most models do not explicitly account for spatial variability of soil hydraulic properties and the temporal dynamics associated with the processes.

Spatial variability of hydraulics parameters such as saturated and unsaturated hydraulic conductivity has been widely reported (Mohanty and Mousli, 2000; Warrick and Nielsen, 1980). Moreover, two kinds of variability have been established in hydrological studies: stochastic variability (which can be depicted by non-spatial statistical data) and structured (organized or deterministic) variability, which requires location-specific data for its description (Merz and Bárdossy, 1998). Whereas stochastic variability is easily understood, structural variability is difficult to understand, apparently due to interactions between ecosystem characteristics, such as geology, topography, climate and vegetation (Ajayi, 2004).

Infiltration capacity, influenced by the structure of hydraulic parameters (Ajayi, 2004, van de Giesen et al., 2000), plays an important role in runoff processes by partitioning precipitation into infiltration and infiltration excess, which becomes surface runoff (Hortonian overland flow) or macropore runoff (Herbst et al., 2006). Adequate understanding of its spatial and temporal dynamics is essential in evaluating and interpreting catchment rainfall-runoff processes. Several structural factors including slope length (Kinnell, 2000; Lal, 1997; Poesen, 1984), initial soil moisture (van de Giesen et al, 2005, 2000), soil surface microtopography (Joel et al., 2002; Darboux, 2002a,b) vegetation (Fiedler et al., 2002; Braud et al., 2001; van Dijk, 2001a,b; Dunne et al., 1991) and stochastic factors such as temporal pattern and direction of rainfall (de Lima et al., 2003; de Lima and Singh, 2002; Wainwright and Parson, 2002), runoff travel time (van de Giesen et al., 2000) among others, have been cited as possible reasons for the widely reported variability in surface runoff response. Most of these studies arrived at their conclusions at the instance of model evaluation (Dunne et al., 1991). However, the different processes of simplification of the runoff routing downslope often place limitations on their application in field studies (Woolhiser et al., 1996). Other deficiencies stem from the failure to couple the infiltration process with the surface runoff process, as well as the inability to adequately represent spatial variability of hydraulic parameters, which moderate infiltration capacities. In this study the effect of spatial structure and orientation of hydraulic characteristics and temporal pattern of rainfall on runoff response was investigated in a combination of simulation experiments with a numerical model. The model was developed and validated for tropical watersheds, and results are reported from a field study in a watershed within the Volta basin during the 2002-2004 rainfall seasons.

MATERIALS AND METHODS

Model description, simulation experiments and scenarios

Simulation experiments were conducted with an event-based two-dimensional hydrodynamic model that characterizes surface runoff process resulting from a varying rainfall intensity event, on an infiltrating soil surface. The soil surface has spatially varied soil physical, hydraulic and microtopographic characteristics. Infiltration process is modeled with the Philip two-term equation and the time before ponding approximated with the time compression algorithm. Vegetation is modeled as a dynamic component with the modified Gash model. The equation is solved with a modified second order Leapfrog explicit finite difference scheme with centered time and space derivatives. The model was validated with standard analytical solutions. Evaluation with results from field campaigns in the Volta Basin of West Africa during the 2002 rainfall season indicate good agreement, with r^2 values ranging from 0.89 to 0.96 (Ajayi et al., 2007; Ajayi, 2004).

Surface runoff responses from four spatial structures of hydraulic conductivity were simulated on a 2 m x 6 m runoff plot. For the experiment, the data from one high and one low rainfall intensity event from those collected during the field study in 2002 were used. The runoff plot was divided into regular grids of 10 cm x 10 cm producing about 1200 grid points. At each grid point, the structural properties including hydraulic conductivity and micro elevation of the soil can be defined. In the first experiment scenario A - "expanding", a linear increase in hydraulic conductivity K_s downslope was assumed. K_s value was increased from 30 mm h^{-1} by 3% in each successive row of grid points along the flow direction yielding the highest value of 171.6 mm h^{-1} at the last row of grid points, before the outlet, where discharge is monitored. The arithmetic average of the hydraulic conductivity distribution was 81.5 mm h^{-1} with a standard deviation of 41 mm h^{-1}. For the second experiment, scenario B-"shrinking", K values were reduced downslope from a maximum of 171.6 mm h^{-1} at the row of grids of the runoff plot upslope to 30 mm hr^{-1} at the grid points just before the outlet. For the third experiment, scenario C - "measured", the actual hydraulic conductivity data measured on the 6 m long plot was used to represent random variation in K at all the grid points. The measured values varied from 30 mm hr^{-1} to 156 mm hr^{-1}. In the fourth simulation experiment scenario D- "homogeneous" the arithmetic average of the K values in the scenarios A and B distributions, i.e. 81.5 mm h^{-1}, was used at all the grid points.

The configuration of the runoff plot used in the simulation experiment in terms of slope, terrain and soil surface microtopography distribution of the plot used for the experiment was based on the field measurement (described in the next section). Also the vegetation component of the model is turned off to ensure that all observed differences in response results from varying infiltration opportunities and soil surface microtopography. The contour map showing scenario A, B, C distributions of K is presented in Figure 1.

