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Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. I. No-till systems[1]

K.P.C. Rao[a], T.S. Steenhuis[b,*], A.L. Cogle[c], S.T. Srinivasan[a], D.F. Yule[c], G.D. Smith[c]

[a] *International Crops Research Institute for the Semi-Arid Tropics, P.O. Patancheru, Hyderabad 502 324, AP, India*
[b] *Department of Agricultural and Biological Engineering, 216 Riley-Robb Hall, Cornell University, Ithaca, NY 14853, USA*
[c] *Queensland Department of Primary Industries, Brisbane, Que., Australia*

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Abstract

Alfisols, which are abundant in the semi-arid tropics, are fragile and subject to crusting, resulting in high runoff amounts and large soil losses. A field experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India, over a 6-year period to study the runoff from Alfisols under no tillage without amendments, and with the addition of farmyard manure (15 Mg $ha^{-1}yr^{-1}$) and rice straw (*Oryza sativa*) (5 Mg ha^{-1} yr^{-1}). Each treatment had three replicates. A total of 211 runoff events were recorded for each plot. For runoff from no-till systems without any plant or straw cover, the infiltration rate was controlled by the surface crust. Infiltration rate through a surface crust was 9.6 mm h^{-1} and showed little change over time. Infiltration rates measured with a ring infiltrometer and disc permeameter were five to six times higher than that observed under natural rainfall. The data was divided into four groups with similar amounts of rain during the preceding 2 days and percent soil cover. The regression analysis found that the amount of precipitation, 30 min intensity, soil cover, and time since the beginning of the experiment were all significant factors in determining the runoff. More than 75% of the variation in runoff was explained by these variables for the zero tillage system without amendments and with farmyard manure applied. Straw amended systems were more difficult to predict. For events with less than 15 mm of rain during the previous 2 days, runoff was mainly related to the amount of rainfall when surface cover was less than 30% and to the product of rainfall amount and 30 min intensity when surface cover was greater than 30%. For events with more than 15 mm of rain during the previous 2 days, infiltration rates were generally higher than for dry soil. Runoff was related to a number of variables. Implication for management practices on Alfisols are that adding organic residue to no-till systems could significantly lower the runoff and increase the amount of water available for the crop. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Runoff; Infiltration; Alfisols; Crust; Semi-arid tropics; No tillage; India

1. Introduction

Thirty-three percent of the soils in semi-arid tropics are Alfisols (Kampen and Burford, 1980). Low infiltration rates on these highly fragile soils are usually

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*Corresponding author. Tel.: 001 607 255 2489; fax: 001 607 255 4080; e-mail: tss1@cornell.edu

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caused by a surface crust. The surface crust (or seal) is formed by physical disintegration of soil aggregates and subsequent dispersion and compaction by the beating action of raindrops (McIntyre, 1958; Agassi et al., 1981; Le Bissonnais et al., 1989) and is enhanced by low organic matter content, poor aggregation, and low soil strength under saturated conditions leading to slumping, high bulk density, and loss of surface roughness (El-Swaify et al., 1987). Infiltration rates can also be reduced by a low argillic horizon with low permeability that occurs at 30–50 cm depth. The low infiltration rates caused by either the surface soil or argillic horizon in Alfisols increase runoff. This, combined with the poor aggregate stability, makes the soil sensitive to soil loss by erosion.

To make Alfisols more productive, management practices should be used that increase infiltration and, thereby, the amount of water that is available for use by crops (El-Swaify et al., 1985; Venkateswarlu, 1987; Smith et al., 1992). Because experimental evidence is lacking about management options, a study was initiated in 1988 at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to examine the long-term effects of several management practices on Alfisols in the semi-arid tropics. The management practices studied included tillage, organic amendments to protect and/or ameliorate soil structure, and biological systems that are capable of improving the structure of both surface and subsurface layers. Partial analysis of the runoff data found significant differences between management practices (Yule et al., 1990, 1992; Smith et al., 1992).

