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Journal of Hydrology 248 (2001) 183–197

Journal of Hydrology

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Analysis of sources of variability of runoff volume in a 40 plot experiment using a numerical model

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Received 28 March 2000; revised 9 April 2001; accepted 17 April 2001

Abstract

Runoff volumes from field plots can be quite variable, but the reasons for this variability are not completely understood. Such variations can be important for understanding the hydrologic system, and for evaluating the effectiveness of infiltration, runoff and sediment models. In this study, we investigated the sources of variability among 40 replications in a previously reported experiment on fallow plots located on a claypan soil in Missouri, USA. A numerical model was calibrated using data from the experiment and from other published data on the variability of soil properties. The results describe qualitatively the trend in the observed relationship between the coefficient of variation (CV) and mean runoff volume per event, as well as the lack of stability in time of the relative differences in runoff volume among plots. Quantitatively, approximately 50% of the observed coefficients of variation among the replicated plots were explained by the spatial variability of K_s, surface storage, and the depth to claypan. The remaining 50% may be due to the variability in rainfall among plots, measurement error in runoff, the fact that some published rather than site specific information was used in the analyses, and simplifications introduced in the modeling process. Our results suggested that changes in the relative differences in runoff volumes between plots during the season might be explained by the modification of the spatial distribution of K_s and surface storage which occurs during tillage. The introduction of these sources of variability in the model formulation produced a realistic description of the variance of the observed values of runoff volume, as well as a relatively clear delineation between the explained and unexplained variability. The results may also serve as an index of model performance in predicting observed data. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Runoff; Infiltration; Variability; Numerical models; Hydraulic conductivity

1. Introduction

Data from runoff plots show a large variability. Rüttimann et al. (1995) reported a coefficient of variation (CV) for seasonal runoff volume ranging from 30 to 50% using three replications of runoff plots per treatment. This CV was in the same general range of magnitude as that reported by Wendt et al. (1986) using 40 replicated plots, wherein the observed CV for seasonal runoff volume was approximately 30%. It has been suggested that the magnitude of the observed CV should decrease as a function of increasing plot size (Bryan 1979; Luk and Morgan, 1981). However, Rüttimann et al. (1995) analyzed published CV values for plots of areas ranging from 0.0929 to 87.68 m^2 and did not find such a relationship apparent in those data.

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PII: S0022-1694(01)00402-4

Attempts to relate the observed differences in runoff between the replications to differences in soil properties were unsuccessful in the studies of Hjemfelt and Burwell (1984) and Wendt et al. (1986), even though an extensive soil-testing program was undertaken. Also in the study of Hjemfelt and Burwell (1984), the relative differences between replications did not persist in time. This result was corroborated by Rüttimann et al. (1995). If one plot yielded more runoff than another in one particular event, the differences could be reversed in another event. Wendt et al. (1986), analyzing the correlation of plot runoff among events, attributed this erratic behavior, in part at least, to the modification of soil surface properties by tillage.

The main consequence of the relatively high level of unexplained CV is the requirement of a large number of replications in the experimental design in order to have statistical significance of the results (Hudson, 1997). As a corollary, small differences in experimental work are difficult to detect. The large variation of replicates also hinders evaluation of simulation models. Unless one has some knowledge of the variability in observed data, it is difficult to delineate that portion of the observed error coming from the model prediction from that coming from the unexplained variability in the data (Nearing et al., 1999).

Freeze (1980) estimated the spatial variability of 20 soil properties or profile characteristics to implement a hydrologic model using the Monte Carlo method to analyze its impact in the variation of runoff at the hillslope scale. In a similar way, Binley et al. (1989) explained with a physically based model the runoff production on heterogeneous hillslopes. Smith and Herbert (1979) also performed a Monte Carlo analysis of the hydrologic effects of spatial variability of infiltration. The objective of these modelling studies was to get insight of the role of spatial variability in the hydrological response of the hillslopes. Apparently, they fulfilled their goals, despite the fact that without knowledge of the spatial dependence scale 'a rigorous treatment of watershed hydrology with spatially distributed properties is not possible' (Smith and Herbert, 1979). The results of the previously cited works showed how this spatial variation might lead to significant differences among hillslopes that are similar in terms of their average properties. Significant efforts have been made in the characterization of the spatial variation of either infiltration rate (De Roo et al., 1992) or hydraulic conductivity (Woolhiser et al., 1996; Gupta et al., 1998), affecting the variability of runoff. There are many reports on the large CV values under field conditions for both infiltration rate (Starr, 1990; Vieira et al., 1981) and hydraulic conductivity (Bosch and West, 1998; Gupta et al., 1993; Logsdon and Jaynes, 1996).

The objective of this study is to improve our understanding of the variability in runoff volume in field plot experiments. For this, we used a physically based model of runoff generation, and the results from 40 replicated plots presented previously (Hjemfelt and Burwell, 1984; Wendt et al., 1986). The spatial variation of soil properties was inferred from published values to estimate the impact on runoff variability from three main sources of variability: hydraulic conductivity, surface storage associated with random roughness, and depth to the claypan. We also improved the extrapolation and prediction capabilities of the numerical model by taking into account the spatial variability of these sources of variability. The inferences from modeling and field studies can be different due, among other reasons, to the degree of simplification of the models used or assumptions made in the calibration process. In the author's opinion, the possibility of compare the results of our simulation analysis with the observed results first reported and analyzed by Hjemfelt and Burwell (1984) could help to improve further field or modeling studies on this subject.