FIELD EXPERIMENT

Site instrumentation and runoff plots

The field experiment was conducted at the Kotokosu watershed in Ejura (7º 19', 1º 16'W; 161–178 m amsl) Ghana. Two sets of runoff plots (located at sites A and B), with each set consisting of a twin plot measuring 2 m x 18 m (long plot, LP), a 2 m x 6 m plot (medium plot, MP) and a 2 m x 2 m plot (short plot, SP), placed close enough to each other to minimize the influence of soil spatial variability. Runoff discharge was recorded with an automated tipping bucket runoff meter. Surface microtopography for the runoff plots was obtained through measurement of elevation data within the plots at a 10 cm x 10 cm grid, using an Ashtech differential GPS (Ashtech Locus Survey System, USA). Data for each plot was interpolated with modeled semi-variograms following the procedures of Chilés et al. (1999). Limited smoothing was applied to digital terrain models using the contouring features of the Surfer package (Golden software, Inc. 2000). The limited smoothing was necessary to eliminate spikes that induce instability in the numerical process (Ajayi, et al., 2007; Fiedler, 1997; Tayfur et al., 1993).

To characterize the hydraulic properties within each runoff plot, infiltration measurement was done at grid points with the Decagon's 0.5 cm suction minidisk infiltrometers (Decagon Devices, Pullman, USA). The 0.5 cm suction represents the suction at which raindrops infiltrate into the soil under natural field conditions. The observed infiltration data were used to plot the cumulative infiltration curves, determine the hydraulic conductivity and estimate the sorptivity value used for simulation following standard procedures specified in Decagon (2005) and Zhang (1997). Rainfall total and intensity within and outside the plots were monitored from a network of tipping bucket-rain gauge fitted with HOBO event loggers.

Figure 2 shows the interpolated hydraulic conductivity maps, following the procedure of Mallant et al. (1996), for the short plots at both sites which were then overlaid on the digital (micro) topography model (DTM) of the respective plots. The contour map shows that the upper and the lower limits of the hypothetical linear variations used in this study are within the scope of observation within the runoff plots. The four scenarios were used to study the dynamic effect of infiltration opportunity on runoff response.

RESULTS AND DISCUSSIONS

Effect of varying infiltration capacity: simulation result

The hydraulic conductivity values used for the simulation experiment are generally within the range of field observation, which are represented in Figure 1c and 2a and b. A comparison of discharge hydrographs for the four scenarios and the rainfall hyetograph in both high and low intensity rainfall events are shown in Figures 3 and 4. The results indicate that the magnitude and

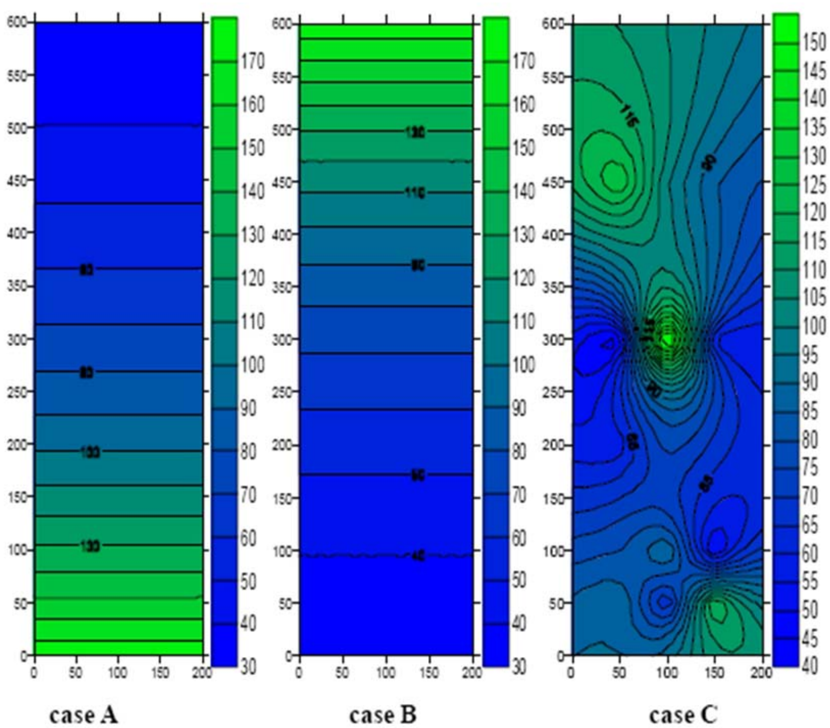

Figure 1. Contour map of hydraulic conductivity distributions for scenarios A, B, and C used in the simulation experiments.

