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SCALE EFFECTS OF HORTONIAN OVERLAND FLOW AND RAINFALL-RUNOFF DYNAMICS: LABORATORY VALIDATION OF A PROCESS-BASED MODEL

T. J. STOMPH,[1]* N. DE RIDDER,[1] T. S. STEENHUIS[2] AND N. C. VAN DE GIESEN[3]

[1] *Department of Plant Sciences, Wageningen University, Wageningen, The Netherlands*
[2] *Department of Biological & Environmental Engineering, Cornell University, Ithaca, NY, USA*
[3] *Center for Development Research, Bonn University, Bonn, Germany*

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ABSTRACT

Hortonian runoff was measured in the laboratory from uniform slopes of lengths of 1·5, 3·0, and 6·0 m for steady, high-intensity rainstorms with durations of 1·0 to 7·5 min. A clear reduction in runoff per unit slope length was found as slope lengths were increased. This effect becomes more pronounced with decreasing storm duration. The runoff data were used to validate a simple process-based model that combines the Philip-two-term infiltration equation with the kinematic wave overland flow principle. The predicted and experimental results agreed well. Laboratory findings were extrapolated with the aid of the model to slopes and rainfall durations similar to those found under West African conditions. The calculated reduction of runoff per unit length is similar to reported observations. Thus, this process-based model can largely explain the phenomenon of runoff reduction with increasing slope length. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: runoff; model validation; laboratory experiments; slope length; scale

INTRODUCTION

In the past 15–20 years, significant progress has been made in the understanding of processes governing the rainfall-runoff processes. However, most hydrological and geomorphologic research and model development takes place in the temperate climate zones. Extensive re-calibration and field experimentation are needed before these research results and models can be used in other climate zones with greatly different rainfall patterns, soils, and vegetation (Bonell and Balek, 1993). This task is expensive and time consuming and may overtax available resources, especially in tropical developing countries. Clearly, adapting process-based models demands much less experimentation than empirical models such as the SCS curve-number method or the Universal Soil Loss Equation. The focus of this paper is on the process of infiltration excess overland (Hortonian) flow, which occurs widely in tropical countries.

Hortonian flow can be found in many parts of the sub-humid and (semi-)arid tropics, such as in West Africa (Rodier and Auvray, 1965; Rodier 1976; Puech and Chabi-Gonnie, 1984), Australia (Williams and Bonell, 1988) and India (Rao *et al*., 1998a,b). Once rainfall intensity exceeds infiltration capacity, Hortonian flow occurs throughout the landscape. Consequently, this type of flow is important for redistribution of water and sediments over the landscape. Runoff plot studies in Côte d'Ivoire (Van de Giesen *et al*., 2000) and in Burkina Faso (Spaan and Stroosnijder, 1997) have shown that not all water that is observed on the surface during a rainstorm reaches the bottom of the hillslope. For example, on small 1 m^2 plots in Côte d'Ivoire as much as 40% of the annual rainfall became runoff, but at the bottom of 100 m hillslopes less than 4% of the rain was found as runoff (Masiyandima, 2000; Van de Giesen *et al*., 2000). The reduction in runoff was also observed elsewhere, such as in Nigeria (Lal, 1983, 1997a,b), Burundi (El-Hassanin *et al*., 1993), and Israel (Yair and Lavee, 1985). The main reason given in the literature for runoff reduction is heterogeneity of

* Correspondence to: T. J. Stomph, Wageningen University, Department of Plant Sciences, Haarweg 333, 6709 RZ Wageningen, The Netherlands. E-mail: tjeerdjan.stomph@cwe.dpw.wag-ur.nl

infiltration capacity (Yair and Lavee, 1985), and increased surface retention of longer hillslopes (Palis *et al.*, 1997). Finally, downhill infiltration of runoff water after the rainfall intensity falls below infiltration capacity also causes reduction of runoff as the slope length is increased (Van de Giesen *et al.*, 2000).

