BARD

FINAL REPORT

PROJECT NO. US-970-85

Rainfall Infiltration as Affected by Soil Aggregation Resulting from Different Tillage Methods

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1990

BARD
P.O.B. 6
Bet Dagan, 50250 ISRAEL

August 15, 1990

BARD Research Project No. US-970-85R

Title of Research Project:

Rainfall Infiltration as Affected by Soil Aggregation Resulting from
Different Tillage Methods

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Project's Commencement Date: October 1, 1986

Type of Report: Final

Signature

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C. Abstract

Limited precipitation limits crop production in semiarid regions. Irrigation increases production, but declining supplies, competition for water, and high pumping costs have caused a major emphasis on water conservation in many regions, especially where dryland farming is practiced. Water conservation, however, often is hindered by soil surface conditions that cause runoff, even from small rainstorms. Besides loss of water, runoff causes erosion. In this study, we used rainfall simulators to determine the influence of tillage-induced soil aggregates and their stability on water infiltration on Pullman (fine, mixed, thermic Torrertic Paleustoll) soil at Bushland, Texas, and on Loess and Gromosol soils in Israel with rainfall simulators. Different tillage methods caused aggregate size and stability differences, which influenced infiltration. However, aggregate factors were not dominant in affecting infiltration. Others included soil organic matter concentration and surface residue cover and soil roughness. With limited residues, soil-loosening tillage increased infiltration. On unstable soils with low residues, surface pitting increased water infiltration, soil water storage, and crop yields. Computer modeling involving long-term rainfall records was effective for determining the surface storage needed to minimize runoff and for selecting appropriate tillage methods for conserving water and improving yields. Use of rainfall simulators is an efficient method of evaluating tillage methods relative to their effectiveness for increasing water storage and crop yields.

D. The objectives

- I. To determine the effect of tillage methods on distribution of aggregates in the upper layer of the soil, and their effect on water infiltration and runoff from rainstorms.
 - a. To determine the influence of applied rainfall on the physical and hydraulic properties of the soil surface.
 - b. To define the relative influence of the stability of different size aggregates on the stability of the entire mixture resulting from different tillage practices.
- II. To use simulated rain on small plots as a tool to evaluate the potential of different tillage methods for conserving water from rainfall.
- III. To compare infiltration results obtained from simulated rainfall and runoff results obtained from precipitation under natural conditions.

E. Body of the report

INTRODUCTION

Limited precipitation limits rainfed crop production in semiarid regions of the world. Where water resources are available, irrigation can greatly increase yield. However, declining water supplies, competition for water, and rapidly increasing energy costs for pumping water have resulted in an increased emphasis on water conservation in many regions of the world, especially in semiarid regions where dryland farming practices are used.

In arid and semiarid regions, the quantity and distribution of rainfall are unfavorable for agriculture. Annual rainfall is low, uncertain, and sporadic. Paradoxical as it may sound, however, in spite of the deficiency in rainfall, substantial amounts of runoff have been measured in such regions, for example, the northern part of the Negev in Israel (Hillel, 1960) and the Texas Panhandle in the northern part of the state (Jones and Hauser, 1975). Runoff is most obvious and has an immediate economic effect on the farmer, but soil erosion may also be a serious problem.

In these areas, tillage is widely used to control weeds, increase water infiltration, and improve soil physical conditions for crop establishment and development. Different amounts of runoff result from different tillage methods used in these regions. These tillage methods also produce different soil structures in the profile and in the surface layer.

The soils in the northern Negev in Israel and in the Texas Panhandle are wind-deposited soils. The soils in Israel and the Pullman soils have very weak structural development, largely because of their high silt content. Different tillage practices for weed control during the fallow period in the rotation and for seedbed preparation result in different aggregate size distributions in the tillage layer (Ap horizon). The behavior of the soil

structure as a result of applied rainstorms on the surface is the key to understanding, controlling, and preventing the loss of water and soil from cultivated fields, and of obtaining water storage at a soil depth that minimizes subsequent loss of the water by evaporation.

Tillage operations performed under different conditions produce aggregate size distributions that result in varying surface stabilities and infiltration capacities. Surface crust formation is a result of the breakdown of soil aggregates when rainfall occurs.

