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Effect of Surface Crust on Rainfall Infiltration in an Aridisoil in Northern Iraq

M. H. Hussein[1], M. M. Awad[2] and A. S. Abdul-Jabbar[2]
[1] *Department of Soil and Water, Babylon University, Hilla, Iraq*
e-mail: husseinmohammad@yahoo.com
[2] *Formerly of the Department of Soil and Water*
Mosul University, Mosul, Iraq

Abstract: The effect of surface crust on rainfall infiltration into a silty clay loam soil that belongs to the Calciorthid suborder was studied under natural rainfall for two rainfall seasons in the semiarid region of northern Iraq. Six natural runoff plots in fallow situated on a 6% uniform slope were used in the study. The experimental site has a mean seasonal rainfall of about 340 mm. It was observed that the crust layer consists of two distinct parts, the upper part was a skin layer with relatively high bulk density and high silt content compared to the lower part of the crust and the bulk soil. The crust layer saturated hydraulic conductivity at the end of rainfall season was one order of magnitude less than that of the bulk soil. Soil basic infiltration rate decreased during the rainfall season due to crust formation and this decrease was proportional to the accumulated rainfall kinetic energy during the season since the last tillage operation. Using this relationship, total rainfall infiltration was calculated for storms with runoff and compared with the difference between rainfall and runoff for these storms assumed to represent the measured total rainfall infiltration. The calculated values agreed reasonably well with the measured ones.

Keywords: rainfall infiltration; surface crust; runoff plots; low intensity rain; semiarid regions

1. INTRODUCTION

Rainfall infiltration (the process of rain water penetration from the ground surface into the soil) is a complex physical phenomenon. This is basically due to the soil being a very heterogeneous and anisotropic layered porous medium, exhibiting several characteristics that change with time. The infiltration process is affected by the intrinsic properties of the soil profile in addition to other dynamic factors such as tillage, hydraulic properties, rainfall conditions and surface sealing and crusting which is probably the most significant single factor affecting the infiltration process (Moore et al. 1980; Bradford et al. 1987; Freebairn et al. 1989; Zhan and Ng 2004; Wang et al. 2006; Savabi et al. 2008).

Formation of surface seals and crusts on bare soils is considered an important feature in many parts of the world particularly in arid and semiarid regions. Crust formation is caused by the destruction of the soil aggregates exposed to the direct raindrop impact, dispersion of clay particles at the soil surface, compaction, slaking in addition to pore filling and clogging by wash-in of fine materials (Agassi et al.1985; Assouline 2004). Soil crust layers are characterized and distinguished by their lower porosity, higher bulk density, lower degree of aggregation and higher amount of silt as compared to that of the underlying bulk soil (Sharma and Agrawal 1974; Awad et al.1992; Bradford and Huang 1992).

Modeling the effect of surface crust on infiltration is needed for a better land and water management in arid and semiarid regions (Hussein 1996; Al-Qinna and Abu-Awwad 1998; Tao et al. 2001). Soil surface crust and its effect on infiltration have been widely researched under controlled conditions like simulated rainfall (Lado et al. 2004; Lado et al. 2005; Fan et al. 2008). However, few studies have been carried out under natural conditions. In this paper, we used experimental data collected under natural rainfall to investigate the soil surface crust and its effect on rainfall infiltration for a soil belongs to the Aridisols order; a proposed relationship between rainfall infiltration and accumulated rainfall kinetic energy during the rainfall season will be tested.

2. SITE AND MEASUREMENTS

Six natural runoff plots were established in March 1988 on a silty clay loam soil with a 6% uniform slope at the Hammam Al-Alil experimental farm ($36^0$10'N, $43^0$20'E) in the northwestern part of Iraq. The soil at the site is classified as fine, mixed, thermic, calcareous, Xerollic Calciorthids. General soil characteristics are given in Table1.The plots were three 30 × 3 m plots followed by three 10 × 3 m plots; the distance between adjacent plots was 1m (Fig.1). Each fall, and after rain showers had moistened the soil, the plots were tilled by spading, then smoothed by hand tools and left bare throughout the rainfall season. Herbicides were used to control weeds.