The conditions under which downhill infiltration plays a significant role seem, in the first instance, rather special. One needs high infiltration rates and, subsequently, high rainfall intensities. Water must not move downhill too fast, implying small to moderate slopes and/or high surface roughness. Finally, the hillslopes must be relatively homogeneous, such that heterogeneity effects are unimportant. On granite/gneiss and sandstone geologies in West Africa, which account for 75% of the land surface (Windmeijer and Andriesse, 1993), all these conditions are met. During the field experiments in the region, runoff reduction was found, but owing to technical limitations, only total runoff could be measured after each rainfall event (Van de Giesen *et al.*, 2000). To study the all-important dynamics of the process better, a laboratory flume was built (Stomph *et al.*, 2001). A simple model describing infiltration and overland flow was developed. The objective of this study is to use the flume data for empirical validation of the model and to investigate if this model can reproduce the significant runoff reduction that was found for longer hillslopes.

The usefulness of a validated model is twofold. First, it will facilitate regionalization of runoff and erosion studies. With a valid physical model, one can select proper soil and water management techniques on the basis of terrain properties. Second, the model can help correct standard distributed models that treat each cell as a point and do not account for sub-pixel scale effects.

THEORETICAL CONSIDERATIONS AND MODEL DEVELOPMENT

After rainfall intensity exceeds the infiltration capacity of the soil, the Hortonian overland flow hydrographs can be divided into a rainfall excess phase and a recession-infiltration phase. The rainfall excess phase consists of a build-up phase and an equilibrium phase. The build-up phase begins when rainfall intensity exceeds infiltration capacity and ends when water from the uppermost part of the hillslope reaches the outlet. The build-up phase is characterized by contributions from an increasingly large part of the hillslope to the outlet. When rainfall excess continues, the equilibrium phase starts, during which the full hillslope contributes to the discharge at the outlet. As soon as the rainfall intensity falls below infiltration capacity, the recession-infiltration phase starts. In the recession-infiltration phase, water still flows overland and continues to reach the outlet, but, increasingly, the upper parts of the hillslope fall dry. When rainfall intensity increases again above infiltration capacity, the process repeats itself.

To calculate when runoff starts and to model infiltration during the rainfall excess and recession-infiltration phases, the model of Van de Giesen *et al.* (2000) is used. In this model, the starting time of runoff is based on the time compression approximation (Reeves and Miller, 1975; Mls, 1980). Infiltration is calculated with the Philip-two-term infiltration equation:

$$I_{\mathrm{cum}}(t) = S\sqrt{t} + Mt$$

Once overland flow starts, the infiltration excess water is routed downhill with the kinematic wave equation for overland flow:

$$vh = \sqrt{(\mathrm{slope})}(1/n)h^{\beta}$$

where I_{cum} (m) is the cumulative infiltration since start of the rainfall, t (s) is the time since infiltration started, S (m s$^{-0.5}$) is the sorptivity, M (m s^{-1}) is the effective equilibrium conductivity, v (m s^{-1}) is the average velocity of the overland flow, h (m) is the depth of the water layer, slope is given as tangent of slope angle, $1/n$ (m$^{2-\beta}$ s^{-1}) is the roughness coefficient and β is the kinematic wave exponent related to flow type.

Four parameters need to be calibrated for simulation of runoff hydrographs, namely sorptivity, effective equilibrium conductivity, exponent β in the kinematic wave equation and the roughness coefficient. In previous work, this model was used to compare predicted and observed total cumulative runoff at the end of natural rainstorms in Côte d'Ivoire, West Africa. In this paper we compare complete predicted and observed runoff hydrographs.

MATERIALS AND METHODS: ARTIFICIAL HILLSLOPE EXPERIMENTS

Experimental set-up

The laboratory experiments were conducted on an artificial hillslope in the Department of Plant Sciences at Wageningen University (Stomph *et al.*, 2001). The hillslope consists of five individual sections of 1·5 m length, 1·75 m width and 0·6 m depth that are connected by hinges. A gutter, located between each section at the soil surface level, can either be open or closed off. When a gutter is closed, water can flow unhindered from one section to the next; when open, the sections act as individual run-off plots. By using different combinations of open and closed gutters, one 6·0 m, two 3·0 m, or four 1·5 m slopes could be formed. Only the upper four sections, having a 7·88% slope, were used.