2. Materials and methods

2.1. Observed data

Wendt et al. (1986) recorded the runoff generated in a 40-plot experiment located near Kingdom City, MO. The data was collected in 1981 (Table 1). Each plot was 3.2-m wide and 27.4-m long, oriented parallel to the steepest line of a slope of 0.03–0.035 m m^{-1}, and separated by a 2.13-m wide border strip. The 40 plots were arranged in two lines occupying an area of approximately 140×100 m^2. The soil was a Mexico silt loam, with a slowly permeable layer of illuvial clay (claypan) beginning at depths between 0.2 and 0.3 m. A complete description of this experiment can

Table 1
Observed rainfall and runoff for the experimental site

Event	Rain date	Rain amount (mm)	Mean runoff (mm)	Runoff CV (%)
Moldboard plowed and disked	3/24–27			
1	4/11	38	0.43	65
2	4/14	8	0.22	87
3	4/19	30	0.91	89
4	4/12–22	43	12.75	26
Spike harrow	4/28			
5	5/9–10	47	1.98	109
6	5/17–19	96	47.52	27
7	5/23–24	18	2.44	38
Field cultivate	5/29			
8	6/1	27	1.90	56
9	6/4	10	0.41	49
10	6/5	5	0.36	50
Field cultivate	6/9			
11	6/16	18	3.23	27
12	6/20	17	6.40	20
13	6/22	70	50.11	18
14	7/1	31	9.96	13
15	7/2	27	22.02	11
16	7/5	24	18.62	7
Field cultivate	7/7			
17	7/18	95	56.65	18
18	7/20	21	16.43	22
19	7/23	96	78.56	17
20	7/25	32	28.75	9
21	7/26–27	33	24.69	20
22	7/28	13	7.47	20
Field cultivate	7/31			
23	8/25	26	1.27	46
24	8/31	25	8.13	18
25	9/13	18	4.14	20

be found in Wendt et al. (1986) and additional comments in Jamison et al. (1968). Rainfall was collected using one recording and one standard rain gage, both 0.2-m in diameter, located at the center of the area covered by the 40 plots. The accuracy of both rain gages was $0.5\ \mathrm{l\ m^{-2}}$ (Brakensiek et al., 1979).

2.2. Hydrologic modeling

An infiltration-runoff model was used to examine the differences caused by the spatial variability of hydraulic conductivity, surface storage, and depth to claypan. The model has two major components for rainfall excess generation and surface runoff computation, respectively.

The infiltration algorithm is based on the Green and Ampt equation adopting the time condensation approach (Reeves and Miller, 1975) whose reliability has been recently confirmed by Parlange et al. (2000). The soil is divided in four layers of 0.15-m depth each one. At the surface, hydraulic conductivity is reduced whenever a crust is developed according to the expression of Risse et al. (1995)

$$K_{\mathrm{bare}} = K_{\mathrm{b}}(\mathrm{CF} + (1 - \mathrm{CF}))\,\mathrm{e}^{-CE_{\mathrm{a}}(1-\mathrm{RR}/4)} \qquad (1)$$

where K_{bare} and K_{b} are the effective hydraulic conductivity for any given event and the baseline hydraulic conductivity, respectively, [L T^{-1}]. CF is a dimensionless crust factor ranging from 0.2 to 1.0, C is a soil stability factor [M^{-1} T^{2}], E_a is the cumulative kinetic energy of the rainfall [M T^{-2}] since the last tillage operation, and RR is the random roughness [L] of the soil surface. The model divided the area into square cells of 1×1 m^2, and used distributed parameters of saturated hydraulic conductivity K_s, random roughness, and depth to claypan for every cell.

Surface runoff was computed by routing the excess water in the cell using slope and aspect. The slope of 0.0325 m m^{-1} was homogeneous for all cells, oriented in the same direction for all cells. The assumption of a constant slope results in predicted fluxes only in one dimension in the downslope direction. A mass balance equation similar to that of the ANSWERS model (Beasley et al., 1980) was used

$$\frac{dS}{dt} = q_e + R - i - q_s \tag{2}$$

where S [L] is the water level on surface, q_e [L T^{-1}] the upstream runoff into the cell, R [L T^{-1}] the rainfall intensity, i [L T^{-1}] the infiltration rate of the cell, and q_s [L T^{-1}] is downstream runoff flow rate. This equation was solved in an explicit scheme using a fourth-order Runge–Kutta method with adaptive step-size (Press et al., 1986). This model has been validated using KINEROS (Woohiser et al., 1990) and field data (Gómez, 1998; Gómez et al., 2001).

The model works on an event basis. The initial soil moisture content for each rainfall event was estimated since no field data were available. The assumed initial soil water content of 0.25 m^3 m^{-3} for the day of first tillage was updated throughout the season. Infiltration rates were computed from the recorded rainfall and runoff rates, whereas the evaporation rates were determined using the FAO methodology for a bare soil (Allen et al., 1998) from the daily temperature measured in a nearby weather station. Four 15 cm soil layers were used. Soil water evaporation was restricted to surface layer (Allen et al., 1998). The increase in soil moisture due to infiltration was computed assuming a uniform depth of the wetting front. Water redistribution in the profile was by downward fluxes, when soil water content was greater than that corresponding to a reference value of the matric component of water potential of -33 J Kg^{-1}. Water redistribution was fixed at a value $q = K(\theta_{-33})$, where $K(\theta_{-33})$ is the soil hydraulic conductivity at the same reference state (Kutílek and Nielsen, 1994). Since the rainfall–runoff model and the update of the soil moisture were not coupled, only an average initial soil moisture content for each date was computed for the 40 plots, to reduce the large computation effort involved.

