Variability of Runoff and Soil Loss from Fallow Experimental Plots[1]

R. C. WENDT, E. E. ALBERTS, AND A. T. HJELMFELT, JR.[2]

ABSTRACT

The amount of unexplained variation in runoff and soil loss studies often limits the interpretation of data. In this study, variability in runoff and soil loss from 40 essentially uniform experimental plots was examined for 25 natural rainfall events occurring during a 155-d period. Plots had been maintained uniformly for the prior 3 yr and were kept fallow with periodic cultivation during the study period. Except for events producing low runoff and soil loss, event coefficients of variation were relatively constant for both runoff and soil loss at about 20%. Differences in runoff and soil loss among plots varied with event. Only minor amounts of observed variability could be attributed to any of several measured plot properties, and plot differences expressed by the 25 events did not persist in prior or subsequent runoff and soil loss observations at the site. The relatively large amount of unexplained variability shows that several replications of treatments are needed to confidently estimate mean runoff or soil loss for comparison purposes and that effects of factors having relatively minor effects on runoff or soil loss may be difficult to detect statistically. The fact that most variability is unexplained indicates important effects of factors or processes that are not currently understood.

Additional Index Words: **soil erosion, spatial variability, simulation models.**

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FIELD PLOTS have long been used to examine management effects on runoff and soil loss under both natural and simulated rainfall. In studies where treatments have been replicated, experimenters have often noted relatively large amounts of variability among replicates (Browning et al., 1948; Bryan, 1981; Gard and Van Doren, 1949; Johnson et al., 1984; Mueller et al., 1984; Nyhan et al., 1984; Simanton and Renard, 1982). Sources of variability have not been obvious, although factors such as tillage induced plot differences (Gard and Van Doren, 1949), formation and breakup of debris dams during events (Simanton and Renard, 1982), and the combined influence of variability in raindrop size, surface water films, and aggregate stability (Bryan, 1981) have been suggested as potential sources.

The magnitude of variability in runoff and soil loss among plots treated alike is of concern in interpreting results of experiments and in experimental design. With large amounts of unexplained variation, several treatment replications may be needed to confidently estimate means for comparison purposes. Variability among plots considered identical is also of concern in the development of mathematical models for simulating management effects on runoff and soil loss. Because simulation models are often abstractions, observed variability for conditions for which model parameters are uniform gives an indication of the importance of unaccounted for variables with which to judge model performance.

In this study, we examine runoff and soil loss variability among fallow experimental plots for which major factors affecting runoff and soil loss were essentially constant. Although the runoff data used were reported earlier (Hjelmfelt and Burwell, 1984), they are subjected to further analysis in this study and are used in the interpretation of soil loss variability.

METHODS

The study was conducted on 40 plots located near Kingdom City, MO, and arranged as illustrated in Fig. 1. Each plot is 3.2-m wide, 27.4-m long, and oriented parallel to a 3 to 3.5% slope. Adjacent plots are separated by a 2.13-m wide border strip. Soil at the site is a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualfs), which has a slowly permeable layer of illuvial clay (claypan) beginning at depths of 0.2 to 0.3 m. Runoff and associated sediment are collected in two volumetrically calibrated tanks arranged in series at the base of each plot. The first tank collects up to the depth equivalent of about 6 mm of plot runoff after which overflow is channeled through a multislot divisor that conveys one-ninth to the second tank. Total capacity of the combined tanks is about 150 mm of plot runoff. After each event, depth of runoff in each tank is measured and the runoff sampled to determine sediment content. Rainfall data are collected adjacent to the site using a single recording raingauge. Although no data are available to document spatial variability in rainfall over the plot area for the events reported, data for 15 nonrecording gauges arranged in a grid