The hillslope was filled with a 0·5 m thick layer of loamy sand (2% gravel >2 mm, 89% sand 50 μm–2 mm, 8% silt 2–50 μm, 1% clay <2 μm, bulk density 1·33 kg l^{-1}). Prior to the current experiments, a rice crop had been grown along the hillslope. Plants were removed with minimal disturbance to the soil surface. Because of previous rainfall applications and applications of a nutrient solution, the soil was slightly crusted. Such crusting is characteristic for West African field conditions (Casenave and Valentin, 1989). The experiments presented were carried out on the bare soil. Soil moisture pressure at the bottom of the soil profile was kept constant by applying suction with an airpump. Soil moisture content was observed at 5, 15, 30, and 45 cm depths in each compartment with the use of dielectric water-content sensors (Hilhorst, 1984).

Rainfall was applied with a moving rod of 27 Unijet TG series nr. 6·5 sprinklers spaced at 0·3 m distance with an average intensity of 200 mm h^{-1}. This relatively high-intensity rainfall is similar to typical intensities measured in West Africa. Actual intensities were measured with a tipping bucket raingauge.

Runoff experiments

Rainfall was applied for 1·0, 1·5, 2·5, 3·75, and 7·5 min. For each of these rainfall durations, runoff was observed in separate experiments from hillslopes of 1·5, 3·0, and 6·0 m. All experiments were carried out in duplicate. In order to minimize the effect of spatial differences between hillslope sections, hydrographs were averaged. The data from the 1·5 m plots are averages of eight runoff hydrographs, namely of the two replicates of each of the four 1·5 m plots. In the same way, the data from the 3·0 m plots are the averages of four runoff hydrographs. The data from the 6·0 m plot are simply averages of the two replicates.

Before starting a series of experiments, the soil was wetted with a rainfall application to improve conductivity of the surface crust. Effects of crust dynamics on infiltration were thus minimized. Before each experiment, the initial soil moisture profile was brought to a standard equilibrium profile by applying rainfall to the surface while maintaining suction at the bottom of the soil profile.

RESULTS

Figure 1 shows the hydrographs of runoff per unit slope length that were observed for the three hillslope lengths monitored and for four rainfall durations. Owing to the representation of discharge on a per-unit-slope-length basis, Figure 1 may give the erroneous impression that runoff starts at a slower rate for longer plots. It can be seen in Figure 2 that hydrographs of total runoff have comparable rising stretches for all plot lengths.

To aid further analysis, three different scenarios of rainfall-runoff dynamics are distinguished (Julien and Moglen, 1990; Van de Giesen *et al.*, 2000). At the end of 1·0 min rainfall, all slopes are still in the build-up phase, i.e. none has reached equilibrium between rainfall and runoff. Scenario I corresponds to this situation in which only the build-up phase is observed. As the rains become longer, equilibrium is first reached on the shorter plot only. For a 1·5 min rain we see that equilibrium is reached on the 1·5 m and has not yet or has just reached equilibrium on the 3·0 m plots. The hydrograph for the 6·0 m plot is clearly still in the build-up phase. Experiments in which short slopes reach equilibrium but long slopes do not reach equilibrium follow Scenario II. Under Scenario III, all hillslopes reach equilibrium phase before the rains stops. Scenario III is illustrated for the 2·5 and 3·75 min rains and is comparable for the 7·5 min rain (not shown; see Figure 4).