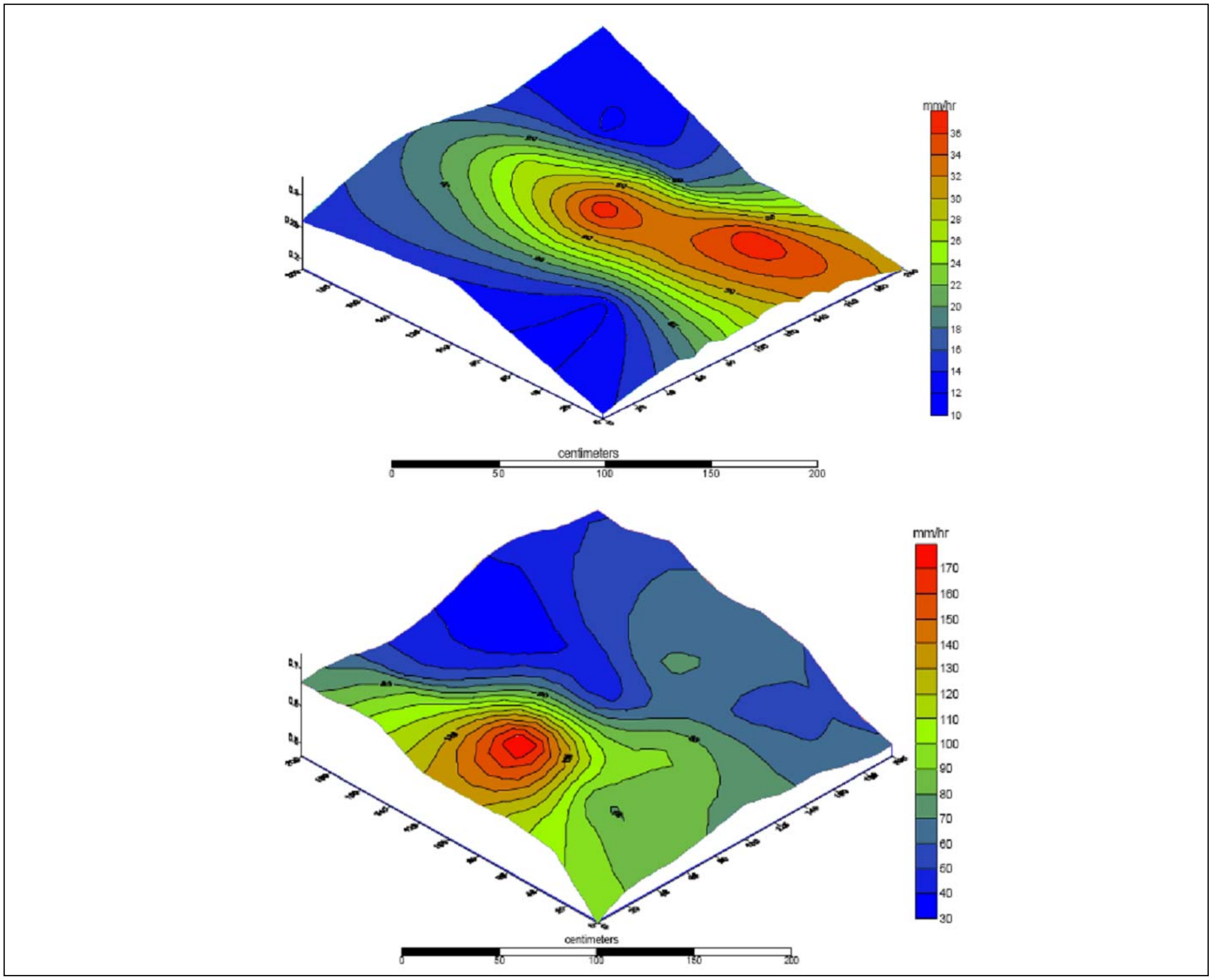

Figure 2. Measured spatial distribution of hydraulic conductivity (K) in the short plots (2m x 2m) at site A and site B.

spatial pattern of K, which translate to different infiltration capacity within a plot or on a hillslope, could significantly affect the observed discharge in a runoff event.

In the simulation experiment for scenario A, it was observed that the gradual increase in the infiltration capacity allows more of the overland flow to infiltrate. This results in a significant reduction in discharge rate and volume as depicted in the hydrograph (Figure 3a). The high value of hydraulic conductivity values around the gutter also induces a substantial reduction in flow depth as clearly displayed in the asymmetric pattern of the flow depths (Figure 4). Even though there was a build up of runoff upslope, it infiltrates into the soil before arriving at the discharge point. For the low intensity rainfall events, runoff was not produced throughout the event. This is understandable looking at the maximum rainfall intensity of the event which was about 75 mmhr^{-1}. The runoff that was built up upslope where infiltration capacity is low, is lost before reaching the discharge point.

The hydrograph from scenario B, where infiltration capacity decreases downslope (shrinking), showed that discharge volume and rate were higher compared to scenario A. Overland flow apparently originating from the regions near the outlet has a short travel distance and hence results in marked increase in discharge. This was clearly noticeable with the low intensity event hydrographs (Figure 3b). Whereas no runoff was recorded in other scenarios simulated (A, C and