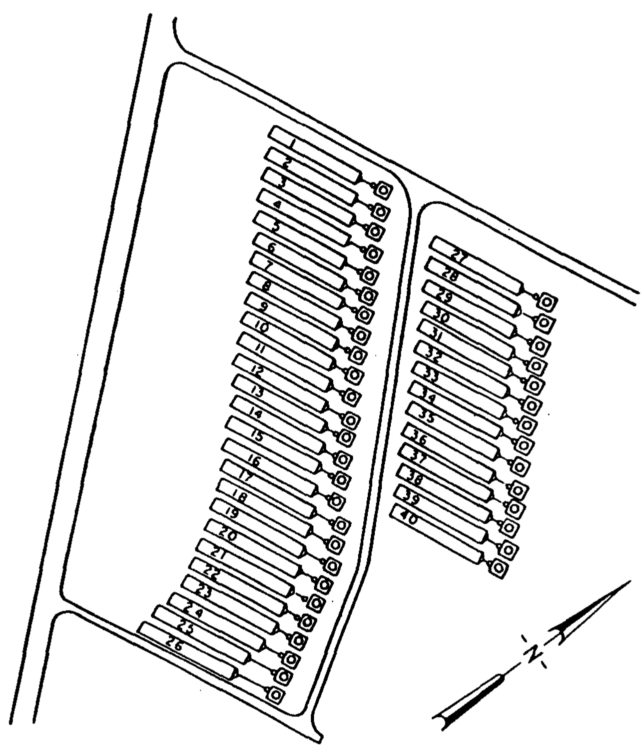

Fig. 1. Configuration of runoff and soil loss study plots located near Kingdom City, MO.

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[2] Soil Scientists and Research Hydraulic Engineer, respectively, Watershed Research Unit, USDA-ARS, Columbia, MO.

pattern over the plot area during 1983 showed minor variability. Coefficients of variation (CVs) for 19 events ranging in size from 8 to 77 mm avg 2.3% and ranged from 0 to 5.3%. Much of this variability was probably due to the limits of precision of the gauges used. Jamison et al. (1968) has given a more complete description of the site, instrumentation, and sampling procedures.

Initial studies on plots 1 through 39 were begun in 1941 (plot 40 was added in 1975). From 1941 through 1977, several studies of management effects on runoff and soil loss were conducted and management of individual plots varied. During 1978, each plot was reshaped to assure slope uniformity and depth to the illuvial clay layer (depth to 40% clay, R.B. Grossman, unpublished data) was determined for each. In 1979 and 1980, all plots were managed uniformly and cropped to soybeans (*Glycine max* L.). During the spring and summer of 1981, plots were maintained in cultivated fallow (as defined by Wischmeier and Smith, 1978) and the events reported herein occurred. All cultivation was parallel to slope.

A topographic survey of each plot was performed during June of 1981. Soil on each plot was sampled by collecting 20 randomly selected cores to a depth of 0.15 m in March 1982. Cores for each plot were combined and the resulting sample analyzed to determine texture and organic matter content. Silt plus clay and clay content were determined using the pipette method (Day, 1965) after dispersion by ultrasound. Organic matter was estimated by dichromate oxidation (Brown and Rodiguez, 1983).

RESULTS

Twenty-five runoff events occurred during the study period. What is defined as an event in our study is in some instances dependent on the length of time required to sample and service collection tanks in preparation for subsequent events (normally done during daylight with about 20 man-hours). Hence, reported events are sometimes composed of multiple rainfall periods separated by an overnight period or time intervals too short to accomplish sampling and servicing activities. Failure to complete these activities prior to subsequent rainfall resulted in missing soil loss data for some plots for events on 20 and 28 July.