The scale effect is produced in the build-up and the infiltration-recession phases, which have different relative importance under the three scenarios. For each of the scenarios, a different scale effect can, therefore,

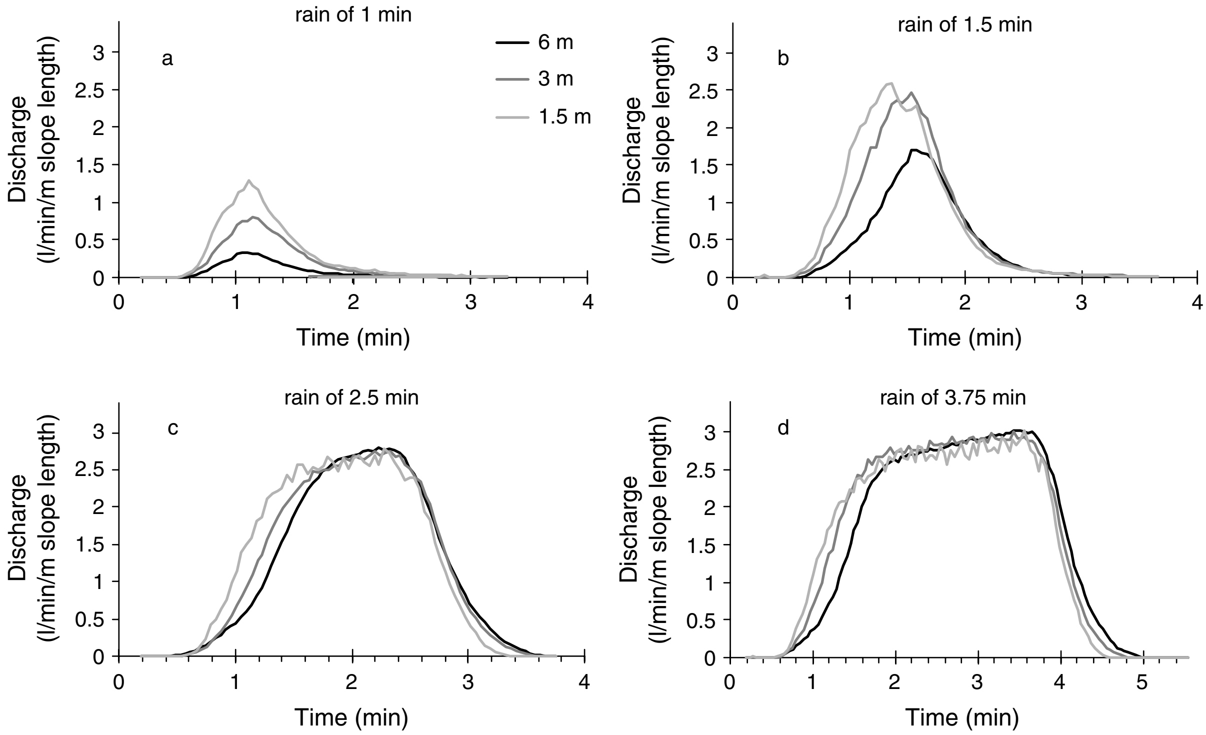

Figure 1. Runoff discharge per unit area (l min^{-1} m^{-1} slope length) from the artificial slope under (a) 1 min, (b) 1·5 min, (C) 2·5 min, and (d) 3·75 min rainfall. The three lines indicate plot lengths of 1·5, 3, and 6 m

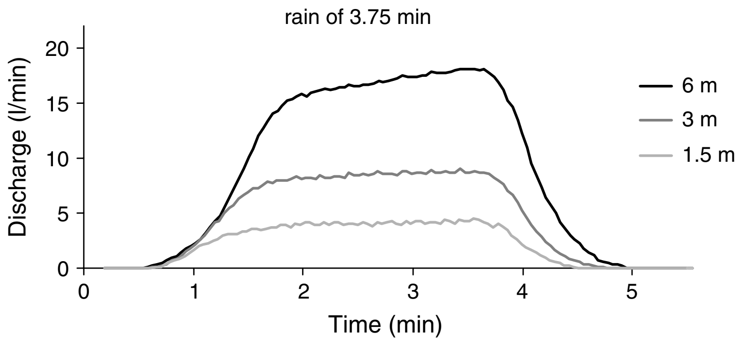

Figure 2. Runoff discharge (l min^{-1}) from the artificial slope under a 3·75 min rainfall event for the three monitored slope lengths (1·5, 3, and 6 m)

be expected. In a Scenario I case, the same plot length contributes to the runoff, independent of total slope length. Theoretically, total runoff will be identical for all plot lengths, which translates into an extreme scale effect. Under a Scenario III case, the full plot contributes to runoff at all lengths and almost no scale effect would be expected. Scenario II cases will give intermediate scale effects. Table I shows clear differences in runoff per unit slope length between plots of 1·5, 3·0, and 6·0 m for rainfall excess periods shorter than 150 s. For periods of rainfall excess exceeding this time, the scale effect gradually declines and eventually disappears. To quantify this effect, the runoff per unit slope length of the 3·0 and 6·0 m hillslopes was divided