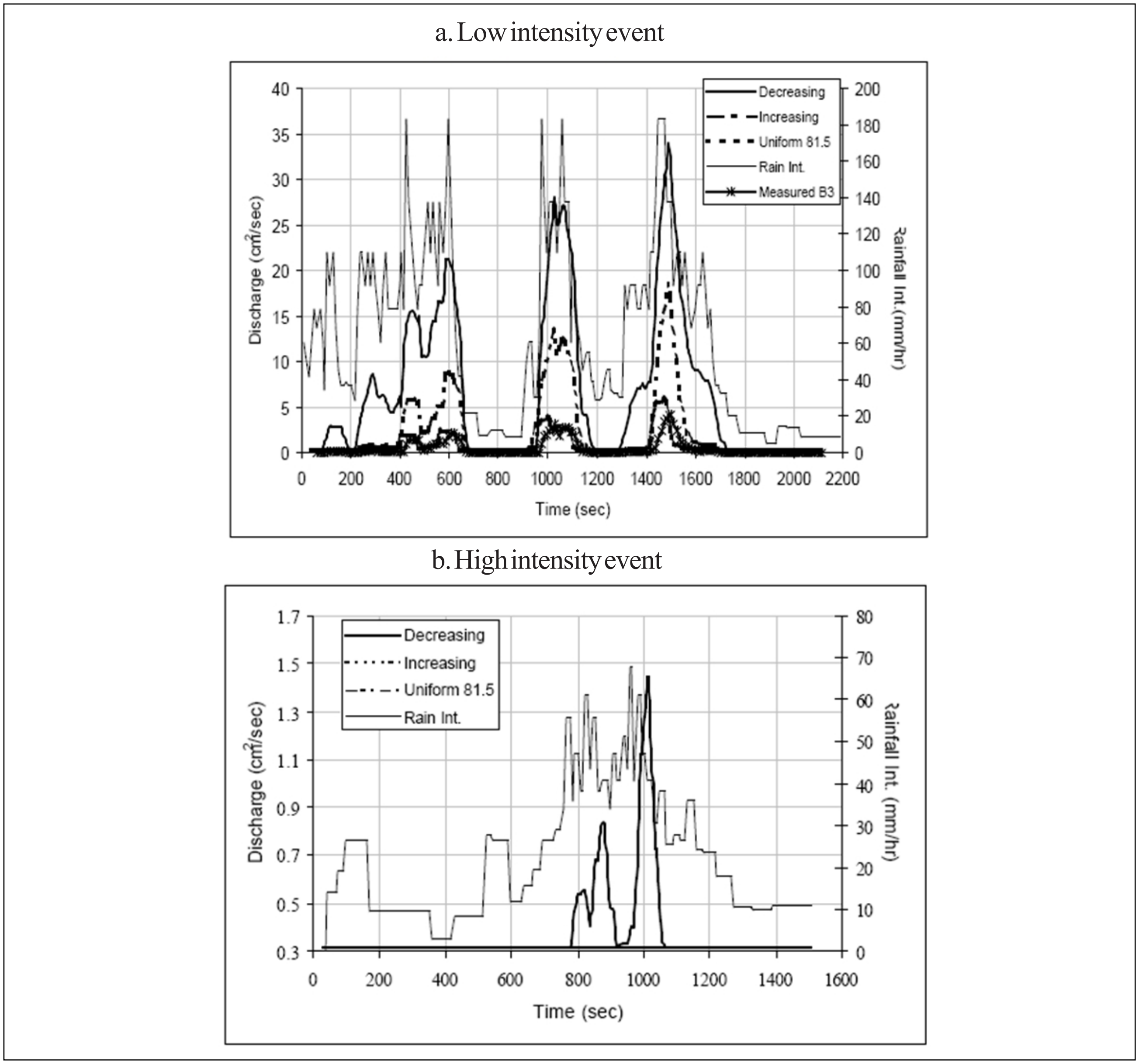

Figure 3. Comparison of simulated discharge hydrograph and rainfall hyetograph showing the effect of variation in distribution of K for high and low intensity rainfall events.

D) with the low intensity event, there was little discharge in the shrinking scenario, B. These observations demonstrated the importance of temporal dynamics in surface runoff routing, which was previously suggested by Wainwright and Parson (2002) and van de Giesen et al., (2000) and showed the significance of proper representation of spatial orientation in understanding and interpreting results from surface runoff experiments.

Simulation with homogenous K value produced more runoff than both shrinking and randomly varying scenarios with the high intensity rainfall event. Since rainfall over the plot was assumed uniform, runoff discharge will commence as soon the soil is saturated and continue thereafter. This was attained at about 400 sec of simulation into the high rainfall intensity event. Simulation with low intensity rate produced no runoff since the intensity was lower than infiltration rate. Random variation in infiltration opportunity as measured in the field and depicted by scenario C produced discharges similar to scenario B (shrinking scenario). This may be due to a prevalence of high conductivity values near the upslope region of the plot, and lower values in the middle and downslope reaches.

For all the simulated scenarios, both for high and low intensity rainfall events, the flow pattern and direction are considerably influenced by the soil surface microtopography (Figures 4 - 6), while the magnitude and speed were moderated by the infiltration capacity. The difference between the hydrograph for the expanding and shrinking scenarios showed that most of the runoff that arrives at the gutter originates from regions near the discharge point. There is similarity in the hydrographs of scenario C and D for the high intensity event. This was also observed by Merz and Bárdossy (1998) in a simulation experiment to examine the effect of spatial variability on the rainfall runoff process in a small loess catchment in southwest Germany. It implies that an appropriately selected average value of K could be used to represent K distribution without loss of accuracy in observed discharge. At 1750 sec, which corresponds to the tailing part of the rainfall event, flow patterns and all other parameters were uniform in the four scenarios under the high intensity event.