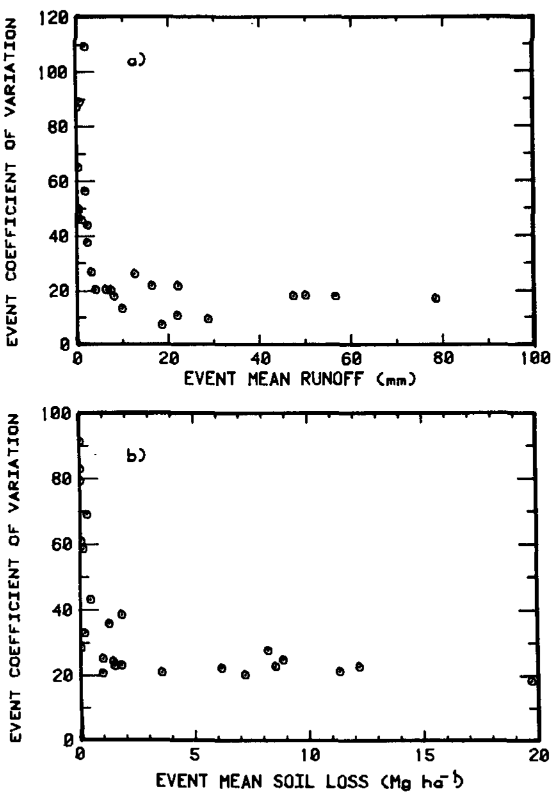

Fig. 2. Relationship between event coefficient of variation and (a) event mean runoff and (b) event mean soil loss for 40 fallow plots.

Summary statistics for events are listed in Table 1 with date of occurrence and proximity to tillage operations. Event size, as expressed by event mean runoff and soil loss, varies at least 2 orders of magnitude and has an approximately log-normal distribution. Although plots are very nearly the same and are treated identically, differences in runoff and soil loss among plots exist for individual events.

Frequency Distributions

Frequency distributions of plot runoff and soil loss for individual events are normal in most cases except for events with low mean runoff and soil loss. For the latter, runoff often did not occur on all plots. For the larger events, dispersion as expressed by the standard deviation is a relatively constant fraction of the mean resulting in CVs near 20% for both runoff and soil loss (Fig. 2).

Although CVs are relatively constant, relative differences among plots in runoff and soil loss vary with event. These differences are expressed by the correlation of observations for individual plots between

Table 1. Precipitation, runoff, and soil loss from cultivated fallow plots in 1981.

Event no.	Rain date	Rain amount	Runoff Mean	Runoff CV	Soil loss Mean	Soil loss CV
		mm	mm	%	Mg ha^{-1}	%
Moldboard plowed and disked	3/24-27					
1	4/11	38	0.43	65	0.16	58
2	4/14†	8	0.22	87	0.03	83
3	4/19†	30	0.91	89	0.06	61
4	4/21-22	43	12.75	26	1.82	38
Spike harrow	4/28					
5	5/9-10†	47	1.98	109	0.03	28
6	5/17-19	96	47.52	27	1.45	24
7	5/23-24	18	2.44	38	0.20	33
Field cultivate	5/29					
8	6/1†	27	1.90	56	0.33	69
9	6/4†	10	0.41	49	0.03	91
10	6/5†	5	0.36	50	0.04	79
Field cultivate	6/9					
11	6/16	18	3.23	27	1.27	36
12	6/20	17	6.40	20	1.00	25
13	6/22	70	50.11	18	12.20	23
14	7/1	31	9.96	13	1.80	23
15	7/2	27	22.02	11	7.21	20
16	7/5	24	18.62	7	6.19	22
Field cultivate	7/7					
17	7/18	95	56.65	18	8.54	23
18	7/20	21	16.43	22	8.88‡	25
19	7/23	96	78.56	17	19.71	18
20	7/25	32	28.75	9	11.35	21
21	7/26-27	33	24.69	20	8.23	25
22	7/28	13	7.47	20	1.51‡	23
Field cultivate	7/31					
23	8/25	26	1.27	46	0.49	43
24	8/31	25	8.13	18	3.56	21
25	9/13	18	4.14	20	0.98	21

† Events for which not all plots had runoff.
‡ Events with missing data.

events (Tables 2 and 3). High correlations indicate similar relative differences among plots and values near zero or negative correlations indicate little or an inverse relationship, respectively. Only correlations between events with observations on all plots are listed; however, these events account for the majority of the total runoff and soil loss. Correlations are positive between most events for both runoff and soil loss. Values of correlation coefficients are, however, quite variable. For soil loss, highest values are most prevalent near the diagonal of the correlation matrix showing greatest consistency of relative differences for events adjacent to one another in the event sequence. Disturbance of the soil surface by cultivation appears to influence differences among plots in some instances. For example, differences in soil loss among plots for events occurring after the last cultivation are negatively correlated with those for many prior events. Similarly, the cultivation between events 16 and 17 appears to markedly affect relative differences among plots.