In this paper, the role of organic amendments in altering the infiltration characteristics of the surface soil under no tillage is discussed. Data on daily runoff were analyzed to quantify rainfall-infiltration-runoff processes for no-till practices, with different organic amendments. Subsequent papers will deal with systems involving tillage and perennial–annual rotation effects.

2. Materials and methods

An experiment with 45 runoff plots, 28.5 m long by 5 m wide with a slope of approximately 2%, was established in July 1988 on the research farm of the ICRISAT Center at Patancheru (18°N, 78°E), 26 km northwest of Hyderabad, Andhra Pradesh, India. A detailed discussion of the experimental set-up was given by Smith et al. (1992). Only a brief description is given below.

The soil belongs to the Patancheru series, a member of the clayey skeletal, mixed, isohyperthermic family of Udic Rhodustalfs (Murthy and Swindale, 1993). The soil consists of 21% clay, >9% silt, and 72% sand and has between 0.5–1% organic matter. The overall experiment consisted of 15 treatments, viz., nine treatments made up of three levels each of tillage and organic amendments in a factorial arrangement plus an additional six perennial pasture treatments. The three treatments used in this analysis were from the factorial arrangement of tillage and organic amendments and involved no tillage (ZT) combined with the application of: (1) no amendment (B), (2) farmyard manure at 15 Mg ha^{-1} (F), and (3) rice straw at 5 Mg ha^{-1} (S). Organic amendments were applied every year at sowing in the second half of June. The plots were cropped annually either with *Sorghum bicolor* (1989, 1990, 1993 and 1994) or *Zea mays* (1991 and 1992). There were three replications for each treatment.

Rainfall and runoff were both measured with tipping buckets at 1 min intervals using a Campbell CR10 logger (Smith and Thomas, 1988). A total of 265 rainfall events over 2.5 mm were recorded between 1989 and 1994, but not all events produced runoff. The data were summarized as total runoff per event, maximum 5, 15, and 30 min rainfall intensities and total rainfall per 24 h period starting at 0900 h. For three events, when rain was continuous, total rainfall was taken over a 48 h period.

Infiltration measurements were made with a double ring infiltrometer (Green et al., 1986) and with a CSIRO (Australia) disc permeameter (Perroux and White, 1988). Steady-state infiltration rates were derived from plots of cumulative infiltration against time.

The amount of soil covered by crop residues and mulch was measured five to six times a year coinciding with important operations: tillage and application of amendments, three times during the crop season, and after harvest of the crop. Photographs covering an area of 1.5×1.5 m^2 were projected onto a screen with a 10×10 cm^2 grid and point contacts were counted. The percentage of soil cover was expressed as a percentage of the total soil by averaging the coverage for the grid cells. Soil cover for all rain events was obtained by linear interpolation.

A regression analysis was performed on the data of 211 runoff events to identify the relationships between runoff and other variables. The minimum rainfall to generate runoff was 4.5 mm. Data from all replicates were used in the analysis (as opposed to their averages) for a total of 633 plot histories. To obtain the most significant regression parameters, we will first examine, in detail, how runoff is generated.

3. Results and discussion

3.1. Runoff

The three zero tillage systems consisted of a bare surface (ZTB), amended with farmyard manure (ZTF) or with rice straw (ZTS). Runoff was always high from ZTB and low from ZTS (Smith et al., 1992; Yule et al., 1992). On average, about 30% of annual rainfall was lost as runoff from ZTB, 16.5% from ZTF, and 9.5% from ZTS. A significant decline in runoff over the years was noticed for ZTF treatment. In 1989, the ratio of runoff from ZTF to that of ZTB was 0.85. This ratio was reduced to 0.50 in 1994. The ratio of runoff from ZTS to that from ZTB remained at about 0.50 throughout the course of the experiment. The decrease in runoff was attributed to improved infiltration rates resulting for ZTF from increased organic matter contents and for ZTS to protection offered by straw mulch from the raindrop impact.