The goal of this study is to better understand the role of soil structure and its stability on the one hand, and the possible use of plant residues as a soil protectant on the other hand, to achieve improved water infiltration and seedbed conditions for overall improved soil and water conservation and crop yields.

Through a knowledge of the influence of the stability of aggregate groups on the stability of the entire aggregate mixture and its influence on the other physical and hydraulic properties of the upper layer, on the infiltration capacity, and on crust formation, we will improve our ability to choose the tillage method that will produce the desired conditions for different purposes (water conservation and seedbeds). The results will be improved water conditions in the soil profile and better establishment and growing conditions for the crops.

LITERATURE REVIEW

The phenomenon of surface runoff as a result of rainfall and resultant loss of water can be attributed to the formation of a surface crust. This crust is formed by the combined action of the kinetic energy of falling raindrops (McIntyre, 1958) and the dispersive effect of the rainwater that is

virtually devoid of electrolytes (Agassi et al., 1981). According to Hillel (1960), the problem is likely to be the most severe in unstable soils of arid regions, and where irrigation and tillage practices are carried out. Tillage practices result in different aggregate size distributions (Benyamini, 1981; Dexter et al., 1983; Hadas et al., 1978; Unger, 1984) which in turn are affected by the soil type, the implement, and soil water content at the time of the operation (Armbrust et al., 1982). The physical and hydraulic properties of the aggregated soil surface are changed by rainstorms (Falayi and Bouma, 1975). These changes in properties are related to the aggregate stability (DeBoodt et al., 1961; Rawitz and Hazan, 1978), the quantity of rain applied to the soil surface (Dexter et al., 1983; Morin and Benyamini, 1977), and the kinetic energy of raindrops (Eigel and Moore, 1983; Wustamidin and Douglas, 1985). The disintegration of the aggregates and the re-oriented particles at the soil surface form the crust which is the main factor affecting the infiltration decreases under natural rainfall.

The disintegration of aggregates starts when they become wet and are hit by raindrops. The rate at which water penetrates into the aggregate depends on aggregate size (Gumbs and Warkentin, 1976). Therefore, large surface aggregates will disintegrate slower than small aggregates (Cogo et al., 1983). Hadas et al. (1978) showed the effects of different tillage practices on aggregate distribution, soil properties, and plant stand. The crust which develops at the soil surface not only decreases the infiltration, but also becomes a mechanical impedance for seed emergence (Taylor, 1962; Parker and Taylor, 1965). The ESP value of the soil has an influence on the stability of the aggregates. There is also an influence of the SAR of the water on the surface-sealing process (Agassi, 1981).

Characterization of the soil properties which are related to infiltration capacity might be done by infiltration curves (Benyamini, 1981; Moore, 1981; Morin and Benyamini, 1977; Morin et al., 1981) and other parameters such as aggregate size distribution and stability, random roughness (Burwell and Larson, 1969), porosity (Allmaras et al., 1967), and crust strength (Lindstrom and Onstad, 1984; Lindstrom et al., 1984; Unger, 1984).

The stability of the surface, which contains a mixture of aggregates, depends on the stability of the different aggregate groups in the mixture. The different tillage operations which develop different aggregate mixtures might be characterized by the infiltration or runoff process.

In order to understand the influence of different tillage methods on the infiltration process, it is essential to understand the role of aggregate stability in soil on crust formation. An understanding of the influence of aggregate size stability groups in soil on stability of the entire mixture will permit us to evaluate the relative contribution of each group and to determine which group is most influential on the stability of the soil surface. This will further permit us to evaluate or to predict the above influences on the infiltration process. Further, choosing the tillage method for obtaining desired surface conditions might be possible when the influence of aggregate condition on the infiltration process and on soil properties is known.

The infiltration process for different tillage methods can be measured and described through use of a rainfall simulator. The model of crusting is described by the equation of Morin and Benyamini (1977) which is:

$$I_t = (I_i - I_f)e^{-\gamma p t} + I_f \quad [1]$$

where I_t = infiltration rate (mm/h),
 t = time from the beginning of rain (h),
 p = rainfall intensity (mm/h),
 I_i = initial infiltration rate (mm/h),
 I_f = final infiltration rate (mm/h), and
 γ = coefficient--relates to aggregate stability or rain (1/mm).