Although relative differences among plots vary with event and may be influenced by tillage, the predominance of positive correlation coefficients indicates a consistency of differences among plots. Overall plot differences were examined by comparing total plot runoff and soil loss. Because of missing data for some plots, results for events 18 and 22 were excluded from plot totals. Frequency distributions for both total plot runoff and soil loss are approximately normal (Fig. 3). The CVs for both are about one-half those for individual events showing that relative differences among plots tend to compensate somewhat when values are summed over several events.

Spatial Trends

Differences in mean total runoff and mean total soil loss for upper and lower tiers of plots are not significant ($p < 0.05$). Similarly, correlations of total runoff or total soil loss for plots aligned between tiers are not

Table 2. Correlation of plot runoff amounts between events indicating the consistency of relative differences among plots.

	Event no.†																
	1	4	6	7	11	12	13	14	15	16	17	19	20	21	23	24	25
	$r \times 100$																
1	100	47	34	29	25	36	07	18	−15	06	10	−19	04	−03	21	15	22
4		100	17	21	04	08	12	26	−07	04	31	−03	00	−03	51	50	41
6			100	45	11	12	41	46	29	28	46	04	12	07	18	02	46
7				100	41	37	20	63	13	19	24	−06	11	11	10	14	19
11					100	16	02	41	−16	−18	03	−18	07	27	19	23	31
12						100	00	24	02	24	07	−09	30	02	03	−06	−04
13							100	40	39	27	20	−18	29	12	26	13	36
14								100	07	05	34	−03	40	26	42	27	50
15									100	66	36	−15	11	09	−15	−11	−07
16										100	41	−06	33	−26	−14	07	−03
17											100	06	16	15	20	19	43
19												100	01	02	−03	−09	14
20													100	−23	11	02	16
21														100	30	12	31
32															100	56	66
24																100	58
25																	100

† Spaces in the matrix indicate tillage was performed between adjacent events.

Table 3. Correlation of plot soil losses between events indicating the consistency of relative differences among plots.

	Event no.†																
	1	4	6	7	11	12	13	14	15	16	17	19	20	21	23	24	25
	$r \times 100$																
1	100	58	17	14	31	25	27	22	01	−01	21	20	−01	01	17	23	10
4		100	30	36	33	35	44	31	23	08	42	19	20	05	38	46	23
6			100	39	27	21	15	05	−17	−03	17	00	−01	−22	28	33	31
7				100	37	67	60	53	37	61	40	48	56	08	−01	24	11
11					100	47	62	67	38	24	30	11	21	02	20	18	37
12						100	71	63	57	59	41	40	51	20	−04	10	04
13							100	83	63	62	42	29	50	32	05	08	11
14								100	65	59	49	42	53	38	−11	13	14
15									100	57	24	34	67	33	−04	−13	−02
16										100	11	56	75	14	−22	12	−09
17											100	20	27	11	17	32	35
19												100	49	−01	−23	15	−24
20													100	00	−18	14	05
21														100	−27	−40	−33
23															100	47	41
24																100	47
25																	100

† Space in the matrix indicate tillage was performed between adjacent events.

significant (p <0.05) indicating an inconsistency in any spatial structure between tiers. For this reason, data for the upper and lower tiers were not combined in examining spatial trends. Spatial distributions of total runoff and soil loss for the upper tier of plots are illustrated in Fig. 4. Total plot runoff tends to increase somewhat from plot 1 to 26 and total soil loss tends to gradually increase and then decline over the same interval. The trend for runoff is reflected in the predominance of positive correlations between runoff amounts from plots separated by a common plot interval (Fig. 5). Due to the shortness of the spatial series (n = 26), however, the confidence interval for the correlation coefficients is rather wide and few are considered significant (p <0.05). Comparable correlations for soil loss show a gradual overall decline in values that is associated with the gradual rise and fall in total soil loss across the upper tier of plots and, also, a cyclical component having a period of about four plot intervals. Upon inspection of the data in Fig. 4, this cyclical pattern in the data is apparent. Due to the shortness of the spatial series represented by the lower tier of plots, no separate investigation of spatial trends for the lower tier was attempted.