Differences in the outflow hydrographs of the various simulated scenarios provide insight for understanding the role of spatial variability of soil hydraulic properties in the Hortonian runoff process. The trend of spatial variation of infiltration properties influences the discharge from runoff plots or hillslopes. However, the effect can only be explained in the context of the temporal changes that occur during the time required for the overland flow to travel from the point of initiation to outlet. The required time depends on the rainfall intensity (which determines the available kinetic energy) and the microtopographic forms (which moderate depression storage and slope). These factors affect the velocity of flow.

This investigation also showed that infiltration opportunities vary with slope length and the pattern of hydraulic conductivity distribution. Differences in infiltration opportunities result in differences in transmission loss potential during surface runoff routing downslope. In addition, surface microtopography, which becomes more varied with increasing slope length, determines surface depression storage shape and network, and consequently influences runoff initiation and flow rate. However, the effect of factors of spatial variability is influenced by the time required to travel from point of runoff initiation to the discharge point. This in turn is influenced by rainfall intensity and field slope (van de Giesen et al., 2005; Wainwright and Parsons, 2002; Esteves et al., 2000). Thus, the temporal pattern and structure of a rainfall event can influence runoff response.

Temporal patterns of rainfall intensity, particularly the distribution in terms of numbers of peaks in the event, the duration of the pulses, the length of time for recession, and magnitude of rainfall intensity coupled with temporal variation in surface runoff travel largely determine the response to high intensity events. Soil related effect in terms of spatial variability in hydraulic properties mainly influences low intensity events. The dominance of temporally induced factors in many tropical catchments could be related to the high intensity events synonymous with tropical storms, which often overwhelm the influence of soil spatial factors.

Effect of varying infiltration capacity: field observation result

The measured hydraulic conductivity values were used to compute effective hydraulic conductivity (K_{eff}) and also generate hydraulic conductivity functions representative of the plots at a particular site. To do this the Mualem-van Genuchten (van Genuchten, 1980) model was used to parameterize the soil water and tension characteristics data measured in the fields using the method by Zhu and Mohanty (2003) and Kasteel et al. (2000). The representative soil water parameters obtained with the RETC optimization software (USDA) are presented in Table 1. Effective hydraulic conductivity (K_{eff}) was estimated as 15.8 mm h^{-1} and 53.6 mm h^{-1} for sites A