2.3. Model calibration

The model was calibrated for an average soil profile at the site. Surface storage was calculated using the Onstad (1984) model with random roughness values proposed in the Water Erosion Prediction Project (WEPP) technical documentation (Flanagan and Nearing, 1995). These values were modified by the rainfall in the manner described by Potter (1990), which considers the cumulative rainfall depth since last tillage. A uniform Manning's coefficient was used in all the events with the values suggested by Engman (1986). A soil profile with four layers was described using the values for the Mexico soil at this location in the WEPP soil database. From this source, volumetric soil moisture content at different soil matric potentials, particle size distribution, CEC and saturated hydraulic conductivity were obtained. Depth to claypan and plot slope were collected from a previous survey of the experimental plots (Wendt et al., 1986), and thickness of the soil layers below the surface horizon were taken from the WEPP soil database for Mexico soil series. The matric potential below the wetting front was calculated according to Rawls and Brakensiek (1989). In order to obtain the best possible agreement between observed and simulated runoff, the value of the freshly tilled, hydraulic conductivity, K_b, was adjusted by minimization of mean square error between observed and simulated runoff for the 25 events reported by Wendt et al. (1986). The parameters used in Eq. (1) for computing the decrease of surface hydraulic conductivity due to crusting were selected according to the WEPP technical documentation procedure (Flanagan and Nearing, 1995). The hydraulic conductivity of the claypan layer was calculated using the ratio between surface and claypan layer K_s in the

Table 2
Selected parameters for the numerical model

Parameter	Layer 1	Layer 2	Layer 3	Layer 4
Bottom depth of soil layer (cm)	24.3	35.5	63.5	109.2
Initial K_s (mm/h)	1.2	0.18	0.18	0.18
CF	0.48			
$\theta_{\text{saturated}}$ (%)	50.6	42.5	45.1	38.9
θ_{-33} (%)	35.9	40.6	44.1	40.6
θ_{residual} (%)	7.3	14.2	17.0	15.2
CEC (meq/100 g)	24.9	34.0	44.0	34.0
Clay (%)	24.5	42.5	55.0	55.0
Silt (%)	69.1	35.0	28.3	28.3
Slope (%)	3.25	–	–	–

WEPP soil database. The adjusted parameter was the initial K_s for soil layer 1 (Table 2) to obtain the results in Fig. 1, where a comparison between simulated and observed average runoff of the 25 events is shown. The observed regression is not significantly different at the 95% probability level of the 1:1 line of perfect agreement. A summary of the most important parameters appears in Table 2.

2.4. Generation of maps of spatially variable soil properties

Maps of spatially distributed random roughness (used to calculate surface storage), depth to claypan, and K_s, were created following the method of Freeze (1980). The procedure is based on the generation of values, Y_{ij}, for each cell. For K_s, $Y_{ij} = \log S_{ij}$, and for the random roughness and depth to claypan $Y_{ij} = S_{ij}$, where S_{ij} is the soil property. Y_{ij} was taken from the normal probability distribution $N[\mu_y, \sigma_y, \alpha_y]$ where μ_y is the mean of Y_{ij}, σ_y its standard deviation, and α_y is an autocorrelation parameter that appears in Eq. (3)

$$\rho_Y(l) = e^{-\alpha_Y|l|} \tag{3}$$

where ρ_Y is a spatial autocorrelation index of the Y parameter that is related to distance, l. Freeze (1980) showed the mean was the most important parameter affecting the runoff generation, followed by

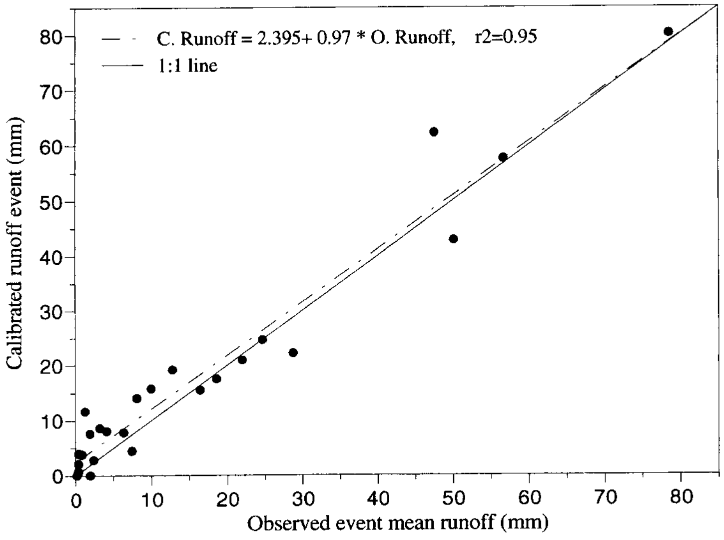

Fig. 1. Regression of calibrated vs. observed event runoff.

Table 3
Summary of values used for the generation of spatially variably maps of soil properties

Property	CV (%)	α	Source	Description
Saturated hydraulic conductivity	43.6[a]	0.6	Gupta et al. (1993)	Rainfall infiltrometer on 1×1 m^2 sampling area
Depth to claypan	9.1	0.2	Wendt et al. (1986)	Soil cores measurements in experimental plots
Surface storage	18.5	0.6	Potter (1990)	Average of 12 experiments using 1×1 m^2 plot size

[a] Note that this CV corresponds to the mean and standard deviation of the log K_s.

the standard deviation and finally the autocorrelation parameter.