Sources of Variation

Potential sources of variation in total runoff and soil loss among plots were examined by simple correlation of observations with several measured plot properties (Table 4). For soil loss, no significant relationships were found. Hence, none individually appear to be responsible for plot differences or the spatial structure exhibited in Fig. 4. Simple correlation between total plot soil loss and total runoff was also not significant. Correlations between plot runoff and soil losses on an event basis, however, varied with event. Highest correlations were observed for events with low runoff and soil loss, but little correlation existed for larger events. The latter events had a disproportionate influence on plot totals causing low correlation between total plot runoff and soil loss.

Several plot properties were related to differences in

Table 4. Summary statistics and simple correlation of total plot runoff and soil loss with measured plot properties.

				Correlation with	
				Runoff	Soil loss
		Mean	SD	r	
Runoff	mm	380	35	1	0.10
Soil loss	Mg/ha	86.6	11.8	0.10	1
Sand	%	5.7	0.7	−0.41**	0.01
Silt	%	70.0	0.9	0.01	0.21
Clay	%	24.3	1.1	0.26	−0.18
Organic matter	%	2.7	0.3	−0.22	0.29
Slope	%	3.2	0.2	−0.38*	0.18
Cumulative soil loss (1941–1977)	mm	14.9	10.2	0.34*	0.06
Depth to 40% clay	mm	243	22	−0.42**	−0.05

*,** Significant at p <0.05 and p <0.01, respectively.

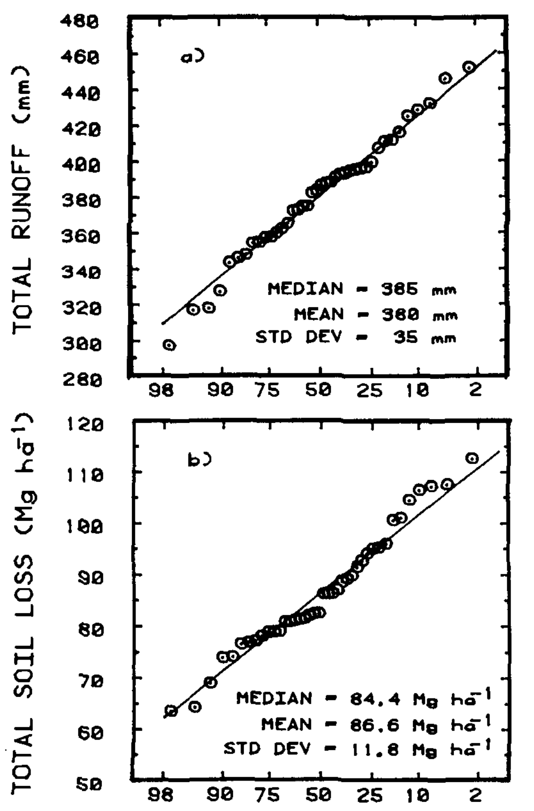

Fig. 3. Frequency distributions for (a) total plot runoff and (b) total plot soil loss from 40 fallow plots.