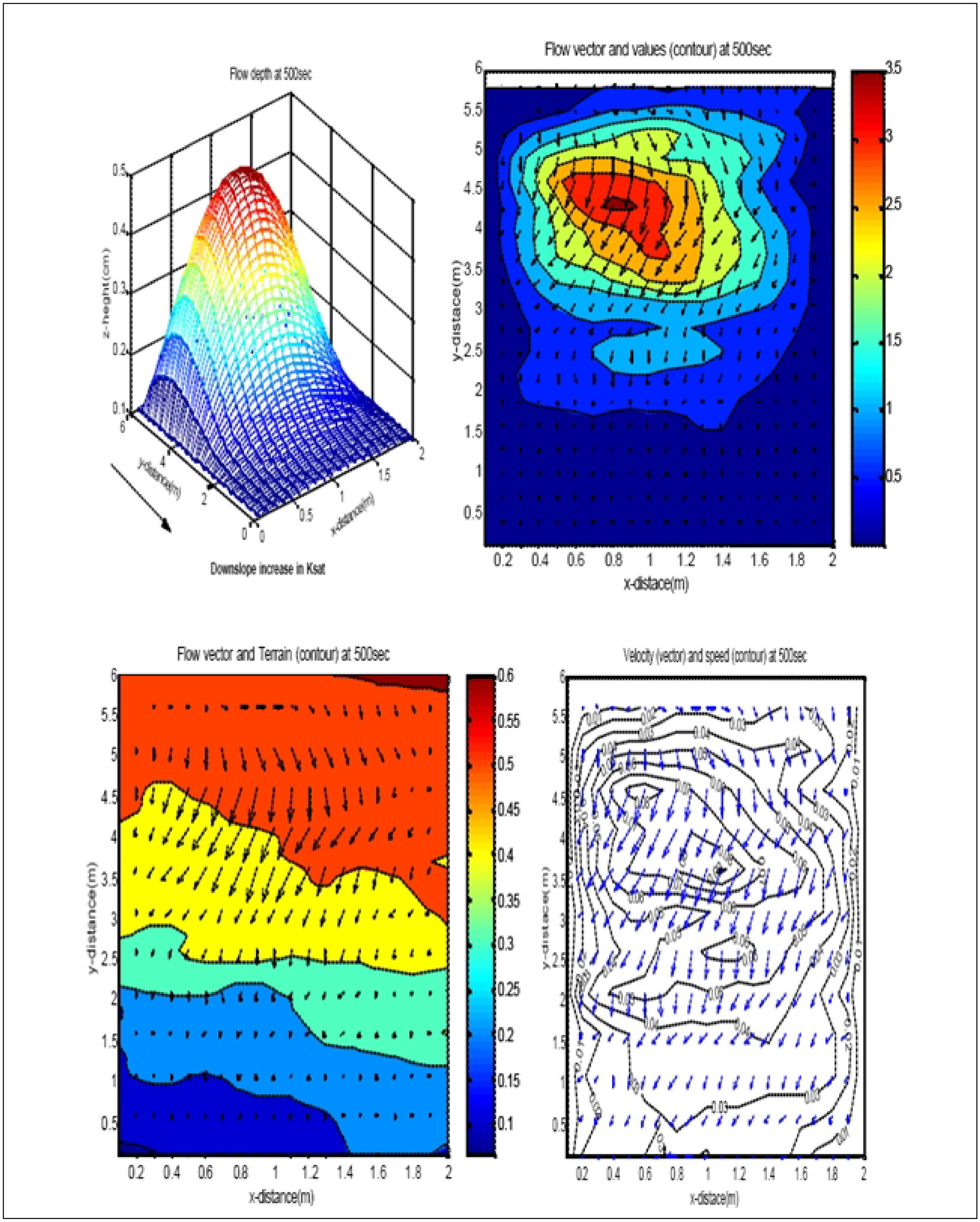

Figure 4. Flow pattern, magnitude and speed for scenario A - "increasing" scenario at 500s into the high intensity event.

and B, respectively. These values yielded a hydraulic conductivity ratio of 3.4 between the sites (B:A). Runoff volume from the sites however did not replicate this scale of difference, suggesting that differences in hydraulic properties need to be coupled with the spatial distribution in trying to appreciate differences in runoff response.

Table 1. Summary of soil water characteristics and hydraulic parameters for site A and site B.

Site	θ_s $m^3 m^{-3}$	θ_r $m^3 m^{-3}$	α mm^{-1}	N	S_e	Ks_{eff} $mm\ h^{-1}$
A	0.51	0.10	0.0633	1.8322	0.53	15.8
B	0.57	0.07	0.0610	1.5716	0.68	53.6

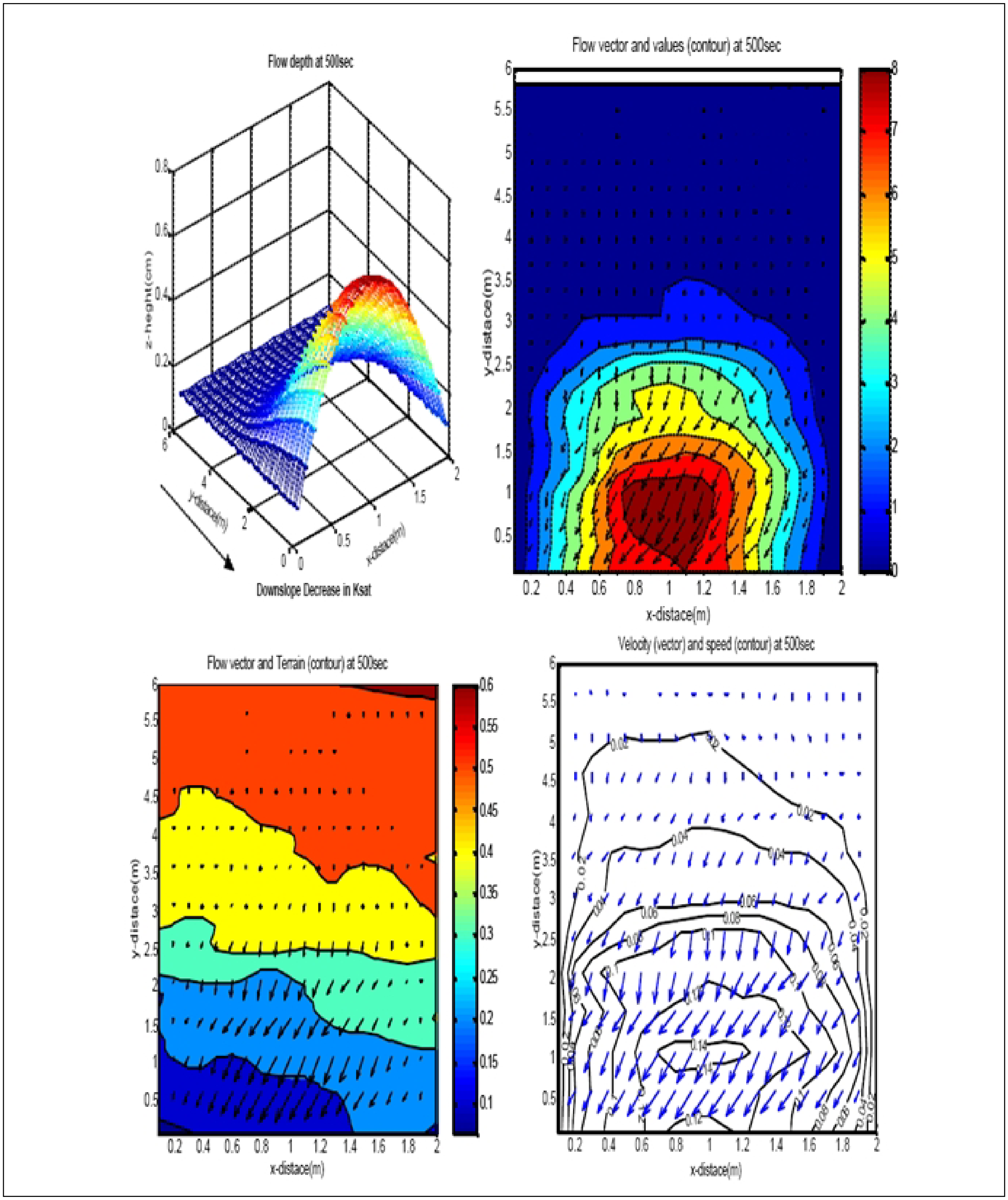

Figure 5. Flow pattern, magnitude and speed for scenario B-“shrinking” scenario at 500s into the high intensity event.