Different maps were prepared using the random number generator of Mejia and Rodriguez-Iturbe (1974). The maps indicated the values of the ratio of A_{ij}/A_{mean}, where A_{ij} is the cell value for the selected soil parameter and A_{mean} is the average value for the whole area. These maps were 140×100-m in size, representing an area equivalent to that which contained the forty plots. The grid space was 1 m, which correspond to one generated value for each cell used in the numerical model of runoff generation. From these larger maps, forty maps of 3×28 m^2, the size of the experimental plots, were selected according to the plot configuration, size, and spacing in the field experiment. Thus, given the 1-D nature of the model calculations, each plot is effectively treated as tree heterogeneous planes in parallel. The required values for generating the larger maps were selected from different sources summarized in Table 3. Mean and standard deviation of depth to claypan were taken from a previous soil survey (Wendt et al., 1986) in the same plots, and the autocorrelation coefficient, α_y, was assumed to be 0.2. This value introduces spatial autocorrelation in the simulated values approximately up to 10 m. The mean value of log K_s was from the calibrated K_s (discussion above).

The CV of the logarithmic values of K_s was chosen from Gupta et al. (1993), who determined it by measuring an area of an extension similar to that used in the simulation of the larger maps containing the 40 plots. They performed their measurements using a rainfall simulator with a sampling area of 1×1 m^2. An α_y value of 0.6 was used assuming spatial autocorrelation up to 4–5 m. This is in the range of reported range of reported spatial autocorrelation of K_s on tilled soils (Logsdon and Jaynes, 1996; Diiwu et al., 1998). The random roughness values were generated with the average values also used in calibration, and the CV was set at the average value reported by Potter (1990) for 12 different experiments on a 1×1 m^2 plot size. The autocorrelation value for random roughness was the same used for K_s.

3. Results

3.1. Observed data

Fig. 2 shows the observed CV in plot event runoff for the study of Wendt et al. (1986). The magnitude of CV was greater for the smaller runoff events, but still significant, at approximately 20%, for the larger runoff events. Fig. 3 shows the time stability parameter, λ, and its 90% confidence interval bars. This parameter is defined according to Starr (1990) as

$$\lambda_{ij} = \frac{X_{ij}}{\bar{X}_j} - 1 \tag{4}$$

and

$$\bar{X}_j = (1/n)\sum_{i=1}^{i=n} X_{ij} \tag{5}$$

where X_{ij} denote the values of runoff at different plot locations (i) and different times (j), over n number of events. Only events without missing runoff data were used. Starr (1990) and Vachaud et al. (1985) evaluated

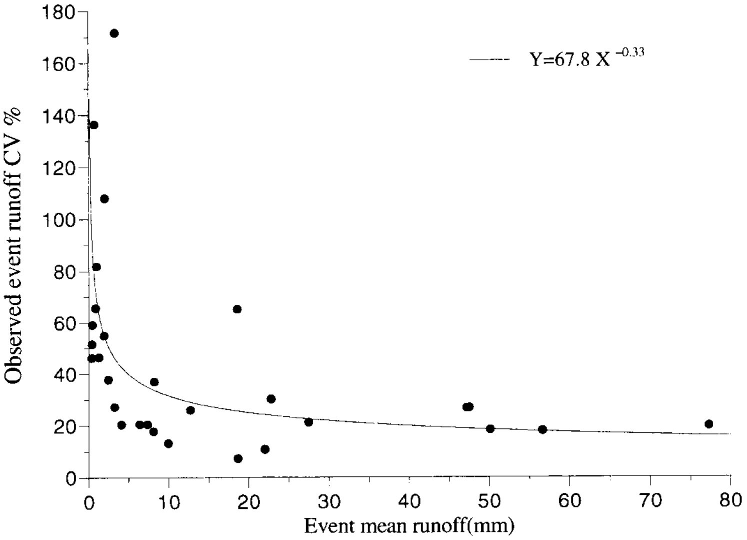

Fig. 2. Relationship between observed event runoff CV and mean runoff event.

with this parameter the temporal stability of spatial differences in several soil properties. The parameter λ should be interpreted as an index of the persistence in time of the relative differences among plots. If these differences are not stable, i.e. if at times plot A generates more runoff than B and at other times less, the bars representing the λ values for the plots will overlap. Many of the plots range between the 90% confidence intervals showing none or very small significant differences, which indicates a lack of stability in time of the relative differences in runoff among the plots.

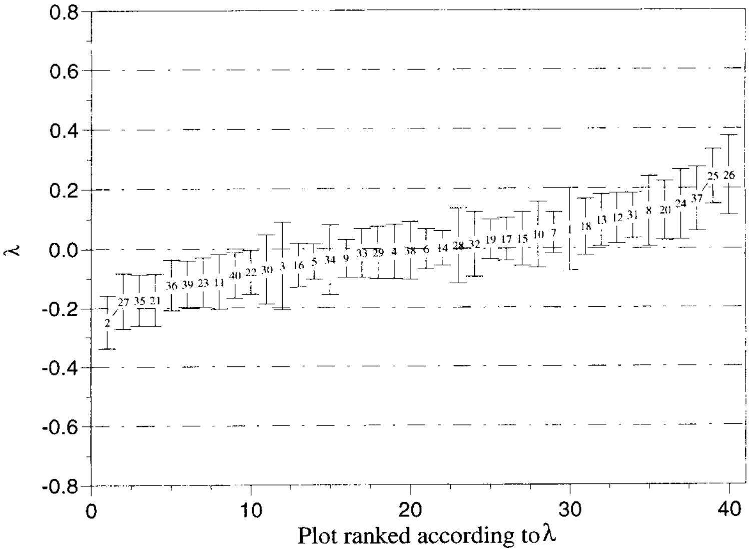

Fig. 3. Ranked time stability parameter, λ, computed using the observed runoff from the 40 plots. Vertical bars correspond to 90% confidence limits. Numbers refer to plot code.