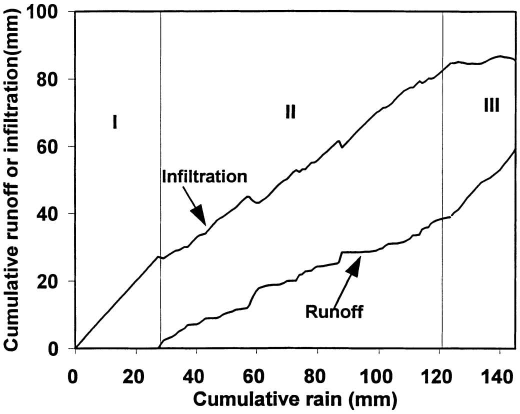

Fig. 1. Relationship between cumulative rainfall and cumulative runoff and infiltration from ZTB (zero tillage with no cover) system (October 7, 1994, total rain=147.5 mm).

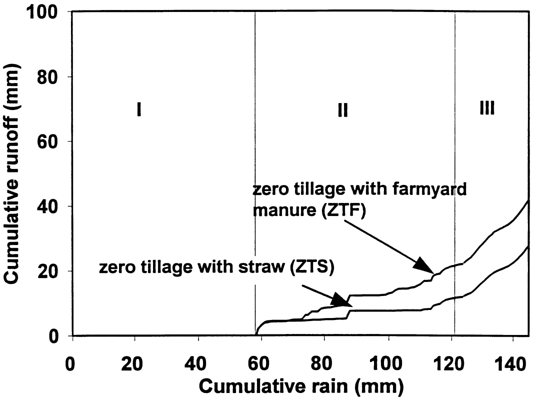

Fig. 2. Relationship between cumulative rainfall and cumulative runoff from ZTF (zero tillage amended with farmyard manure) and ZTS (zero tillage amended with straw) systems (October 10, 1994, total rain=147.5 mm).

3.2. Rainfall–infiltration–runoff process

We analyzed the hydrographs to understand the changing infiltration and runoff processes at the surface. In Fig. 1 the relationship between cumulative rainfall and cumulative runoff for the largest storm (147.5 mm on October 7, 1994) after the harvest of crop is shown for the ZTB (zero tillage without amendments). Three distinct stages in the rainfall–infiltration–runoff process can be distinguished: In stage I, defined as the period from the start of rainfall to initiation of runoff, all rainfall infiltrates. Stage II represents the period in which infiltration and runoff occur at the same time. The near linear relationship between rainfall and runoff indicates a constant rate of infiltration. Stage III starts with a sudden decrease in infiltration rate. During this stage, the runoff equals rainfall and, thus, infiltration is negligible. Although the effect of straw and farmyard manure (ZTS and ZTF systems) showed similar infiltration patterns (Fig. 2), the infiltration capacity was higher than ZTB during stage I and stage II. Consequently, the period was longer before runoff began (stage I) and there was less runoff overall. During stage III, no water infiltrated through the crust. For three other rainfall events, we observed that no water entered the soil during stage III. These storms occurred on July 17, 1989 (115 mm), May 13, 1990 (48 mm), and July 2, 1992 (70 mm). In all cases, there was very little crop or mulch cover on the surface and rain fell in two distinct periods, less than 1 h apart. Stage III started at the beginning of the second burst of rain when all rainfall ran off the plot and was attributed to the sealing of the surface with a thin layer of washed-in material, as suggested by McIntyre (1958) and Chen et al. (1980). Infiltration rates were restored when the thin seal was eroded by runoff water.

Because the reduction in infiltration occurred at the same time for different treatments and was independent of the amount of water infiltrated, it seems that the infiltration was more controlled by the surface layer than ponding on top of the subsurface argillic layer.