The rainfall season in the region usually extends from October to May with normal rainfall intensity being less than 20 mm h^{-1}. The mean seasonal rainfall at the site is about 340 mm. The site was equipped with a nonrecording raingauge. A daily type recording raingauge was used since the 1989-1990 rainfall season. Differences in mean temperature between winter and summer months in the region are usually more than 20^0C. During the winter months, the minimum daily temperature occasionally drops below the freezing point. During the summer months, the maximum daily temperature is usually above 40^0C.

At the lower end of each plot a container was placed to collect surface runoff for each rainstorm producing runoff in order to measure the runoff volume, then calculating accumulated rainfall infiltration (evaporation during the rainstorm was neglected).The measurements discontinued at the end of the1991-1992 rainfall season. No measurements were taken during the1990-1991 rainfall season.

Table 1. Soil and crust characteristics at the experimental site

Soil/ crust layer	Thick (mm)	Particle size dist.: %clay	%silt	%sand	Bulk dens. (Mgm^{-3})	Rock Fragm. (%)	Org. mat. (%)	$CaCO_3$ (%)	CEC[a] (Cmol Kg^{-1})	MWD[b] of agg. (mm)	Sat. cond. (mm h^{-1})
Surface soil	300	36	44	20	1.30	13	1.5	28	24	0.26	37
Upper crust	3.3	28	62	10	1.52						3.2
Lower crust	4	28	54	18	1.36						

[a] *Cation exchange capacity.*
[b] *Mean weighted diameter.*

Crust development during the rainfall season was monitored by periodic measurements using a pocket penetrometer (Bradford 1986). At each reading time, three measurements were taken on each side of the small plots compared to five measurements on each side of the large plots. The penetrometer readings were recorded when 5 mm of the conical point penetrates through the soil surface. Due to its effect on penetration resistance, soil moisture was recorded at each reading time by using the neutron probe method; maximum penetration resistance on the plots (about 0.4 MPa) was recorded at the end of rainfall season when the soil moisture at the soil surface was between 0.2 and 0.25 V/V (Hussein et al. 1993; Lampurlanes and Centro-Martinez 2003; Topp et al. 2003).

At the end of each rainfall season, we separated the crust layer for a small spot of each plot. These samples were used to determine: (a) thickness of the crust layer using a vernier (b) its bulk density using the paraffin wax method (Blake and Hartge 1986) (c) its particle size distribution using the hydrometer method (Gee and Bauder 1986). Undisturbed soil core samples were taken with and without the crust layer for measurement of the saturated hydraulic conductivity by using the falling head method (Klute and Dirksen 1986).

(a)

(b)

Figure 1. Natural runoff plots used in the study. (a) small plots; (b) large plots

3. MODELING THE EFFECT OF SURFACE CRUST ON RAINFALL INFILTRATION

In arid and semiarid regions a Hotanian overland flow is usually assumed which means that runoff occurs when rainfall intensity exceeds soil infiltration rate (Chow et al. 1988). In not ponding rain (i.e. no runoff), infiltration rate is assumed to occur at the storm rainfall intensity and nearly all rainfall will be infiltrated into the soil (Rigby and Porporato 2006). For storms with runoff, infiltration rate after ponding decreases with time until it reaches a nearly constant value called the basic infiltration rate (f_c); therefore for such storms it can be assumed:

$$I_c / f_c > 1 \tag{1}$$

where I_c = characteristic intensity for the storm. Both I_c and f_c are expressed in mm h^{-1}. A rainfall intensity for a duration equal to or greater than the time of concentration for the plots is a suitable characteristic rainfall intensity. It was found (Hussein et al. 1994) that the maximum 5 min intensity (I_5) is a suitable characteristic rainfall intensity at this site.

Surface sealing and crusting significantly reduce soil infiltration rate on bare soils. Hussein (1996) proposed the following formula to describe soil basic infiltration rate for the crust affected soil during the rainfall season:

$$f_c = \alpha / E_* + \beta \tag{2}$$

where E_* = ratio of total kinetic energy (KE) of rain occurred since the last tillage operation to total seasonal kinetic energy of rain after that tillage and α, β are coefficients which reflect rainfall pattern and crust characteristics. Soil basic infiltration rate for the freshly tilled and smoothed soil as measured by a double ring infiltrometer (Bouwer 1986) was 46 mm h^{-1}. At the end of rainfall season, soil basic infiltration rate drops to as low as 3.2 mm h^{-1}(Table1).