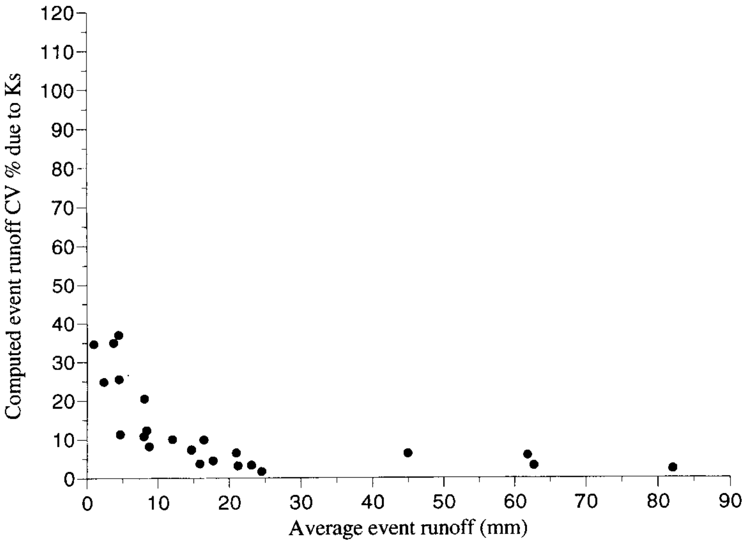

Fig. 4. Relationship between event runoff CV, from simulated runoff values, and mean runoff event when only K_s is considered spatially variable.

3.2. Simulated data

Initially, we generated a map for K_s, depth to claypan, and surface storage for all of the forty plots as discussed above and used those maps to simulate the 25 events. Figs. 4–6 show the CV using only one of these three properties as the source of variation, and the calibrated average value for the other two. The spatial variability of K_s (Fig. 4) results in the greatest CV of the runoff and maintains its significance for the large runoff events. Differences due to surface storage (Fig. 5) are relatively important in small runoff events

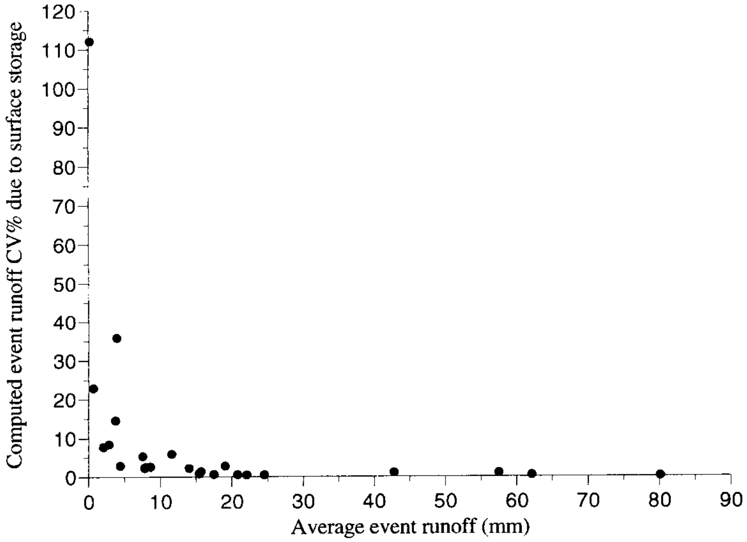

Fig. 5. Relationship between event runoff CV, from simulated runoff values, and mean runoff event when only random roughness is considered spatially variable.

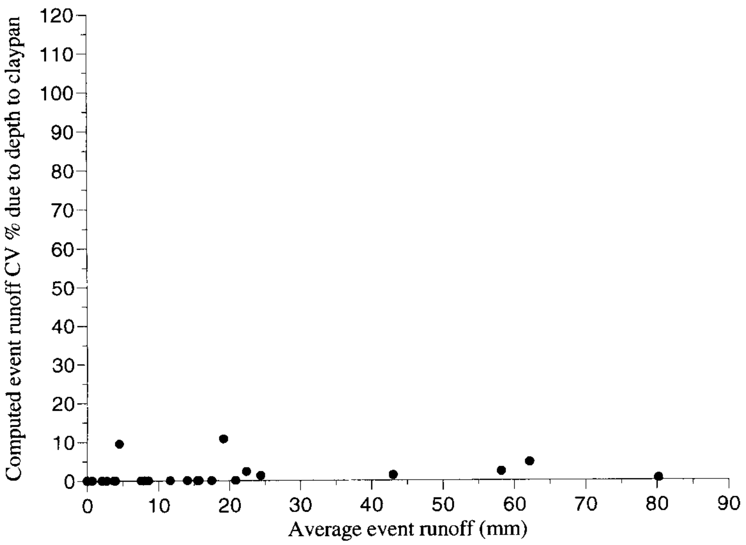

Fig. 6. Relationship between event runoff CV, from simulated runoff values, and mean runoff event when only depth to claypan is considered spatially variable.

and less so in the large ones. In our simulations, depth to claypan (Fig. 6) appears as a source of variability only in events related to high initial soil moisture content or large infiltration, with values of CV ranging from 0 to 10%. Of the four storms that showed a response to variability in depth to claypan, two of those storms had the greatest rainfall depth value of all the 25 storms, and the other two had the greatest initial moisture content. When the three sources were considered together we obtained the CV for runoff shown in Fig. 7. The simulated CV was approximately 50% of that observed (Fig. 2).