3.3. *Infiltration rates and runoff for the zero tillage system without amendments*

Infiltrometer measurements and rainfall-runoff data on the no-till plots were used to determine the infiltration rate of a crusted soil. The infiltrometers consisted of a double ring infiltrometer and disc permeameter method with a 10 mm negative head. Steady-state infiltration, attained very quickly, was 45 mm h^{-1} by the ring infiltrometer method and 61 mm h^{-1} using the disc permeameter (Fig. 3). These infiltration rates were higher than most rainfall intensities and cannot explain the high runoff observed in this system. We, therefore, estimated the infiltration rate from a natural rainfall event for a storm which occurred a few days after infiltrometer measurements were made (Fig. 4). The cumulative infiltration was obtained by summing the difference between precipitation and runoff. Two approximate straight linear segments can be distinguished in Fig. 4, between 0–0.25 h, and 0.25–0.75 h. The last segment gives a steady infiltration rate of 9.6 mm h^{-1}. This is 5–6 times lower than the infiltrometer tests. The rates obtained with infiltrometers shortly after tillage remained high because a crust did not form. Ben-Hur et al. (1987) found similar differences by using ring (no crust) and sprinkler infiltrometers (crusted) in Israel.

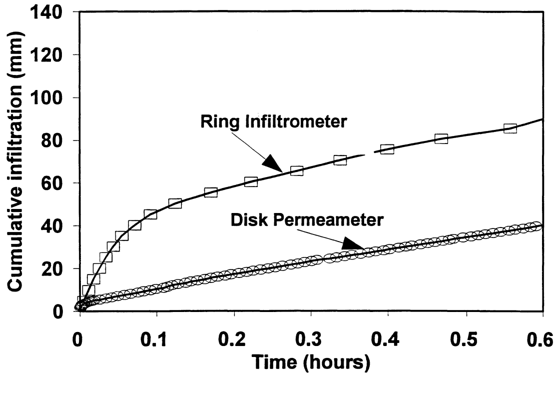

Fig. 3. Cumulative infiltration measured with ring infiltrometer and disc permeameter.

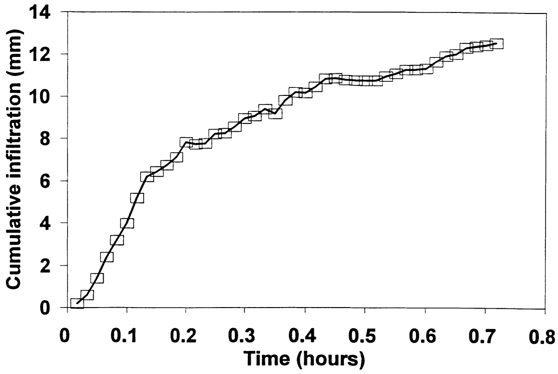

Fig. 4. Cumulative infiltration from rainfall and runoff hydrographs recorded on March 11, 1989 with 61 mm of rainfall.

In general, the runoff can be estimated by subtracting the steady-state infiltration rate from the precipitation after runoff begins, viz

$$Q = \int_{t=t_n}^{t} (p - i)\mathrm{d}\bar{t} \qquad (1)$$

$$I_a = \int_{t=0}^{t_n} p\mathrm{d}\bar{t} \qquad (2)$$

where Q is the event runoff, I_a is the amount of rainfall before runoff starts (also called initial abstraction and equal to the total rainfall during stage I), p is the rainfall rate, I is the infiltration rate, t is the time, and t_n is the time that the runoff starts.

For the zero tillage systems with no amendments and less than 30% plant cover, estimated runoff is

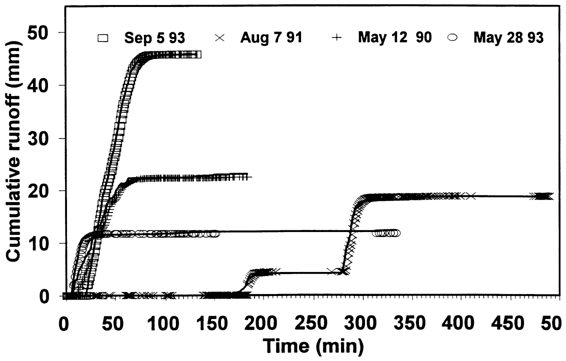

Fig. 5. Predicted (symbols) and observed (solid line) hydrographs for the ZTB (zero tillage with no cover) system for the following storms: May 12, 1990 (rainfall=38 mm, 30 min intensity=36 mm h^{-1}, runoff=24 mm); August 7, 1991 (rainfall=42 mm, 30 min intensity=35 mm h^{-1}, runoff=20 mm); May 28, 1993 (rainfall=23 mm, 30 min intensity=37 mm h^{-1}, runoff=12 mm); September 5, 1989 (rainfall=68 mm, 30 min intensity=68 mm h^{-1}, runoff=46 mm).