Table I. Runoff totals per unit slope length for different slope lengths and rainfall durations

Slope length (m)	Runoff (l m^{-1})				
	1·0 min	1·5 min	2·5 min	3·75 min	7·5 min
1·5	1·53	3·39	5·90	10·61	24·10
3·0	1·06	2·94	5·93	10·46	24·23
6·0	0·58	2·07	5·43	9·84	24·60

by the runoff per unit slope length of the 1·5 m hillslope. We will call this quotient the fractional runoff:

$$\text{Fractional runoff} = \frac{\text{Runoff}_{\text{long plot}}/\text{length}_{\text{long plot}}}{\text{Runoff}_{\text{short plot}}/\text{length}_{\text{short plot}}}$$

The maximum value for the fraction will be unity under conditions of equal runoff per unit area regardless of the length of the hillslopes. These are the conditions under which no scale effect is observed (Scenario III). If total runoff from the longer hillslope equals runoff from the shorter hillslope (Scenario I), the fractional runoff will equal the ratio of the length of the shorter hillslope to the length of the longer hillslope (0·5 for the ratio of 3·0 and 1·5 m hillslopes and 0·25 for the ratio of the 6·0 and 1·5 m hillslopes). In all cases where Scenario II prevails, the fractional runoff will have intermediate values.

Figure 3 shows the fractional runoff as a function of rainfall duration. The fractional runoff approaches unity at longer rainfall durations. The fractional runoff from the comparison of 3·0 and 1·5 m plot lengths is always larger than that from the comparison of 6·0 and 1·5 m plots. It can also be seen that the minimal fractional runoff approaches 0·5 and 0·25 for the shorter periods of rainfall excess.

MODEL ANALYSIS

Model calibration

The model was calibrated on a small number of the experiments. The model was run with combinations of values for effective equilibrium conductivity M (between $1{\cdot}8 \times 10^{-5}$ and $3{\cdot}2 \times 10^{-5}$ m s^{-1} with steps of $2{\cdot}8 \times 10^{-6}$ m s^{-1}), sorptivity S (between 2×10^{-5} and 24×10^{-5} m $s^{-0{\cdot}5}$ with steps of 2×10^{-5} m $s^{-0{\cdot}5}$), kinematic wave exponent β (between 1·7 and 2 with steps of 0·1) and $1/n$ (between 10 and 80 $m^{(2-\beta)}$ s^{-1} with steps of 10 $m^{(2-\beta)}$ s^{-1}). Calibration values for the effective equilibrium conductivity were obtained by minimizing deviations between simulated and observed hydrographs during equilibrium runoff from the

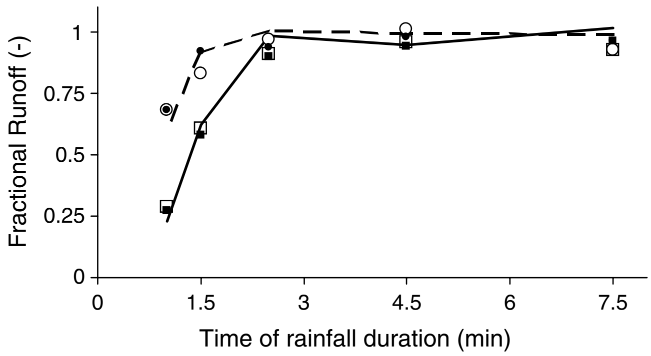

Figure 3. Fractional runoff (see text) as a function of rainfall duration for a comparison between plots of 3 and 1·5 m (○) and of 6 and 1·5 m (□). The data points are observed values from the artificial slope experiment, where open symbols and closed symbols represent different replicates. The lines link simulated values

7·5 min rainfall experiment on the four 1·5 m plots, because sensitivity with respect to M is at its largest under longer rainfall durations. The simulated runoff hydrograph for a 1·5 m plot was compared with the average hydrograph of the four 1·5 m units. The best value for M was $2{\cdot}36 \times 10^{-5}$ m s^{-1}.