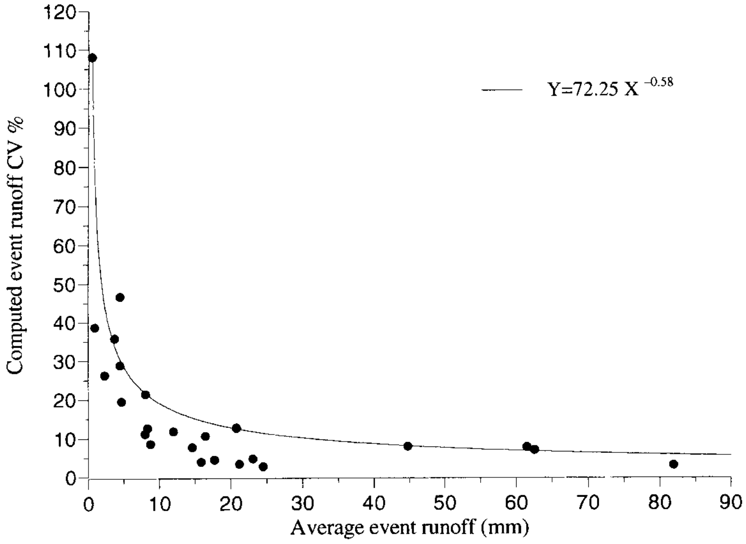

Fig. 7. Relationship between event runoff CV, from simulated runoff values, and mean runoff event, when K_s, random roughness and depth to claypan are considered spatially variable.

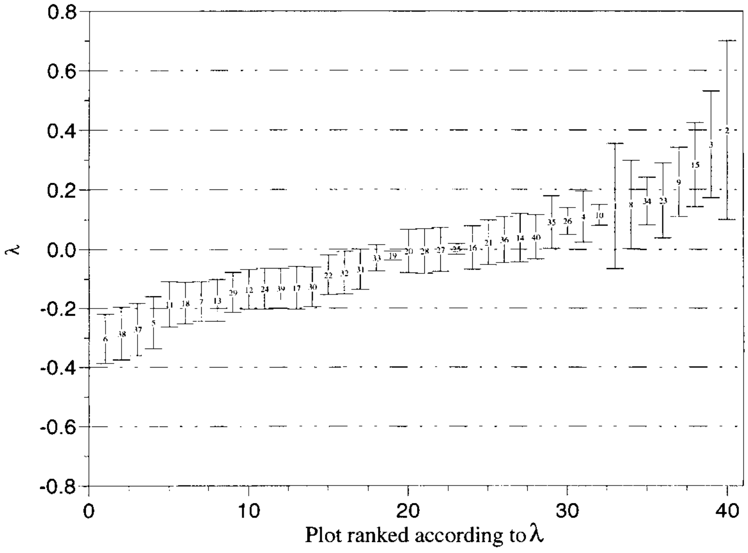

Fig. 8. Ranked time stability parameter, λ, computed using the simulated runoff from the 40 plots without changing the spatial variability maps of random roughness and K_s after each tillage operation. Vertical bars correspond to 90% confidence limits. Numbers refer to plot code.

There was an observable difference in the time stability parameter, λ, for the observed data (Fig. 3) and the simulated data (Fig. 8). The simulated values showed greater time stability than did the observed, with plots significantly different in runoff production for the entire set of events. As previously commented, Wendt et al. (1986) showed how the correlation in the differences among plots changed after tillage operations. Based on this, and the results of Logsdon and Jaynes, (1996) showing how the tillage destroyed the inherent soil properties but did not reduce the variability of K_S, we performed a new simulation

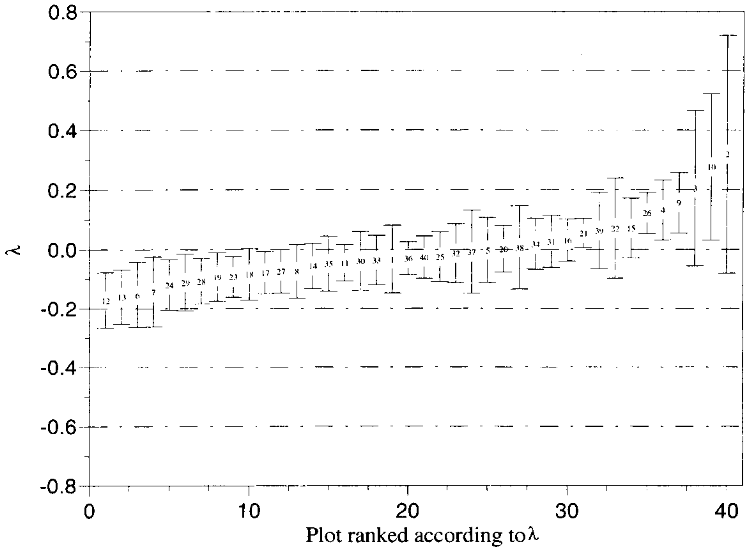

Fig. 9. Ranked time stability parameter, λ, computed using the simulated runoff from the 40 plots considering modification of the spatial variability of random roughness and K_s after each tillage. Vertical bars correspond to 90% confidence limits. Numbers refer to plot code.

assuming that after each tillage operation the spatial arrangement of K_s and surface storage was randomly modified. A new set of the 40 maps of K_s and surface storage was generated in conjunction with each tillage operation and used for the rainfall events following that tillage until a new operation was performed (see Table 1). To do this we maintained the same mean, standard deviation and autocorrelation parameter and generated different maps using the procedure explained in material and methods. The generated λ values with this new scheme (Fig. 9) showed time stability more of the level shown by the observed data (Fig. 3), with most of the plots ranging between the 90% confidence intervals bars. There was also a slight difference in the CV values (Fig. 10) compared to the initial simulation runs (Fig. 7) as a result of small differences induced by the random generation.