The form of equation 2 satisfactorily approximates the rapid decrease in soil infiltration rate associated with the crust development (Morin and Benyamini 1977). To evaluate α and β, we assumed that f_c is a maximum (46 mm h^{-1}) until the accumulated rainfall kinetic energy during the rainfall season after the last tillage operation reaches 2 MJ ha^{-1}. This amount of kinetic energy is considered sufficient to initiate surface sealing (De Ploey 1985). The periodic field penetrometer measurements indicated a gradually developing crust thickness during the rainfall season (Awad et al. 1992). Hence, f_c reaches its minimum value (3.2 mm h^{-1}) at the end of rainfall season where E_* is assumed equal to unity. Accumulated rainfall kinetic energy after the last tillage operation was 33.5 MJ ha^{-1} for the1989-1990 rainfall season and 40.25 MJ ha^{-1} for the1991-1992 rainfall season. The1989-1990 rainfall season is considered more representative of the rainfall pattern in the region compared to the1991-1992 rainfall season as will be shown later in this paper. For this reason, we evaluated α and β separately for these two rainfall seasons. The obtained α values were 2.72 and 2.22 for the1989-1990 and1991-1992 rainfall seasons respectively. The corresponding β values were 0.48 and 0.98 for the1989-1990 and1991-1992 rainfall seasons respectively.

A check on the above procedure to evaluate α and β values was made using the relationships developed for the WEPP model (Alberts et al. 1995) with the assumption that the saturated hydraulic conductivity is a good estimator of f_c (Hsu et al. 2002). The soil stability factor in WEPP for this soil (represents the rapidity in which the hydraulic conductivity declines to its fully-crusted value) was 0.001335 m^2J^{-1}; the values obtained for the WEPP model using natural runoff plot data were between 0.00006 and 0.0312 m^2J^{-1}. The crust factor in WEPP for this soil (a factor can adequately predict the maximum reduction in hydraulic conductivity due to crust formation) was 0.0577. When the crust factor was multiplied by 46 mm h^{-1} the result was 2.65 mm h^{-1}, a value considered comparable to the 3.2 mm h^{-1} value used in this analysis. Furthermore, substitution of these two hydraulic conductivity values (i.e. 46, 3.2 mm h^{-1}) in the WEPP relationship between freshly tilled and crust affected hydraulic conductivities (random roughness is assumed zero due to the smoothed soil surface) gives an accumulated seasonal rainfall kinetic energy of 32.77 MJ ha^{-1} which is comparable to the value obtained for the1989-1990 rainfall season.

Accumulated rainfall infiltration (F) during the storm expressed in mm is calculated from:

$$F = f_c(T + \varepsilon - T_e) + a \tag{3}$$

where T = characteristic storm duration (h) given by:

$$T = V_r / I_c \tag{4}$$

where V_r = rainfall depth (mm).ε = runoff receding time (i.e. time that runoff continues after the end of rain storm). For the tilled and smoothed plots in this study, ε can be approximated by:

$$\varepsilon = T_c \quad (5)$$

where T_c = time of concentration for the plots (h) estimated (Kerby 1959) from:

$$T_c = (2.2 n \lambda / \sqrt{s})^{0.467} / 60 \quad (6)$$

where n = Manning's roughness coefficient, λ = length of plot (m) and s = sine of slope angle. T_e = the characteristic delay time (h) (i.e. time lag between rainfall and runoff) estimated by the following equation:

$$T_e = (a / V_r) T \quad (7)$$

where a = rainfall depth (mm) required to saturate the crust layer at the beginning of storm estimated from:

$$a = (\theta_s - \theta_i) \Delta d \quad (8)$$

where θ_s = saturated soil moisture level (V/V), θ_i = initial soil moisture level (V/V) just before the start of rain and Δd = thickness of the crust layer (mm).

The continuity principles described above may be sufficient to describe the accumulated rainfall infiltration for small areas similar to the small sized plots in this study. However, routing becomes necessary for the large plots. Hussein (1996) used hydrologic routing and the concept of linear reservoirs (Nash 1957) to estimate water storage on the large plots during the storm event:

$$Z = 1/2\,(T_c + a / I_c)(I_c - f_c) \quad (9)$$

where Z = total water storage (mm). Hence for the large plots, equation 3 becomes:

$$F = f_c (T + \varepsilon - T_e) + a + Z \quad (10)$$

Measured total rainfall infiltration (F_m) on the plots expressed in mm is approximated by the difference between rainfall and runoff depths:

$$F_m = V_r - V_u \quad (11)$$

where V_u = storm runoff depth (mm).