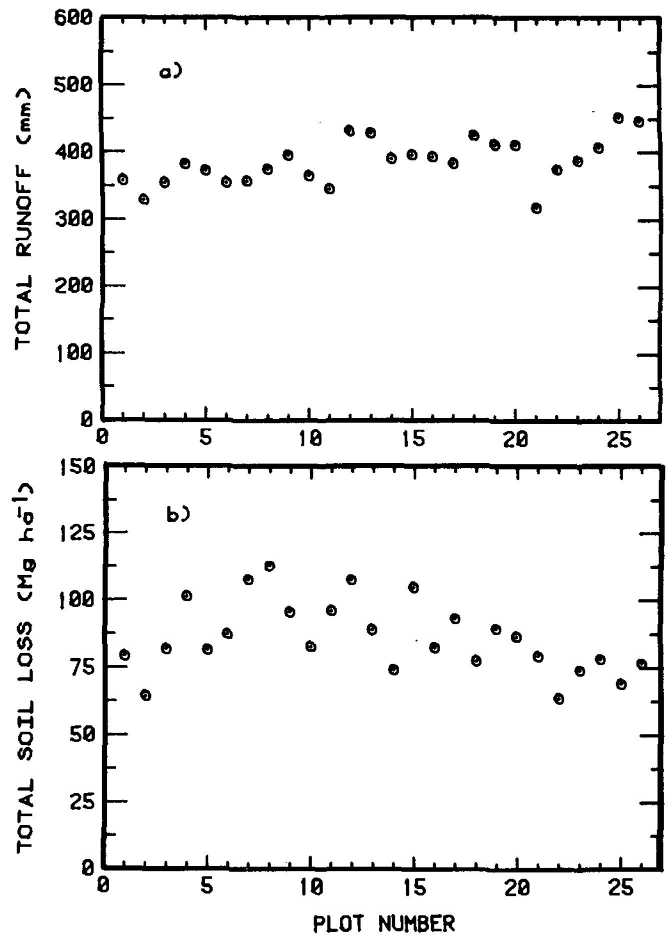

Fig. 4. Spatial distributions of (a) total plot runoff and (b) total plot soil loss for the upper tier of plots.

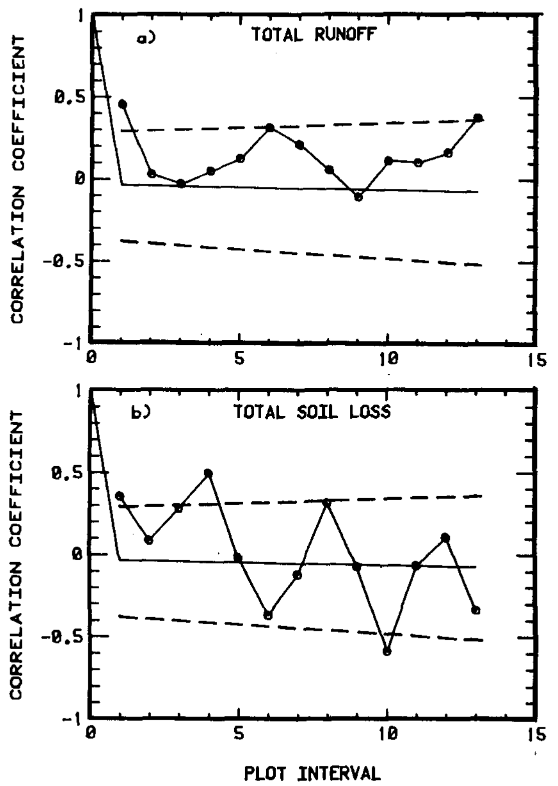

Fig. 5. Serial correlations of (a) total plot runoff and (b) total plot loss for the upper tier of plots. Solid and dashed lines are the expected mean and 95% confidence interval, respectively.

total runoff, but none individually accounted for a major portion of runoff variability. Highest correlations were obtained with depth to the claypan layer and sand content. The negative correlation with runoff shows lesser amounts of runoff with increasing depth of soil and, hence, fillable porosity above the relatively impermeable clay layer. Soil depth above the claypan appears to be at least partially responsible for the observed trend of increasing runoff across the upper tier of plots, as depth tends to decrease somewhat over the same interval. The negative correlation of runoff with sand content may indicate a more rapid infiltration rate as soil texture becomes more coarse or may simply be a consequence of depth to the claypan. Because tillage tends to homogenize soil in the plow layer, the nearer the plow sole to the clay zone the finer the texture in the homogenized zone is likely to be. Therefore, the correlation of total runoff with sand content may be coincidental. The significance of the correlation of total runoff with total 37-yr soil loss is questionable as the distribution of the latter is highly skewed. Likewise, the negative correlation with plot slope is of questionable significance as the range of slopes is quite small and the negative correlation is inconsistent with prior observations of slope effects on runoff (Wischmeier, 1966).

Multiple correlations of total plot soil loss with silt, clay, organic matter, slope, and depth to claypan was not significant ($p < 0.05$). A similar correlation for total plot runoff was significant, but depth to claypan and slope were the only independent variables of significance.