4. Discussion

The observed plot runoff showed coefficients of variation quite large for small events and still important for the larger runoff events (Fig. 2). Similar results have been reported by Smith and Herbert (1979) and De Roo et al. (1992) simulating with the Monte Carlo method spatially variable infiltration in both a virtual and an actual catchment. We are not aware of previous works trying to explain the observed CV in plot experiments using numerical models. Our results indicate that the numerical approach explained approximately 50% of the observed levels of variation (Fig. 10). The differences between observed and simulated variations in runoff could be explained by various factors. In our numerical study, the CV attributed to measurement error of runoff and spatial variation of rainfall was not considered. The errors for these factors were estimated for this experiment as ±2% for runoff and ±2.3% for rainfall (Wendt et al., 1986). A second reason for the difference is that the approach used for calibrating K_s tended to increase simulated runoff for low runoff events in comparison to the observed ones, leading to lower simulated CV values. A third factor is that published values from other locations were used for generating spatial variability for roughness and K_s, which will vary somewhat from this particular experimental area. Finally, some simplifications are assumed in the numerical model. Among them, the assumption of homogeneous initial water content for the 40 plots that could be significant especially in rainfall events shortly spaced in time. Spatially varied crusting of the soil surface (Bielders et al. 1996), and a more detailed modeling of the routing of the runoff and the effect of microrelief (Fiedler and Ramirez, 2000) are some of possible improvements in further studies.

Among the simplification assumed in our study, we are aware that the one dimensional description of the overland flow, what due to our numerical grid size, 1 m we think is reasonable, somehow exacerbates the effect of the heterogeneity in soil properties. A more detailed 2-D description of the overland flow using smaller grid size and considering microrelief would result in slightly CV of runoff for the different plots. However, the maps of variable soil properties used in this analysis should be based on measurements made at the same scale of the computational grid used. For one of the key parameters, K_s, a relationship between the sampling area of the infiltrometer and the CV of K_s has been reported by several authors (Shouse et al., 1994; Zobeck et al., 1985) with a general trend of higher CV for smaller sampling area. We are not aware of any work comparing the effect of these two factors that might be acting balancing each other, on the description of overland flow. It is, in our opinion, an area in which a combination of field and modeling studies is necessary. Since our grid size is representative of many overland flow models, and it is consistent with the scale of the experiments used to calibrate the model, 1 m^2 see Table 3, we still considering our analysis justified, however, assuming the limitations of the relatively simplified model used.

The results of our study rely on the values used to generate the spatial variation of the properties. Are the values used in Table 3 abnormally high? We consider our approach unbiased, in the sense that the variability assumed in the analyzed properties can easily be found in a tilled hillslope. We base our consideration on the following reasons. About the values considered in the generation, depth to claypan came from an extensive survey of 20 cores per plot in each of the 40 plots. The values chosen for random roughness assumed the average CV of 12 different experiments, where random roughness was measured on an area,

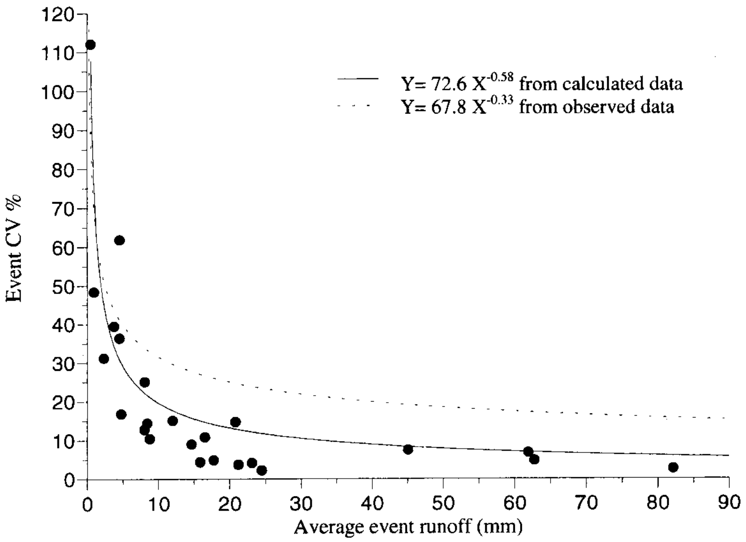

Fig. 10. Relationship between event runoff CV, from simulated runoff values, and mean runoff event, when K_s, surface storage and depth to claypan are considered spatially variable and modified after each tillage. The exponential fit corresponding to the simulated points showed in this figure, and those showed in Fig. 2 are included for shake of easy comparison.

1×1 m^2, equal to that used in the grid of the numerical model what provides a reliable estimation of the expected CV avoiding the error introduced by the change of 'support' (Starks, 1986), due to the different working scale between the measurement and the modeling. The CV of K_s taken from Gupta et al. (1993), which is the only work we were aware of studying K_s in an area similar to that used in our work, used an infiltrometer that extended along an area equal in size to the numerical grid, and also, Gupta et al. (1993) also used different techniques to determine the K_s which allowed a qualitative control on the results. The literature show coefficients of variation, understood as the CV of the log K_s, ranging from the 134% from Starr (1990) to the 11% reported by Russo and Bresler (1981). We think that the 43% of CV found by Gupta et al. (1993) was reasonable, and similar to those found by other authors, for instance, the 39% of CV reported by Nielsen et al. (1973). Finally, we have used a Gaussian generator to create the maps of spatially variable properties. These generators have been reported to generate realizations with a maximum entropy character, i.e. spatial disorder (Journel, 1989), and when using for simulation purposes they do not provided the best possible simulation (Journel and Huijbregts, 1978). We hypothesize that if spatially referenced observations had been available to perform a conditional simulation honoring the measured values at selected points, for example, simulate annealing (Sterk and Stein, 1997), the resulting maps had resulted with a less entropy character and more remarkable differences among different areas, or different plots in our case.