4. RESULTS AND DISCUSSION

4.1 Nature of the surface crust

The structure of the surface crust was investigated seasonally at the end of each rainfall season. It was found that the crust layer consists of two distinct parts, an upper skin seal and another lower thin layer. Table1shows an increase in silt content and a decrease in both clay and sand contents in the crust layer compared to their contents in the bulk soil. Soil aggregates disintegrate due to raindrop impact which leads to crust formation. The small aggregates contain little or no sand while the clay content in the large aggregates is substantially less compared to that in the original soil (Foster et al. 1985). The mean weighted diameter of aggregates (MWD) in Table1 indicates a mixture of small and large aggregates in the original soil. Hence, the disintegration of these aggregates by raindrop impact results in a surface crust texture which is higher in silt and lower in sand and clay compared to that of the original soil. The crust high bulk density and small pore size lowered its hydraulic conductivity (Table1).

4.2 Infiltration rate into the crusted soil

We observed from the double ring infiltrometer measurements a sharp decrease in soil infiltration rate with and without the crust layer after a few minutes. The crusted soil infiltration capacity (infiltrability) was higher than the uncrusted soil. The reason is related to the higher driving force in the crusted soil at the beginning of measurements. However, infiltration rate decreased more rapidly in the crusted soil compared to the uncrusted soil due mainly to the effect of the crust layer on the saturated hydraulic conductivity. In applying equation (2), f_c calculated at the start of rain is considered the characteristic f_c during the storm event (Table 2); this is because the time required for the rainfall infiltration rate to drop to f_c is, in general, considerably less than total storm duration (Stone et al. 2008).

4.3 Total rainfall infiltration

Total rainfall infiltration values estimated by equations (3) and (10) are given in Table 2 for both types of plots. The measured values in Table 2 are the averages of the three replicates since statistical tests indicate no significant differences at the 95% level in runoff depth among the replicates. Figure 2 is a plot of the predicted total rainfall infiltration versus the measured one for the small and the large plots; there is no significant difference at the 95% level between predicted and measured total rainfall infiltration for both types of plots. During the1989-1990 rainfall season, there is noticeable under prediction by the model for the storm of 15-3-1990 for both types of plots. For this normal storm (I_c < 20 mm h^{-1}), the ratio f_c / I_c is small (Table 2); this will result in an appreciable reduction in the calculated total rainfall infiltration by equations 3 and 10. Although the severe storm ($I_c \geq$ 20 mm h^{-1}) of 14-3-1990 has also a small f_c / I_c ratio (Table 2), no under prediction of total rainfall infiltration by the model occurred; the reason is probably related to the rapidness of runoff accumulation at the outlets of these generally short field plots caused by the storm high intensity; high rainfall intensity results in a higher runoff ratio (ratio of runoff to rainfall) on short field plots and subsequently, the ratio of total rainfall infiltration to rainfall depth will be reduced. During the1991-1992 rainfall season, noticeable under prediction of total rainfall infiltration by the model occurred for the normal storms of 25-2-1992 and 6-3-1992; Hussein et al. (2005) reported a diminishing runoff on these plots from normal storms during this season starting from the late winter due to the dominance of low intensity rain storms occurred during this season.

Under prediction of total rainfall infiltration by the model is more pronounced on the large plots compared to the small plots (Fig. 2) due to the ratio f_c / I_c being affecting both F and Z values in equations (3) and (9) respectively. Using variable α and β values during the rainfall season will probably improve the prediction by equation (2).

There were one storm in the1989-1990 rainfall season and two storms in the1991-1992 rainfall season where $I_c < f_c$ (Table 2). According to the proposed concept, all rainfall will be infiltrated into the soil; however, measured total rainfall infiltration for these storms was less than total rainfall especially for the small plots (Table 2).The reason is likely related to the relative rapidness of any accumulated runoff in reaching the plot outlet especially in the case of small plots.