The infiltration process can also be described by a similar equation which is related to the kinetic energy of rainfall (Eigel and Moore, 1983). This equation is:

$$I_t = (I_i - I_f)e^{-(\beta_e(E_{sp}))} + I_f \quad [2]$$

where β_e = cumulative kinetic energy coefficient (m^2/J),
 E = kinetic energy (J/m^2), and
 E_{sp} = cumulative rainfall energy at the time of surface ponding (J/m^2).

The β_e coefficient is functionally the same as the soil stability factor S (m^2/J).

The stability of the soil is not dependent on any one property of the soil alone, but is affected by a combination of many factors. Wustamidin and Douglas (1985) used a model based on multiple regression analysis to show that a combination of several factors affected aggregate stability.

The amount of runoff from cultivated soils can be calculated by combining the infiltration rates of the soil with the recorded rainstorms in the region (Morin and Jarosch, 1977). Surface storage is the water depth which remains on the surface without flow. A long-term analysis of runoff probabilities can be calculated for the known infiltration area and for any desired surface

storage. Field experiments in Israel and Arizona using a rainfall simulator on small plots verified the ability of the infiltration-rainfall model to predict runoff from large scale fields (Morin and Cluff, 1980; Rawitz et al., 1983).

Various infiltration curves for loess soil were obtained for different tillage methods by using a Rotary Disk Type Rainfall Simulator (Benyamini, 1981; Morin et al., 1984; Rawitz et al., 1983). The rainfall simulators (a lab unit and portable one) were developed at the Soil Erosion Research Station in Israel according to plans for the original type described by Morin et al. (1967). The main advantage of this simulator is that it simulates the energy and the intensities of natural rainfall (Morin et al., 1967). The same type of rainfall simulator with the same characteristics was built at the USDA Conservation and Production Research Laboratory at Bushland, Texas, in 1983. Early data show that differences in infiltration result from different tillage methods.

A study was conducted in Israel on a soil with 34% silt, 34% clay, and 32% sand to compare different tillage methods. A rainfall simulator was used to apply simulated rainfall at 56.0 mm/h until the final infiltration rate was achieved. Infiltration curves for the study are shown in Fig. 1 (Benyamini, 1981).

The different tillage methods were:

1. Plow, disk four times
2. Plow, disk four times, roll
3. Rotary
4. Rotary, roll
5. Disk two times
6. Disk two times, roll

Fig. 1. Tillage treatment effects on water infiltration.

These tillage operations gave different aggregate size distribution in the surface as shown in Fig. 2. The curves in Fig. 2 describe the aggregate size distribution based on the relationship between the aggregate percentage by weight and their diameter. The curves were different for the above tillage methods.

Fig. 2. Aggregate distribution as affected by tillage treatment.

DETAILS OF STUDIES

Field and laboratory studies associated with this report were conducted at Bushland, Texas (USA), and in Israel. In this section, the details of the various studies are presented separately. This is followed by general discussion and conclusions sections pertaining to the results of all studies.

Bushland, Texas -- Study 1

Tillage and Crop Residue Effects on Water Infiltration

Tillage per se may increase or decrease water infiltration. It increases infiltration when it loosens surface crusts or dense soil layers, or provides surface depressions for temporary storage. Tillage may decrease infiltration when it smooths the surface, disperses aggregates, eliminates surface residues, or causes compaction. Crop residues retained on or near the soil surface usually enhance infiltration by dissipating raindrop energy, thus minimizing aggregate dispersion and surface sealing, and by retarding surface water flow, thus providing more time for infiltration. Incorporated residues result in favorable infiltration when they maintain favorable soil porosity and organic matter concentrations. In this study, we determined the influence of tillage and residue treatments on infiltration using a rainfall simulator. Various soil parameters associated with water infiltration also were measured to aid in interpreting the results.

METHODS AND MATERIALS

Infiltration studies were conducted at the USDA Conservation and Production Research Laboratory, Bushland, Texas (USA). Water was applied to field plots with a rotating disk type rainfall simulator (Morin et al., 1967) until the runoff rate became constant. Infiltration rate was calculated as the difference between measured runoff and water application rates. The

infiltration parameters (I_t , I_f , and γ for a storm were obtained from the determined values of I_f , p , and t using the least squares fit of the equation (Eq. [1]) of Morin and Benyamini (1977).