compared with measured runoff in Figs. 5 and 6. The estimated runoff was based on Eq. (1) using an infiltration rate of 9.6 mm h^{-1}. Other input data were the rainfall intensities and time when runoff starts. Four different types of rainfall patterns were compared. In Fig. 5 the May 12, 1990 and August 7, 1991 storms had similar rainfall amounts and intensity but the distribution was different. The amount of precipitation for the May 28, 1993 storm was the smallest, while the 30 min intensity for the September 5, 1989 storm was almost twice as high as the other storms. In all, the predicted and observed runoff hydrographs agreed well, maybe with the exception of a slight time offset. One of the reasons is that Eq. (1) assumes that there is no time delay for runoff while, in reality, there is a finite time for the water to run down the plot causing the delay. Shown in Fig. 6 is the comparison of predicted and observed runoff amounts for the remaining 95 storms at which time plant cover was less than 30%. Again, a good fit between observed and predicted values for runoff (coefficient of determination of 0.91). The initial abstraction was less than 6 mm for more than 70% of these runoff events.

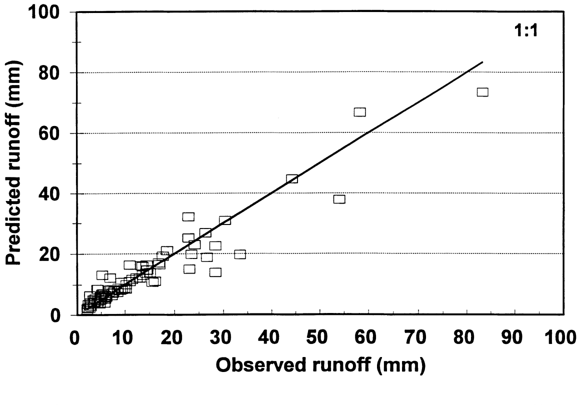

Fig. 6. Relationship between observed and predicted runoff for ZTB (zero tillage with no cover) system.

The infiltration for the two zero tillage systems in which amendments were used, ZTF and ZTS, showed great seasonal and annual differences that could not be predicted with Eq. (1). Also, when the plant cover was more than 30%, Eq. (1) could not be used for the zero tillage systems without amendments (ZTB). In these cases, soil fauna and flora affected the integrity of the crust. For management purposes, it is important to predict runoff for all systems with data that are easily available. We, therefore, developed simple relationships with the aid of regression analysis using a few important variables that can be measured easily.

3.4. Selecting major factors affecting runoff

The variables considered initially for the regression analysis were amount of rainfall (P), maximum intensities during 5, 15, and 30 min (I5, I15, and I30), erosivity index (EI30), soil cover (SC), days after rain (DAR), previous days rain (PDR), previous 2 days rain (P2R), previous 3 days rain (P3R), time from the start of the experiment, logarithms of time and soil cover, and product of rainfall amount and 30 min intensity (PI30). The list of independent variables was reduced by leaving out those that were correlated.

Rainfall intensity variables, I5, I15, and I30 are highly related with a correlation coefficient, r>0.832. The rainfall intensity during a 30 min period (I30), was selected because it both had the highest correlation coefficient with runoff and is widely available. The variables PDR, P2R, P3R, and DAR were all related to the degree of wetness and/or dryness of the soil at the time of rainfall. DAR correlated poorly with runoff. P2R, which had a high correlation with both P3R (r=0.904) and PDR (r=0.713), was used as the indicator of soil wetness. Logarithmic transformation