A widely used infiltration model in hydrologic modeling is the Green-Ampt model (Chow et al. 1988). However, this model failed to predict total rainfall infiltration in this experiment except for one severe type storm (storm of 30-11-1989). The Green-Ampt model is ill-fitted to the analysis of infiltration into crusted soils (Philip 1998). Furthermore, rainfall pattern in the region includes long periods of low intensity or zero rainfall; this will cause the wetted soil profile to redistribute and the Green-Ampt model will no longer be valid (Skagg and Khaleel 1982). More research data are needed, however, to test the validity of the Green-Ampt model and other infiltration models in the region.

Table 2. Measured and predicted accumulated rainfall infiltration for single storm events (S = small plots, L = large plots)[a]

Date of storm	V_r (mm)	I_5 (mm h^{-1})	θ_i (V/ V)	Acc. KE[b] (MJ ha^{-1})	E_*	f_c (mm h^{-1})	F_m (mm) S	F_m (mm) L	F^d (mm) S	F^d (mm) L
1989-1990 rainfall season										
30-11-89	23.5	55	0.22	0.15	-[c]	9.55	6.50	7.50	5.97	7.80
09-12-89	8.5	20	0.25	10.11	0.30	9.55	5.70	5.87	5.22	6.04
05-01-90	13	10	0.24	11.03	0.33	8.72	9.04	11.72	11.77	12.04
23-01-90	7.5	6	0.24	12.80	0.38	7.64	5.19	7.09	7.50[e]	7.50
15-02-90	9	9	0.26	18.34	0.55	5.42	5.55	8.61	6.26	6.75
19-02-90	10	21	0.29	19.50	0.58	5.17	4.70	6.71	3.75	4.69
14-03-90	20	50	0.29	22.30	0.67	4.54	3.00	4.00	3.30	4.90
15-03-90	12	19	0.29	26.84	0.80	3.88	6.00	8.00	3.75	4.70
03-04-90	10	6	0.29	29.34	0.88	3.57	8.95	9.70	6.64	7.04
06-04-90	6	24	0.30	31.00	0.93	3.40	2.33	3.02	2.18	3.23
1991-1992 rainfall season										
31-12-91	16	9	0.23	11.53	0.29	8.64	12.33	14.55	15.64	15.82
07-01-92	11	4	0.23	14.15	0.35	7.32	8.98	10.20	11.00[e]	11.00
20-01-92	14.5	6	0.24	16.02	0.40	6.53	13.80	14.00	14.50[e]	14.50
11-02-92	7.5	6	0.30	26.73	0.66	4.34	6.12	6.96	5.94	6.23
23-02-92	10	6	0.31	27.83	0.69	4.20	8.20	9.30	7.53	7.83
25-02-92	10	9	0.30	29.18	0.72	4.06	8.20	9.30	5.40	5.95
26-02-92	4.2	20	0.30	30.74	0.76	3.90	2.39	3.89	2.08	3.02
06-03-92	11	10	0.31	33.00	0.82	3.69	8.27	10.72	5.02	5.62

a: Storms before the last tillage operation and storms with negligible runoff were not included.

b: Accumulated rainfall kinetic energy at the start of storm and since the last tillage operation (27-11-1989 for the 1989-1990 rainfall season and 10-12-1991 for the 1991-1992 rainfall season).Total accumulated kinetic energies were 33.5 and 40.25 MJ ha^{-1} for the 1989-199 and 1991-1992 rainfall seasons respectively. Rainfall kinetic energy was estimated by breaking the storm into increments of approximately uniform intensity and calculating rainfall energy for each increment using a rainfall energy equation (Hussein and Mahmood 1993; Renard et al. 1997).

c: This high intensity short duration storm was the first significant storm occurring after tillage. In this case, rainfall consolidates the soil and increases its bulk density (Onstad et al. 1984). For this reason, accumulated rainfall kinetic energy at the end of storm was considered.

d: Calculated using equation (3) for the small plots and equation (10) for the large plots; n = 0.02 (Table 1; Foster et al. 1980), θ_s = 0.5 (Hussein et al. 1993), Δd = 7.3 mm (Table 1).

e: $I_c < f_c$ for these storms; F = total rainfall.