Potential influences of differences in past management on results were examined by comparing total runoff and soil loss between plot groups having a common treatment during the period 1970 to 1977. Conventional and no-till corn (*Zea mays* L.) represented treatment extremes during this time period. Results showed no significant ($p < 0.05$) differences in 1981 total runoff or soil loss for plots that had previously been conventionally tilled ($n = 6$) and those that were no-till ($n = 7$), indicating little effect of prior treatment.

Persistence of Plot Differences

Observed differences in total 1981 runoff and soil loss among plots might express inherent plot differences in soil erodibility and factors affecting runoff. If this is the case, variability among replicated plots in past or future studies might be partially the result of these inherent differences. The relative importance of such differences was examined by testing the significance of total 1981 plot runoff and soil losses as covariates in the analysis of treatment effects on runoff and soil loss for two data sets. The first set consisted of total 6-yr plot runoff and soil losses for the six conventional and seven no-till plots mentioned in the prior section. The second consisted of data from three rainfall events during 1983 comparing runoff and soil losses for fallow and both corn and soybeans cropped using three tillage methods in a randomized complete block design with four blocks. In neither case were covariates significant ($p < 0.05$), suggesting that plot differences and spatial trends expressed by the 1981 data either were not persistent or were a relatively minor part of unexplained variability.

DISCUSSION

Although major factors affecting runoff and soil loss, including soil type, slope, slope length, rainfall and management, are essentially constant among plots, substantial unexplained variability in observed runoff and soil loss exists. A portion of this variability is undoubtedly caused by measurement error. A potential source of measurement error is bias in collection tank calibration or in the performance of multislot divisors separating collection tanks. These errors, however, should be systematic. The fact that differences among plots vary with event suggests that bias is not a dominant source of unexplained variability. Another source of uncertainty is imposed by limits of precision of equipment used to gauge water levels in collection tanks and to measure sediment content. Relative uncertainties vary inversely with the magnitude of the measurement, but, for midrange values, are approximately $\pm 2\%$ for runoff and approximately $\pm 3\%$ for combined runoff and sediment measurements. Hence, measurement uncertainty also appears to be a relatively minor source of variability.

The relatively constant CVs for soil loss for all but the smallest events suggest differences in soil erodibility among plots. Differences in erodibility would cause variability of soil loss proportional to event size. The nearly constant CVs for event runoff indicate widening differences in infiltration rate among plots with increasing event runoff. Although the magnitude of dispersion for both runoff and soil loss tends to remain constant relative to the event mean, low correlations of plot values between events (Tables 2 and 3) suggest inconsistent changes among plots in both erodibility and infiltration between events.

Vieira et al. (1981) and Sisson and Wierenga (1981) have shown spatial variability in infiltration rates within soils classified as homogenous. Spatial variation of infiltration rate on a scale smaller than the plot scale could cause variability among plots in infiltration rates and, hence, plot runoff. Within-plot spatial variation might be present initially after tillage or gradually develop as a result of differential rates of rainfall-induced changes in soil conditions affecting infiltration, such as surface seal development. Moreover, Hawkins (1982) has demonstrated that spatially varying infiltration may result in an integrated infiltration rate that varies with rainfall intensity. Hence, differences in infiltration among plots might be influenced by the magnitude and time distribution of event intensities. Differing plot infiltration response to rainfall intensity could be a reason for inconsistent differences in runoff among plots between events.

Variability in soil loss among plots may also be partially the result of spatially varying infiltration (Hawkins, 1982). Such could arise from differences among plots in areas experiencing rainfall in excess of infiltration rate during events and, hence, contributing runoff and associated soil. However, lack of correlation between runoff and soil loss (Table 4) suggests additional contributing factors. Soil erodibility may also be spatially variable. Run-on from upslope areas may make the spatial arrangement of any variability in infiltration rate or soil erodibility with respect to the point of measurement an important factor. In addition, surface features of plots that influence surface drainage patterns and sediment transport capacity might be influential.