Table 1
Correlation matrix of variables used in the regression analysis

Variable	T	P	PI30	I30	P2R	ZTB	SCZTB	ZTF	SCZTF	ZTS	SCZTS
T	1.000										
P	−0.042	1.000									
PI30	−0.078	0.903	1.000								
I30	−0.064	0.733	0.806	1.000							
P2R	−0.010	0.044	−0.007	−0.069	1.000						
ZTB	−0.064	0.899	0.882	0.744	0.193	1.000					
SCZTB	0.173	−0.010	−0.029	−0.056	−0.058	−0.155	1.000				
ZTF	−0.131	0.840	0.848	0.691	0.136	0.912	−0.197	1.000			
SCZTF	0.209	−0.032	−0.019	−0.104	−0.015	−0.158	0.809	−0.247	1.000		
ZTS	−0.068	0.750	0.783	0.546	0.010	0.760	−0.159	0.847	−0.182	1.000	
SCZTS	0.111	−0.014	0.004	−0.068	0.076	−0.062	0.507	−0.205	0.715	−0.253	1.000

Significance for 631 degrees of freedom: P(0.05)=0.081 and P(0.01)=0.106.

Legend: T=time from the start of experiment; P=rainfall; PI30=product of rainfall and 30 min intensity by 100; I30=30 min rainfall intensity; P2R=previous 2 days' rainfall; ZTB=runoff from the ZTB (zero tillage with no cover) system; SCZTB=soil cover for the ZTB system; ZTF=runoff from the ZTF (zero tillage amended with farmyard manure) system; SCZTF=soil cover for the ZTF system; ZTS=runoff from the ZTS (zero tillage amended with rice straw) system; SCZTS=soil cover for the ZTS system.

of time and soil cover did not improve the correlation with runoff. Correlation between runoff and the erosivity index (EI30), was generally similar in magnitude compared with the product of rainfall amount and 30 min intensity (PI30). The correlation matrix of the selected variables is given in Table 1. Rainfall amount and intensity, soil cover, and previous 2 days rainfall showed significant correlation with runoff of all three no-till systems, as well as time from the start of the experiment with runoff of ZTF systems. Multiple regression analyses were performed with these variables. This is discussed in the next sections.

3.5. Regression analysis

Best fit regression equations for runoff from the three zero tillage systems were developed based on the predictability (R^2) and the significance of the variable (Student test t-value). Because the rainfall based variables (P, PI30, and I30) were related to each other, only one of these variables with the best fit was used. The regression equation for the three tillage systems are given below:

$$\begin{aligned}
&\text{ZTB}: Q = 0.546 * P - 0.062 * \text{SC} - 2.386 \quad R^2 = 0.830\, N = 633\\
&\text{ZTF}: Q = 0.371 * P - 0.060 * \text{SC} - 0.860 \quad R^2 = 0.754\, N = 633\\
&\text{ZTS}: Q = 0.249 * P - 0.038 * \text{SC} - 0.067 \quad R^2 = 0.620\, N = 633
\end{aligned}$$

where SC is the soil cover expressed in percent and Q and P are the total runoff and precipitation in mm, respectively.

The inclusion of other variables (rainfall intensity, previous 2 days rainfall and time) improved the predictability by another 2–3%. Those relationships were rejected considering the marginal improvement in predictability over that with only rainfall and soil cover.

To improve the regression coefficients, the data were stratified into four groups partly based on experiments by Littleboy et al. (1996) in which wetness of the surface and soil cover were the most important factors in quantifying the rainfall–runoff relationship. The data set was divided as follows: First, the data was split into dry and wet groups, based on the antecedent soil moisture condition as represented by the previous 2 days' rainfall. Wet events were those that had more than 15 mm of rainfall in the previous 2 days (P2R> 15 mm) and dry events had less than or equal to 15 mm rainfall in the same period. Then, each group was further divided into runoff events in which the soil cover was less or more than 30%. Regression

Table 2
Regression equations for estimating runoff from three untilled systems for different antecedent moisture/soil cover conditions