Measurements were made in 1987 at two field areas on a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll) that contained about 17% sand, 53% silt, and 30% clay, and had less than 1% slope. Dryland grain sorghum [*Sorghum bicolor* (L.) Moench] was grown on Area 1 in 1986 (planted in June, harvested in October). Dryland winter wheat (*Triticum aestivum* L.) was grown on Area 2 during the 1986-87 season (planted in October 1986, harvested in June 1987). On both areas, crop residues remained undisturbed until treatments were imposed. Residue amounts were 4.49 Mg/ha after sorghum and 2.17 Mg/ha after wheat. Treatments applied to both areas were: MB--moldboard plowing about 15 cm deep followed by one disking (residues plowed under); RT--rotary tillage about 15 cm deep (residues mixed with soil); ST-Res--sweep tillage about 15 cm deep after residues were removed; ST+Res--sweep tillage about 15 cm deep with residues not removed; NT-Res--no-tillage with residues removed; and NT+Res--no-tillage with residues retained. Plots were 4 m wide and at least 10 m long. All treatments were replicated four times. On each area, the experiment had a randomized block, split-plot design with blocks being replications and subplots being tillage treatments. For residue removal treatments, residues were cut at 2 to 5 cm above the soil surface with a forage chopper and removed.

In addition to the measurements directly associated with the application of simulated rainfall (water application rate, runoff), other measurements were made either on the areas enclosed by the metal frames, on areas adjacent to the frames, or on samples collected from areas adjacent to the frames.

These measurements were:

1. Dry aggregate size distribution before and after applying the water by using the rotary sieving procedure of Chepil (1952).
2. Size distribution of water stable aggregates by wet sieving before and after applying the water using the procedure of Kemper and Chepil (1965).
3. Random roughness of the surface before and after applying water using the technique of Allmaras et al. (1966).
4. Percent surface residue cover using a procedure similar to that of Sloneker and Moldenhauer (1977).
5. Soil pH using standard procedures on a 1:1 soil to water paste.
6. Soil salinity (ESP) determined by procedures outlined in Agric. Handbook 60 [Richards (ed.), 1954].
7. Electrical conductivity and sodium content of the water determined by procedures outlined in Agric. Handbook 60.
8. Soil bulk density and porosity determined by drying and weighing soil contained in a known-volume sample, then calculating the density and porosity. A particle density of 2.65 Mg/m^3 was used to calculate the porosity.
9. Sediment losses resulting from the runoff determined by collecting, drying, and weighing soil that moves from the runoff areas. (These soil losses will not be directly applicable to potential soil losses from standard runoff plots, but should be satisfactory for establishing relative differences in soil losses among tillage treatments.)
10. Soil water content measured in the upper soil profile (0- to 10-cm depth) and for the 0- to 1.2-m profile before applying water.

Stored rainwater was applied at a rate of about 52 mm/h. The water had an electrical conductivity (EC) of 0.0039 S/m and a sodium concentration of 0.196 mg/kg. The exchangeable sodium concentration (ESP) of the soil averaged 14.0 and 15.2 mg/kg on Areas 1 and 2, respectively. Infiltration measurements were made on 1.5-m² areas enclosed by a metal frame that was designed to permit measurement of runoff. Water was applied to dry soil (first rain) and to wet soil (second rain) after a few days.

Data were analyzed by the analysis of variance technique with separate analyses being performed on data from each site. The infiltration data were analyzed with infiltration models based on rain depth (amount of water applied).

In addition to the above analyses, data were further analyzed by regression and correlation techniques to establish relationships among the various measured factors that affect infiltration and runoff. Finally, the data will be available for use in models to predict runoff from field-size watersheds (Morin and Jarosch, 1977). To test the models, runoff data from instrumented watersheds at Bushland, Texas, could be used. Runoff data are available for the last 29 years and precipitation data are available for the last 47 years.

RESULTS AND DISCUSSION

Tillage and residue treatment effects on infiltration parameters for the first and second rains for the two areas are given in Table 1. Results of other determinations made in association with the infiltration measurements on Areas 1 and 2 are given in Tables 2 and 3, respectively.

Infiltration

For the first rain after sorghum (Area 1), I_1 was highest for the ST-Res treatment and lowest for the NT+Res treatment (Table 1). Reason for

Table 1. Infiltration parameters^{1/} for first and second simulated rains on Pullman soil field areas as affected by tillage treatments, Bushland, Texas.