5. CONCLUDING REMARKS

The basic concluding remarks are the following:

- Soil basic infiltration rate on a bare soil decreases sharply during the rainfall season after initial tillage due to surface seal and crust development.
- Soil basic infiltration rate into a crusted soil at a date during a cultivation season can be satisfactory predicted by using the accumulated rainfall kinetic energy for the season, up to that date.

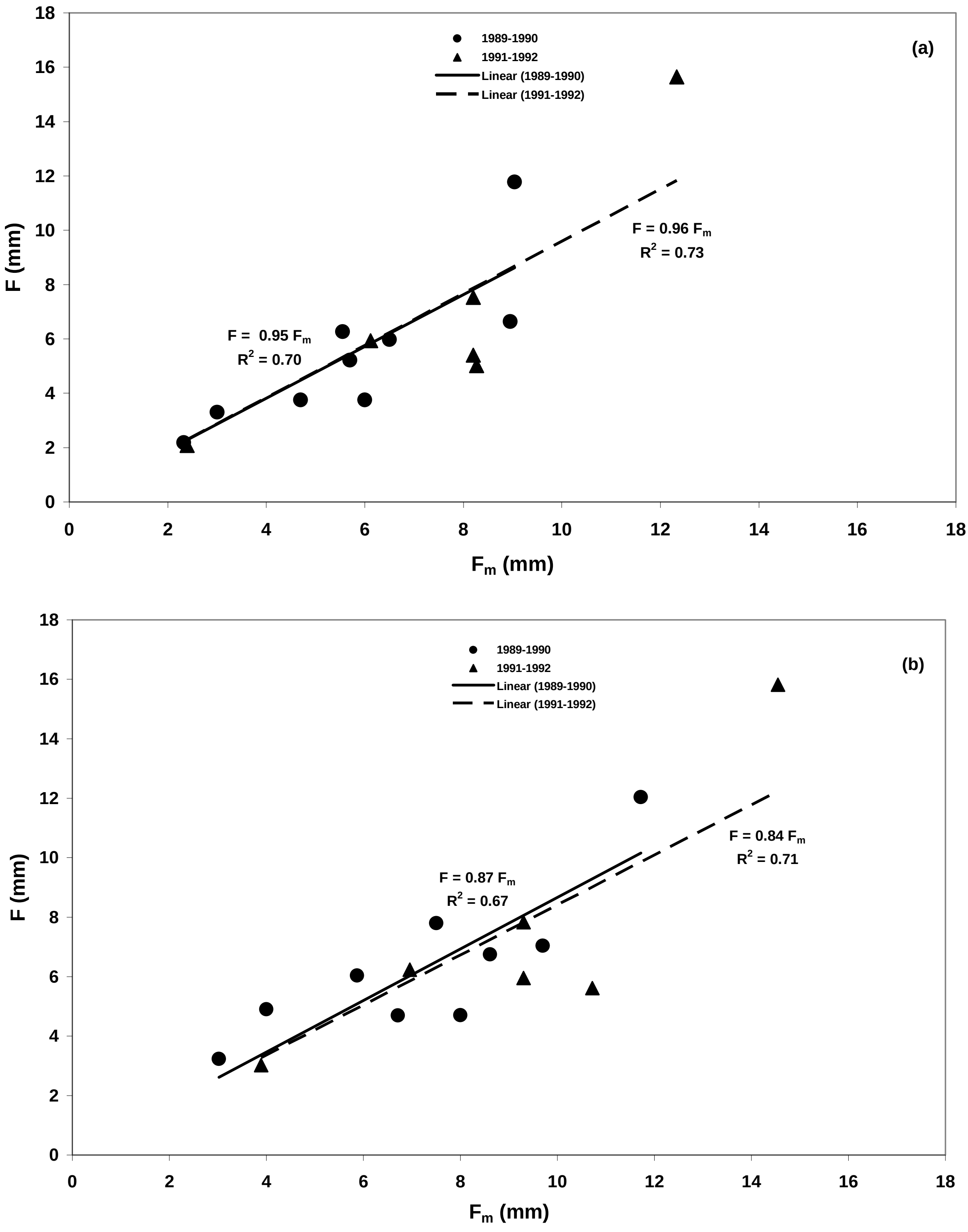

Figure 2. Predicted versus measured total rainfall infiltration for storms with $I_c > f_c$. (a) small plots; (b) large plots

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