Group/System	Regression equation	R^2	N
Group 1 (P2R<15 mm and SC<30%)			
ZTB	$Q=0.695*P-5.813$	0.925	237
ZTF	$Q=0.542*P-4.415$	0.862	168
ZTS	$Q=0.417*P-3.050$	0.756	126
Group 2 (P2R<15 mm and SC>30%)			
ZTB	$Q=0.797*\mathrm{PI30}-0.192$	0.881	249
ZTF	$Q=0.556*\mathrm{PI30}-0.998$	0.898	318
ZTS	$Q=0.414*\mathrm{PI30}-1.208$	0.786	360
Group 3 (P2R>15 mm and SC<30%)			
ZTB	$Q=1.831*\mathrm{PI30}+1.150$	0.821	84
ZTF	$Q=0.228*P+0.273*\mathrm{I30}-4.879*\log \mathrm{SC}-0.384$	0.743	48
ZTS	$Q=0.930*\mathrm{PI30}+0.620$	0.655	33
Group 4 (P2R>15 mm and SC>30%)			
ZTB	$Q=0.556*P-4.068$	0.825	63
ZTF	$Q=0.209*P-0.272*T-0.880$	0.604	99
ZTS	$Q=0.058*P-0.180*T+0.260$	0.388	114

Legend: R^2=predictability; N=number of events; P2R=previous 2 days rainfall; SC=soil cover; ZTB=zero tillage with no cover; ZTF=zero tillage amended with farmyard manure; ZTS=zero tillage amended with rice straw; Q=runoff (mm); P=rainfall (mm); PI30=product of rainfall and 30 min intensity by 100.

equations, fitted separately for each of these groups and treatments, are summarized in Table 2.

3.5.1. Group 1 (P2R<15 mm and SC<30%)

This group, consisting of rainfall events in which there was less than 15 mm of rain in the previous 2 days and for which the soil cover was less than 30%, contained 37%, 27%, and 20% of the total number of runoff events for ZTB, ZTF, and ZTS systems, respectively, and accounted for 43–45% of the total runoff. Most of the events occurred either during the fallow period (between October and May) or during the early part of the crop season (June–July) when conditions favor the formation of a crust. As expected from our earlier analysis, as much as 92.5% of the variation in ZTB runoff was linearly related to the amount of rainfall (Table 2). The predictability of the equations for ZTF and ZTS systems was relatively low and showed less than 2% improvement when other variables were included. The high dependence of runoff on the amount of rainfall and the poor correlation with rainfall intensity is attributed to the low infiltration rate of the crust.

3.5.2. Group 2 (P2R<15 mm and SC>30%)

This group consists of rainfall events in which it rained less than 15 mm in the preceding 2 days and the soil cover was greater than 30%. It includes 39% of the total number of runoff events for ZTB, 50% for ZTF, and 57% for ZTS. Although this group had a greater number of rainfall events than Group 1, the total runoff as a percentage of the total runoff during the duration of the experiment is less: 28% for ZTB, 31% for ZTF, and 34% for ZTS.

For Group 2, runoff correlated better with the product of rainfall amount and 30 min intensity than with the amount of rainfall such as in Group 1 (Table 2, Fig. 7). The reason is that protective action of soil cover and amendments resulted in high infiltration rates. Under these conditions, runoff occurs when the rainfall intensity is high. This is supported by an improvement in the predictability after the inclusion of intensities in the regression equation. The effects of rainfall and intensities were not additive because the predictability was not improved when rainfall and intensity were used as independent variables. Note, that in Fig. 7 the decrease in slope of the regression line for the different tillage practices is directly related to its potential benefit in reducing the runoff.

3.5.3. Group 3 (P2R>15 mm and SC<30%)

Group 3 includes rainfall events in which there was more than 15 mm rain during the preceding 2 days and