Calibration values of the kinematic wave exponent and of the roughness coefficient were obtained by minimizing deviations between simulated and observed hydrographs from one replicate of each of the 1·5 m and of the 3·0 m plots at rainfall durations of 1·5 and 2·5 min. Deviations were minimized by minimizing sums of squares, a method suggested to be appropriate for comparing shapes of simulated and observed hydrographs (Green and Stephenson, 1986). The results were $\beta = 1{\cdot}7$ and $1/n = 20$ m$^{0{\cdot}3}$ s^{-1}. The sorptivity value was left free in this optimization, as small differences in initial moisture profile could not be avoided. The fitted sorptivity values varied between 6 and 20 m s$^{-0{\cdot}5}$ for the individual experiments and did not show a clear relation to the observed moisture contents measured at 5, 15, 30 and 45 cm depths, either for any individual depth or for any combination of depths. Given the presence of crusts, conductivity at shallower depth may have differed initially, but the sensors could not be used at more shallow depths (Hilhorst, 1984).

The model parameters were also calibrated by fitting only simulated total discharge to observed total discharge. The hydrographs that correspond to the best fits from calibration on total discharges were clearly of a different form than the observed hydrographs. Parameter values estimated on the basis of total runoff amounts are apparently not reliable, which stresses the need for hydrograph measurements in the field.

Validation

With the three parameters from the calibrations and with a sorptivity open to variation between experiments, the hydrographs of the other experiments were now simulated. Figure 4 shows the observed and simulated hydrographs. The closeness of fit is generally satisfying. Largest deviations are observed for the very short rains (60 s). During these short rains a very thin water layer can be expected, and rainfall increases turbulence of the overland flow water for only a very short time. It can be expected that β increases, as laminar flow becomes more important under these conditions (Singh, 1996). Modelling β dynamically would possibly improve closeness of fit for these very short rains. The model is aimed at estimating the runoff reduction that can be expected under different conditions. As runoff from larger storms is most important, there seems little advantage in the kind of improvement that can be expected from inclusion of a dynamic β. The comparable trend in simulated and observed values of the fractional runoff at increasing hillslope length and rainfall excess period (Figure 3) is an indication that the model contains the most relevant elements of the processes that cause the scale effect along homogeneous hillslopes.

Extrapolation to longer hillslopes and rainfall durations using the simulation model

The results presented on simulation of runoff hydrographs and on the trend in fractional runoff concur with previous total discharge measurement results for hillslopes of 1·25 m and 12 m in West Africa (Van de Giesen *et al.*, 2000). It is important to know if this phenomenon, modelled and validated for a short hillslope of 6·0 m, can indeed explain the strong scale effects in total runoff observed at longer hillslopes in the region. We used the model to explore the effects of hillslope lengths between 1·25 and 500 m and of rainfall events with a rainfall excess duration between 30 s and 25 minutes on fractional runoff per unit area. In the simulations, we further used the slope angle of the artificial hillslope and values for $\beta = 1{\cdot}7$, $1/n = 60$ m$^{0{\cdot}3}$ s, $M = 2{\cdot}36 \times 10^{-5}$ m s^{-1}, and $S = 12 \times 10^{-5}$ m s$^{-0{\cdot}5}$. Figure 5 shows the plot of the simulated fractional runoff against both duration of rainfall excess and slope length. The resulting surface shows that, for longer slopes and longer periods of rainfall excess, a substantial reduction in runoff per unit area can be expected even for the conditions used in the simulations that correspond to a rather low roughness, a steep slope (7·88%) and constant rainfall intensity. In typical West African situations, the scale effect would be more pronounced owing to the more moderate slopes and higher surface roughness. The constant rainfall would, in reality, be much more irregular, with several peaks and troughs. Rainfall intensity may even temporarily drop under infiltration capacity, causing a recession-infiltration phase within a rainstorm. The effect of several recession-infiltration and build-up phases would again be that the scale effect under natural conditions is larger than simulated here.