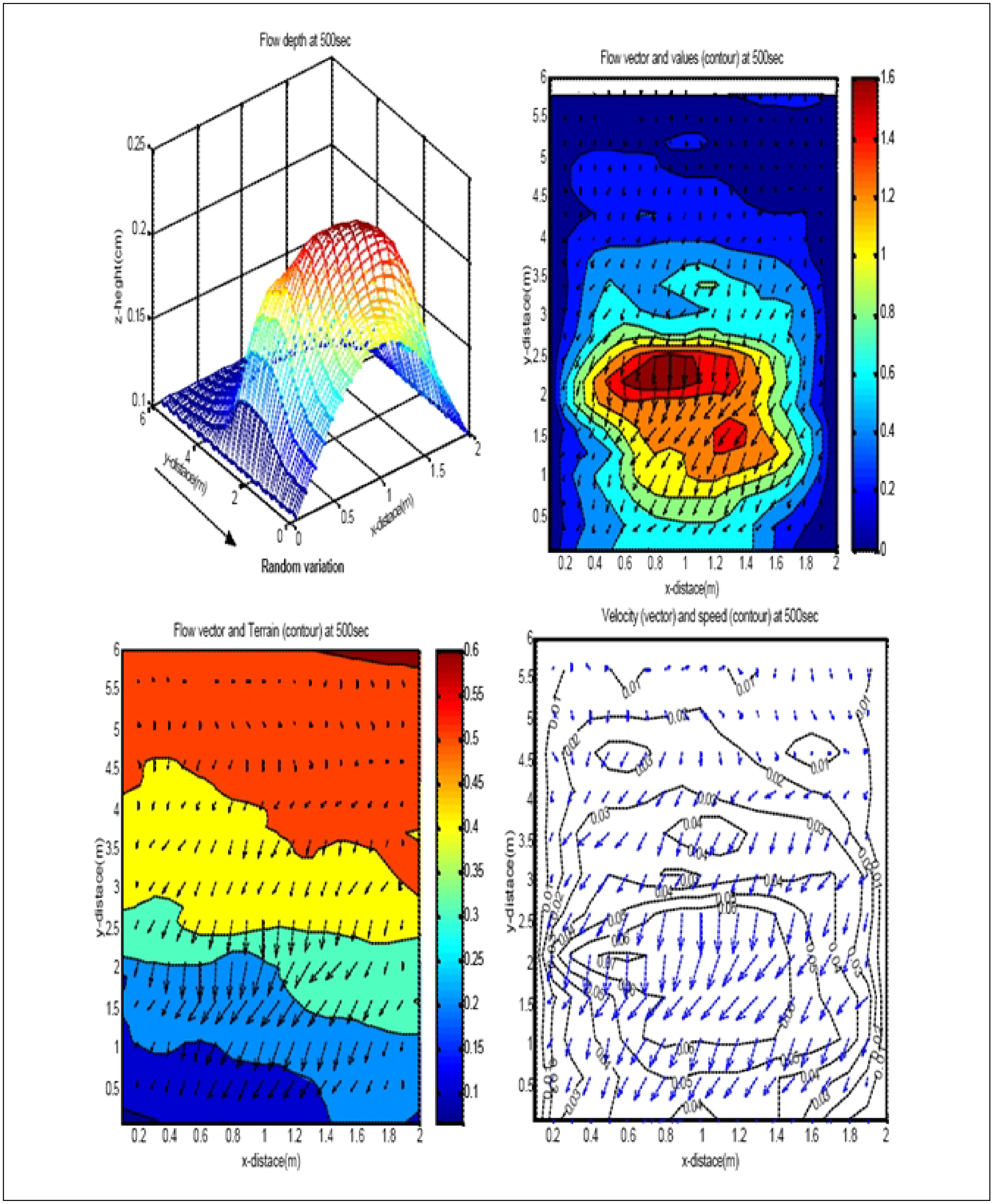

Figure 6. Flow pattern, magnitude and speed for scenario C-“random” variation scenario at 500s into the high intensity event.

To evaluate the effect of hydraulic conductivity difference on unit runoff discharge under different rainfall events, runoff coefficient was calculated by dividing the volume of runoff collected during an event by the plot area. This gives an idea of discharge per unit area and presents a unique parameter for evaluating and comparing the behavior of sites A and B (van de Giesen et al., 2000; Joel et al., 2002). The corresponding runoff plot sizes on the two sites are compared in Figure 7**.**

Figure 7 (a, b) clearly shows marked differences in runoff response at both sites. One clear observation from the result is the obvious effect of travel time on runoff response. Despite similarities in infiltration capacity, short plots generally have higher unit runoff discharge compared to longer plots. This apparently results from the shorter travel time to the discharge point. This observation was similar to the simulation result for the shrinking scenario. Another point of interest was the apparent absence of significant differences in unit discharge for low intensity monsoon events between DOY 175 and DOY 220 in the study area. In spite of the high rainfall depth, the unit runoff discharges were low and similar in all the plots. This was because most of the rainfall infiltrated into the soil. This was also simulated with low intensity event, and further confirmed the efficiency of the model in reproducing field observation. The lack of linearity between infiltration capacity and unit runoff shows that there is a need for adequate representation of spatial structure in explaining the effect of hydraulic properties on runoff