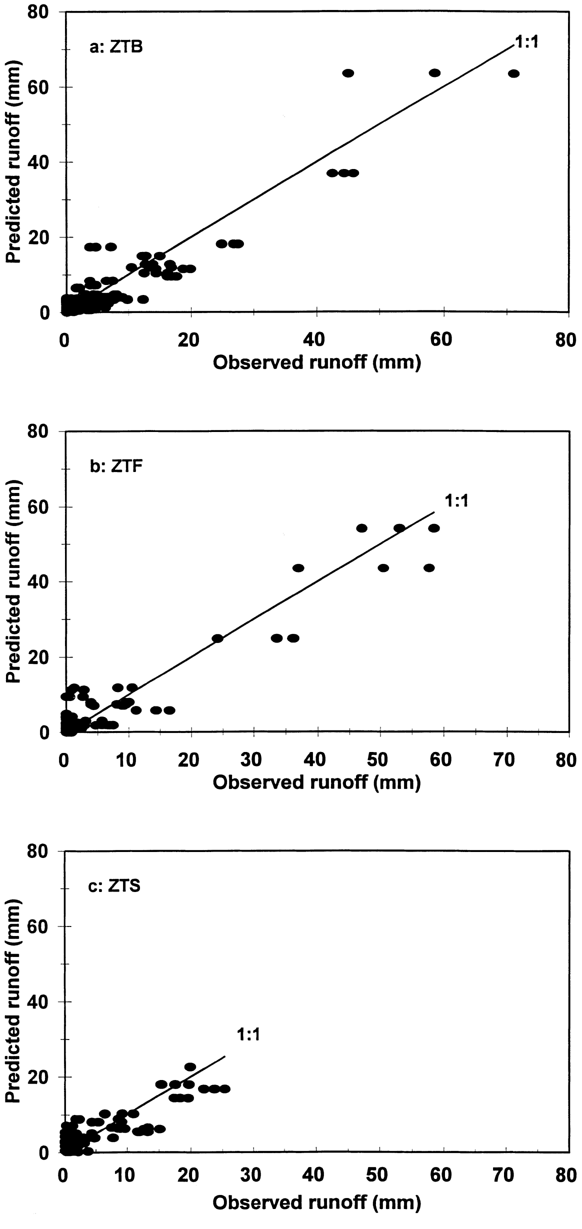

Fig. 7. Relationship between observed and predicted runoff for events in Group 2 using equations in Table 2 (with previous 2 days rainfall less than 15 mm and soil cover of more than 30%): (a) ZTB (zero tillage with no cover), (b) ZTF (zero tillage amended with farmyard manure), and (c) ZTS (zero tillage amended with straw).

the soil was covered by less than 30%. Relatively few of the rainfall events fell in this category: Only 5%, 8%, and 13% for ZTF, ZTS, and ZTB, respectively. Runoff as a percentage of the total runoff over the experimental period was 20% (ZTB), 18% (ZTF), and 16% (ZTS). Both rainfall amount and intensity were found to be important factors in predicting runoff (Table 2). Infiltration rates, in general, were higher than for Group 1 and might be related to a decrease in aggregate breakdown for wet soils compared with dry soils (Le Bissonnais and Singer, 1992).

3.5.4. *Group 4 (P2R>15 mm and SC>30%)*

The group containing 18%, 16%, and 10% of the events for ZTS, ZTF, and ZTB, respectively, had a soil cover that was greater than 30% and it had rained more than 15 mm during the preceding 2 days. Runoff which was mostly related to rainfall amount, was the least of all groups. It contributed to less than 10% of the 6 years total. The coefficient of determination for the ZTF and ZTS systems improved by about 5% when time was included in the regression (Table 2). However, the predictability is low for ZTF and ZTS systems.

4. Conclusion

The surface crust formed on Alfisols greatly affected the infiltration rate in the soil. On bare untilled soil, the crust limited the infiltration rate to approximately 10 mm h^{-1}. For bare soil, runoff rate can be estimated by subtracting the steady-state infiltration rate from precipitation.

The regression analysis performed on the data showed that when the soil was covered by less than 30% with organic residue or amendments, the rainfall amount was the best predictive parameter for estimating runoff. When the soil was covered by more than 30%, rainfall amount and intensity, soil cover, and time from the beginning of the experiment were needed to estimate the runoff.

Loss of rainwater as runoff on the structurally unstable crusting Alfisols was reduced effectively by maintaining a high soil cover. Therefore, from a management point of view, amount of water available to the crop can be increased by application of straw and farmyard manure.

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