Area ^{2/} and treatment ^{3/}	First rain				Second rain			
	I _f	I _f	γ	R ²	I _f	I _f	γ	R ²
Area 1								
MB	139.8	11.4	-0.026	0.931	29.0	6.3	-0.022	0.744
RT	125.6	16.0	-0.030	0.940	31.5	8.6	-0.035	0.644
ST-Res	284.5	24.5	-0.035	0.842	49.6	5.1	-0.024	0.941
ST+Res	97.5	24.2	-0.027	0.866	59.5	14.9	-0.019	0.947
NT-Res	138.7	13.9	-0.046	0.839	34.0	6.8	-0.022	0.708
NT+Res	38.4	12.1	-0.012	0.629	73.2	13.1	-0.037	0.921
Area 2								
MB	73.5	2.7	-0.014	0.950	33.3	5.2	-0.035	0.855
RT	99.9	7.0	-0.026	0.929	27.7	7.3	-0.037	0.878
ST-Res	75.0	6.9	-0.017	0.898	41.0	9.0	-0.036	0.916
ST+Res	110.3	3.3	-0.021	0.965	37.8	26.3	-0.020	0.667
NT-Res	73.2	3.4	-0.051	0.925	48.1	3.7	-0.067	0.842
NT+Res	72.5	9.2	-0.055	0.817	36.4	3.3	-0.054	0.740

^{1/} See text for description of parameters.

^{2/} Area 1--after dryland grain sorghum; Area 2--after dryland winter wheat.

^{3/} Tillage treatments: MB--moldboard + disk; RT--rotary; ST-Res--sweep, residues removed; ST+Res--sweep, residues in place; NT-Res--no-tillage, residues removed; NT+Res--no-tillage, residues in place.

Table 2. Soil parameters for Area 1^{1/} of Pullman soil determined before or after simulated rainfall, Bushland, Texas.

Type and time of measurement	Tillage treatments ^{2/}					
	MB	RT	ST-Res	ST+Res	NT-Res	NT+Res
Dry aggregate size (MWD)--mm						
Before	23.6a ^{3/}	10.9c	17.4b	18.5b	2.1d	3.8d
After	26.0ab	14.5c	20.7bc	19.7bc	24.2ab	29.2a
Water stable aggregate size (MWD)--mm						
Before	2.5a	2.1ab	1.6bc	2.6a	0.8d	1.0cd
After	2.6a	3.0a	2.4a	2.3a	3.0a	2.4a
Random roughness--mm						
Before	18.0a	8.0c	10.5b	11.9b	6.6c	7.3c
After	10.3a	6.0b	6.5b	9.5a	6.0b	6.8b
Surface residue cover--%	2.9b	3.1b	1.6b	8.3a	2.1b	9.6a
pH	7.25b	7.30b	7.43ab	7.53a	7.45ab	7.40ab
Bulk density--Mg/m ³						
Before	1.13b	1.02c	1.18b	1.16b	1.39a	1.36a
After	1.16b	1.16b	1.21b	1.21b	1.37a	1.34a
Porosity--m ³ /m ³						
Before	0.57b	0.62a	0.56b	0.57b	0.48c	0.50c
After	0.55ab	0.56a	0.54ab	0.54ab	0.48c	0.52bc
Sediment loss--kg/m ²						
First rain	0.48a	0.25b	0.21b	0.26b	0.14b	0.09b
Second rain	0.43a	0.19bc	0.16bc	0.21b	0.12bc	0.09c

Table 2 cont'd. Soil parameters for Area 1^{1/} of Pullman soil determined before or after simulated rainfall, Bushland, Texas.

Type and time of measurement	Tillage treatments ^{2/}					
	MB	RT	ST-Res	ST+Res	NT-Res	NT+Res
Soil water content (0-100 mm depth)--mm PAW						
	17b	30a	32a	36a	29a	34a
Soil water content (0-1.2 m depth)--mm PAW						
	146a	140a	140a	152a	137a	148a
Organic matter concentration--g/kg						
	18.9c	21.7bc	34.2a	24.9bc	33.7a	27.6ab

^{1/} After dryland grain sorghum.