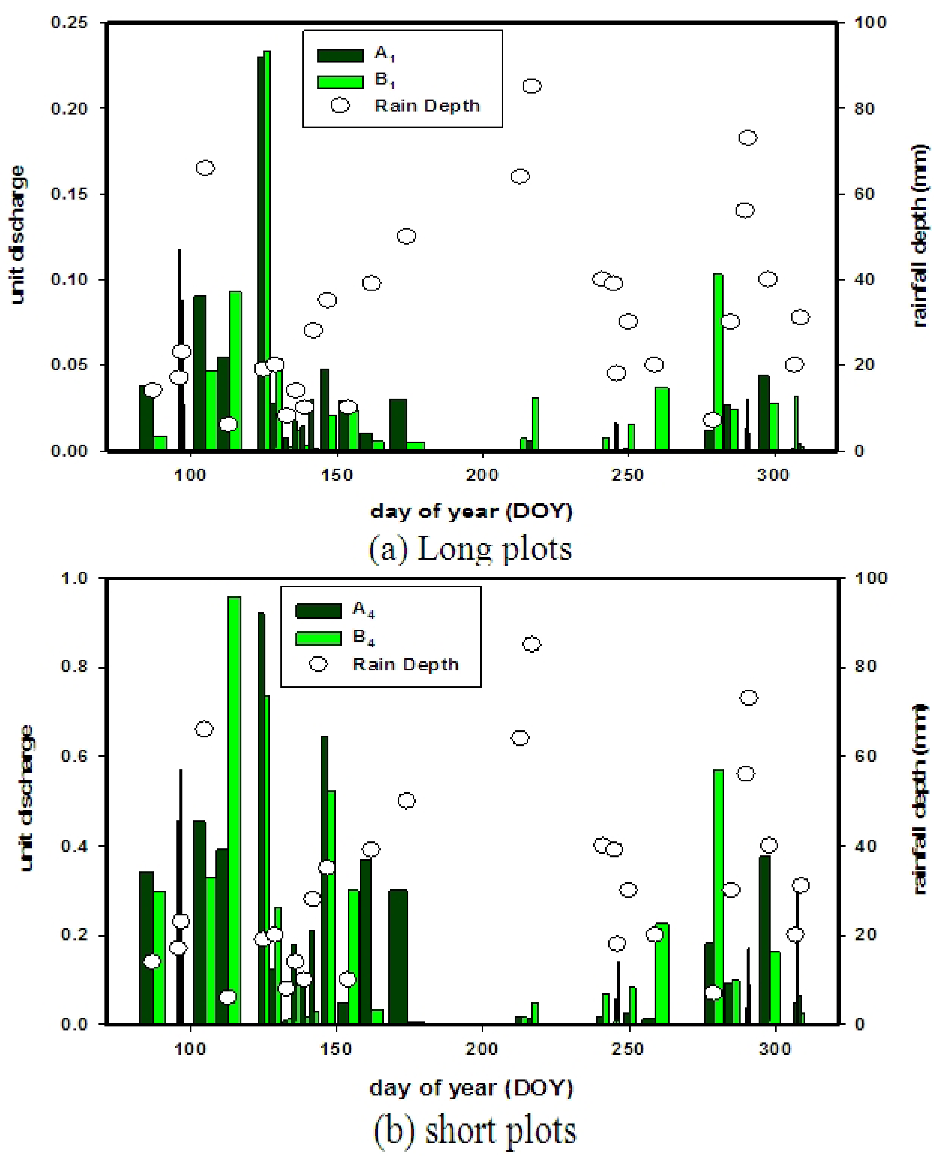

Figure 7. Comparison of unit discharge in corresponding runoff plots at site A and B.

response. It equally shows that some of the hydraulic parameters are dynamic and can change as the season progresses. This result lends credence to conclusions from previous studies (Ajayi, et al,. 2007; Parsons et al., 2006; van de Giesen et al., 2004; Wainwright and Parsons, 2002; Chaplot and Le Bissonnais, 2003; Esteves et al., 2000; Chaplot and Le Bissonnais, 2000) that extrapolation of results from runoff and erosion experiments should be handled with utmost care.

CONCLUSION

The results from both simulation and field trials showed that surface runoff response in terms of flow magnitude and discharge was considerably affected by spatial distribution and orientation of infiltration capacity and slope length. This response could vary depending on rainfall intensity and temporal distribution pattern. Therefore, in describing observations in runoff response such as scale dependency, runoff coefficient, unit runoff discharge, etc., there is the need to consider the temporal dynamics of surface runoff travel, the infiltration capacity and the temporal distribution and intensity of the rainfall event used for numerical simulation or as observed. Using an average intensity may obscure most of these spatio-temporal dynamics. Hence, this study further enhanced the understanding of rainfall runoff dynamics under spatially variable infiltration opportunities, which was made possible by the use of a model that is capable of accommodating heterogeneity in rainfall intensity, as well as the authors adequate knowledge of the field conditions.

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