The variation in hydraulic conductivity, K_s, was the most important contributor to runoff variability of the three factors analyzed. This result is in consistent with previous works such as Freeze (1980), Hawkins (1982), Loague and Freeze (1998) and Gupta et al. (1998). The depth to claypan was a relatively minor contributor to runoff CV. Undoubtedly, our approach using a single average initial soil moisture content for the 40 plots and the used of random instead of surveyed depths influenced this result. Nevertheless, our results showing the small influence of depth to claypan implicitly agrees with the analysis of Wendt et al. (1986) where they did not find that any soil property accounted for a major proportion of the variation in runoff among plots. The soil moisture regime during the experiment may help to explain this. Depth to an impermeable soil layer becomes important mainly when the soil is saturated and infiltration is thereby inhibited, and will only be a sporadic source of runoff variation.

The contribution of surface storage to the variation of runoff was more important in small runoff events, as might be expected. Surface storage may also be an important contributor to variance in events where there are several peaks of rainfall intensities with transition periods between them in which surface water infiltrates (Mitchell and Jones, 1978). Surface storage amounts, and hence their contribution to runoff variance, are related to the initial random roughness after tillage and the rainfall and time of roughness decay since the last tillage.

The instability in time of the differences in runoff among plots cannot be explained in our simulations without assuming that tillage modifies the spatial distribution of K_s (Figs. 3, 8 and 9). The variations shown by the error bars in Fig. 8, for the case when modification by tillage was not considered, indicate the differences among plots of infiltration rates as a function of the interactions between spatial variability of K_s (and possibly also surface storage) and rainfall intensities (Wendt et al., 1986). This phenomenon is a consequence of the existence within the plot of areas of greater K_s that can act as sinks for the runoff at particular rainfall rates (Hawkins, 1982). In our study, the average K_s (and the maximum expected K_s in any one cell) was generally low compared to rainfall rates, which means that in most of the events the rainfall intensity at some point in the storm exceeded the infiltration rate in all of the simulated cells on the plot. The source/sink phenomena discussed above would have had even greater importance in conditions where higher infiltration rates exist, such as in soils with macroporosity (Hawkins, 1982) or with patches of vegetation (Morin and Kosovksy, 1995). Nevertheless, Yu et al. (1998) observed on fallow plots of similar size to ours a relationship between apparent infiltration rate and rainfall intensity that he attributed to the spatial variability of the maximum infiltration rate within the plot. This suggests that this effect can be significant on fallow soil at the plot scale and that the results of our simulation incorporate that effect to some extent.

A primary assumption in our analysis which explains the lack of time correlation of runoff volumes among plots is that the spatial arrangement of K_s and surface storage is modified after each tillage operation, which leads to the results shown in Fig. 9. We are not aware of any study that has mapped the spatial arrangement of these properties after two different tillage operations, so this hypothesis remains unproven experimentally. Logsdon et al. (1996) also hypothesized that tillage may have a major effect on the spatial structure of K_S, overwhelming inherent soil differences due to fact that tillage introduces non-homogeneities such as cracks, fissures, clods (Klute, 1982). Since the tillage implements experience variation in speed and depth of penetration during operation (Gebresenbet, 1992) it is reasonable to expect that these variations will occur in different areas of a field during successive operations, producing the rearrangement in the spatial distribution of K_s and random roughness. Since this hypothesis proved to be fruitful in our simulations we think that it deserves further research to confirm or discard its validity.

The CV of runoff was great even though relatively homogeneous soil conditions existed in this case. The CV may be greater yet in conditions where spatial variability of soil properties are greater, such as in soils with a large amount of macroporosity (Lauren et al., 1988) or in semiarid conditions with sparse vegetation (Morin and Kosovksy, 1995). These conditions may indicate a need for longer measurement duration for the experiment in order to achieve significant results (Nearing et al., 1999), or to the expectation of obtaining significant results only when treatment differences are large. An integrated approach in which the plot measurements are combined with field surveys to assess the variability in the soil properties could increase the performance of runoff experiments. Such approach might allow the detection of unexplained differences between plots and the generation of confidence intervals for the different treatments using numerical models.

The introduction of the spatial variability of relevant soil properties into the model design allows for a more realistic description of the system, as the resultant output is not just a single estimation of runoff but rather a set of output values as is observed in field experiments. This allowed us to consider in the evaluation not only the agreement between average observed and calculated values, but also the distribution and the evolution in time of the differences within replications. A more precise evaluation of the model performance is also made possible, with a clearer distinction made between variations that can be attributed to the model itself from the variation that is intrinsic to the system.

5. Conclusions

The analysis of the CV in runoff volume between replicated plots from a field experiment using a numerical model showed that the spatial variability of K_s within individual plots, surface storage, and depth to claypan explain qualitatively the observed trend and approximately 50% of the observed CV. Experimental error and assumptions made during the calibration and modeling steps could explain this quantitative difference. The experimental plots exhibited time instability in terms of the relative differences between plots: plots that produced the greater runoff in one storm did not necessarily do so in other storms. The modification of spatial variability of K_s and surface storage after each tillage operation is suggested as a primary mechanism that generates the lack of time stability in the differences in runoff volume among plots. An integrated approach using field surveys for assessing the spatial variability of the principal variation inducing factors along with numerical simulations is suggested to increase the efficiency in the analysis of the results from runoff plots. The introduction of such variability into the numerical simulations of runoff generation could increase the capability of the model to simulate natural variation. It also could allow a better analysis of the model performance, with a clearer distinction of the CV that remains unaccounted for and can therefore be attributed to imperfections of the model.

Acknowledgements

This work was made when the senior author was a visiting scientist at the USDA-ARS-National Soil Erosion Research Laboratory, on a grant from the Spanish Ministry of Education. This support is gratefully acknowledged. We also appreciate the comments made by A. de Roo and one anonymous reviewer during the revision process that helped improving the quality of the manuscript.

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