It should be stressed that these extrapolations are a necessary but not sufficient test for our working hypothesis, that temporal dynamics may indeed produce a pronounced reduction in fractional runoff per unit

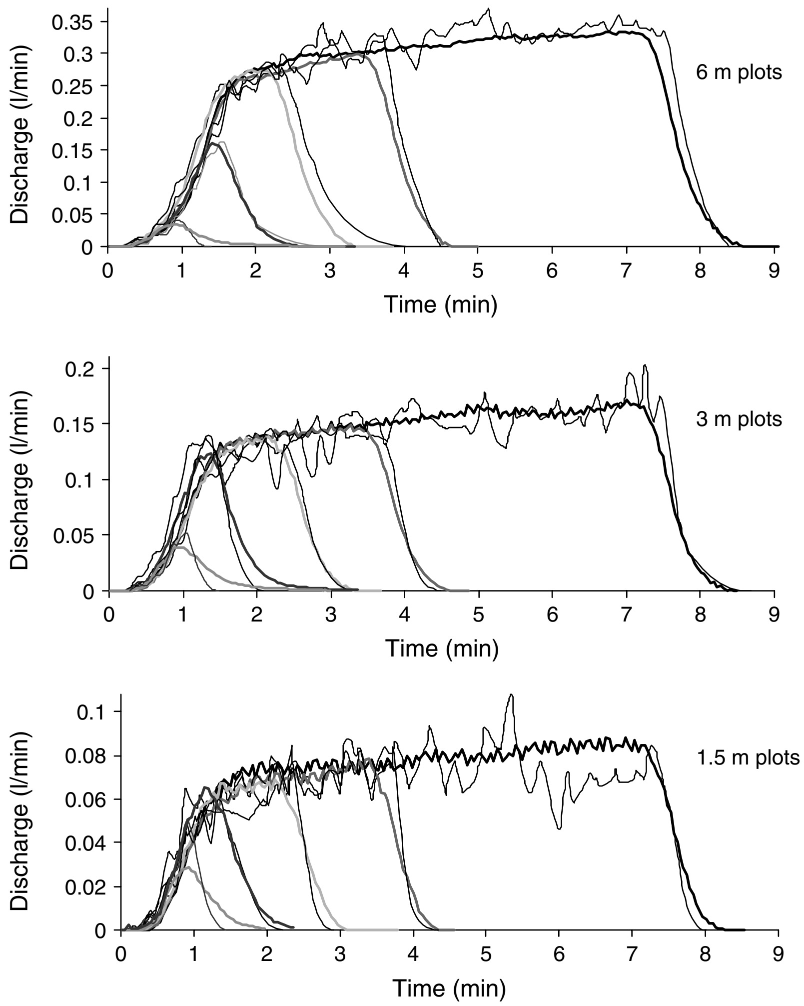

Figure 4. Observed (thick lines) and simulated (thin lines) runoff hydrographs at rainfall durations of 7·5, 3·75, 2·5, 1·5, and 1 min for (a) 1·5 m, (b) 3 m, and (c) 6 m slope length

area. Clearly, if extrapolation had only shown minor reductions for longer hillslopes, further modelling and laboratory work would have been needed. The present results make it possible to design follow-up field experiments to verify the modelling results on longer hillslopes.

DISCUSSION AND CONCLUSIONS

We found that scale effects on runoff also occur along homogeneous hillslopes. The theoretical considerations presented by Julien and Moglen (1990) and by Van de Giesen *et al.* (2000) were shown to be at the base of this scale effect. For this reason, we can conclude that the scale effect is related to the differences in time needed to reach the equilibrium phase in the hydrograph. An extended residence time of overland flow on a hillslope of greater length can explain to a large extent a substantial reduction of runoff per unit length. The residence time changes with slope length and with resistance to overland flow. The third variable that determines the scale-dependent reduction is the duration of the rainfall excess.