A tilled soil surface, such as the one we studied, initially contains small ridges and furrows left by the tillage implement. In addition, small clods are typically scattered about the soil surface. In furrows, clods may influence runoff flow rates and sediment transport capacity. Differences in the number, spatial arrangement, and breakdown rate of clods in furrows as well as minor fluctuations in furrow geometry could cause differences in runoff and soil loss among plots for initial events after tillage. In this way, clods may behave similarly to the debris dams mentioned by Simanton and Renard (1982). For subsequent events, we have observed a general degradation of surface features with little evidence of rill development. Although this action might be expected to reduce the magnitude of variation among plots, such is not observed in the data. With subsequent events, a network of more concentrated flow is usually observed to develop on the soil surface. Differences in the pattern and extent of development of this network may be a source of variability for later events; however, no quantitative evaluations of flow patterns were made to evaluate this possibility. If such patterns are important, successive events should be affected somewhat by patterns developed in prior events. This may partially explain the tendency for plot soil loss for adjacent events in time not separated by tillage to be correlated, and why pattern disruption by tillage apparently causes a reordering of differences among plots. The fact that correlations between events for plot runoff are not as great as those for soil loss suggests that surface drainage patterns may have a greater influence on sediment transport capacity of runoff than on runoff amounts.

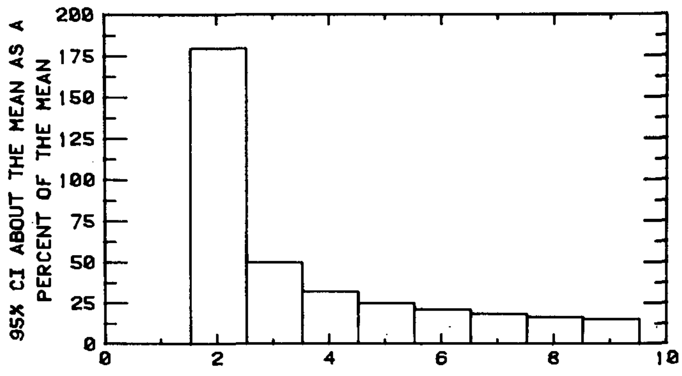

Fig. 6. The 95% confidence interval about the mean as a function of number of replications for a coefficient of variation of 20%.

With the magnitude of unexplained variability observed, several replications of a given management practice would be needed to confidently estimate event mean runoff and soil loss (Fig. 6). For example, five replications would be needed to estimate a treatment mean having a 95% confidence interval of about ±25% of the estimated mean value. The importance of the magnitude of the confidence interval would depend on experiment objectives; however, it is obvious that management factors having rather subtle effects on runoff and soil loss would be very difficult to detect experimentally. Although our results indicate variability might be reduced by averaging or summing over multiple events, variability in runoff and soil loss was reduced in our study only by about one-half when summed over 18 events. Hence, this would not appear to be a practical alternative for reducing experimental error in most cases.

It should be noted that the magnitude of variability we observed will probably not translate directly to other plot sizes, slopes, soil types or management alternatives. For example, additional factors that may be associated with management alternatives under consideration, such as spatially variable residue cover, canopy cover, or soil-water depletion by plants, may cause the magnitude of unexplained variability to differ and, perhaps, be greater than what we observed. Although little data are available to evaluate effects of these and other factors, results similar to ours have been reported for bare soil with several different soils and plot sizes using simulated rainfall (Bryan, 1981). Hence, our results should be a useful reference for experimental design.

The implications of the unexplained variability we observed with respect to numerical models for simulating runoff and soil loss depend somewhat on the type of model. Few models attempt to simulate the within-plot heterogeneities that are apparently responsible for the majority of variability we observed. Hence, an event-based model not capable of distinguishing among plots that might accurately estimate event means would still be subject to error characterized by the variability we measured. As indicated by the correlation matrices in Tables 2 and 3, this error component does not randomly distribute itself among plots between events, but is influenced by tillage and prior events. Hence, a random stochastic model component would not appear to adequately express its effect over all events.

For models calibrated with a longer-term data base to estimate long-term average values, such as the Universal Soil Loss equation (Wischmeier and Smith, 1978), the variability we have observed may be of lesser importance. Because variability among identical plots diminished when multiple events were summed, such variability would be expected to converge somewhat over the many events making up a long-term data base. Hence, the influence on model parameters derived by calibration with a long-term data base should be lessened. However, the unexplained variability we observed could greatly influence parameter values estimated with relatively short-term data bases or with single or a relatively few simulated rainstorms.

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