Earlier, we showed that a simple model, combining a Philip-two-term infiltration module and a kinematic overland flow module, simulates differences in total discharges between plots of different lengths under field

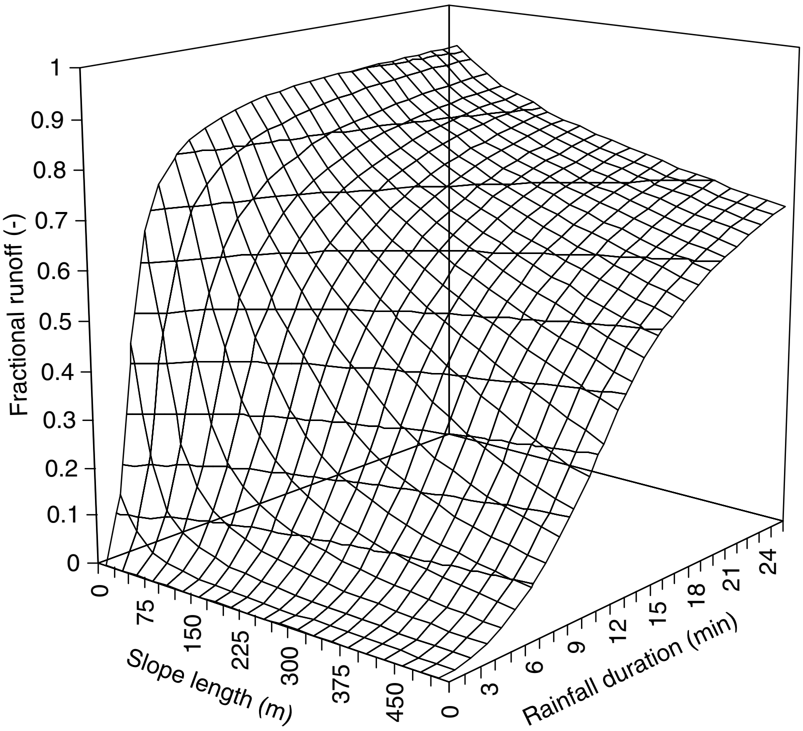

Figure 5. Graph of simulated fractional runoff (see text) as a function of slope length and rainfall duration. The shorter plot is always taken to be 1·5 m length, the length of the longer plot is as indicated in the graph

conditions and natural rain (Van de Giesen *et al.*, 2000). However, simulating total discharges is a poor check of a dynamic process simulation model. In fact, we found that optimization of the minimum difference between simulated and observed discharge totals often yields combinations of parameter values that result in poor fits to the hydrographs. Now, we have shown that the model does indeed simulate runoff hydrographs well for the different combinations of plot lengths and periods of rainfall excess. The model combines the most essential processes necessary for an analysis of possible effects of different factors that influence residence time along hillslopes of different lengths. Ideally, one would rely on independent and direct observations of different parameters, such as water velocity and depth, which, however, remain difficult to measure. Given that all major processes are included, the model may serve to tackle the problem of scaling-up experimental results in water and sediment transport from research plots to landscape (Van Noordwijk and Ong, 1996).

Water and erosion management techniques affect parameters such as surface roughness, slope, and slope length. The effect of water and erosion management on surface runoff depends on how the fractional runoff (Figure 5) changes with changes in the parameters. At present, hardly any quantitative information is available on the effect of crop cover, agricultural practices and simple soil and water conservation techniques on the critical parameters. Many experiments have been undertaken to assess the overall effect of cultural practices, but rarely are observations included that enable estimation of the relevant parameters (Kiepe, 1995; Paningbatan *et al.*, 1995). Runoff hydrograph observations from different slope lengths can provide information on parameter values. Process-based simulation models, such as the one presented here, can subsequently be used for up-scaling and regionalization of results from small experimental plots.

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