^{2/} Tillage treatments: MB--moldboard + disk; RT--rotary; ST-Res--sweep, residues removed; ST+Res--sweep, residues in place; NT-Res--no-tillage, residues removed; NT+Res--no-tillage, residues in place.

^{3/} Row values followed by the same letter or letters are not significantly differed at $P = 0.05$ level (Duncan's multiple range test).

Table 3. Soil parameters for Area 2^{1/} of Pullman soil determined before or after simulated rainfall, Bushland, Texas.

Type and time of measurement	Tillage treatments ^{2/}					
	MB	RT	ST-Res	ST+Res	NT-Res	NT+Res
Dry aggregate size (MWD)--mm						
Before	28.7a ^{3/}	18.7b	15.6b	18.2b	4.0c	4.5c
After	27.0a	26.5a	21.8b	22.0b	19.5bc	17.1c
Water stable aggregate size (MWD)--mm						
Before	1.6a	1.5a	1.3a	1.6a	0.5b	0.7b
After	0.9a	0.8a	0.4a	0.8a	0.7a	0.8a
Random roughness--mm						
Before	17.6a	10.5c	12.5bc	14.5b	6.6d	8.0d
After	11.1a	6.4cd	8.3bc	10.5ab	5.2d	7.0cd
Surface residue cover--%	9.9c	28.0b	11.5c	63.1a	15.6c	68.4a
pH	6.45a	6.36a	6.38a	6.31a	6.49a	6.35a
Bulk density--Mg/m ³						
Before	1.12bc	1.01c	1.22ab	1.20ab	1.32a	1.33a
After	1.19bc	1.17c	1.25bc	1.28b	1.38a	1.27b
Porosity--m ³ /m ³						
Before	0.58ab	0.63a	0.56b	0.55b	0.50c	0.49c
After	0.55ab	0.56a	0.53ab	0.52ab	0.48b	0.52ab
Sediment loss--kg/m ²						
First rain	0.44a	0.31ab	0.29ab	0.18bc	0.13c	0.10c
Second rain	0.27a	0.21ab	0.24a	0.14ab	0.11ab	0.06b

Table 3 cont'd. Soil parameters for Area 2^{1/} of Pullman soil determined before or after simulated rainfall, Bushland, Texas.

Type and time of measurement	Tillage treatments ^{2/}					
	MB	RT	ST-Res	ST+Res	NT-Res	NT+Res
Soil water content (0-100 mm depth)--mm PAW						
	41a	44a	29a	43a	29a	41a
Soil water content (0-1.2 m depth)--mm PAW						
	119ab	122ab	111b	133ab	77c	144a
Organic matter concentration--g/kg						
	13.5c	14.0bc	14.1bc	14.9a	14.6ab	14.6ab

^{1/} After dryland winter wheat.

^{2/} Tillage treatments: MB--moldboard + disk; RT--rotary; ST-Res--sweep, residues removed; ST+Res--sweep, residues in place; NT-Res--no-tillage, residues removed; NT+Res--no-tillage, residues in place.

^{3/} Row values followed by the same letter or letters are not significantly differed at P = 0.05 level (Duncan's multiple range test).

the unusually high I_1 (284.5 mm/h) for the ST-Res treatment is not apparent. Low I_1 for the NT+Res treatment is attributed to low residue cover (<10%) combined with a relatively smooth, crusted surface which is common after dryland grain sorghum and which rapidly results in runoff. Higher I_1 with the NT-Res treatments than for the NT+Res treatment is attributed to soil surface disturbance during the residue removal operation. Surface loosening by tillage resulted in relatively high I_1 with other treatments.

The high I_f was similarly high (about 24 mm/h) for the ST-Res and ST+Res treatments and lowest (11.4 mm/h) for the MB treatment. Relatively high I_f for ST-Res and ST+Res treatments is attributed to soil loosening and surface protection (although limited) afforded by residues. In contrast, residue incorporation with the RT and MB treatments afforded little or no surface protection and, hence, surface sealing and lower I_f . Low I_f for NT-Res and NT+Res treatments is attributed to no soil loosening and limited surface cover.

The range in I_1 for the first rain for different treatments after wheat (Area 2) was much lower than after sorghum, with similarly low I_1 (72.5 to 75.0 mm/h) resulting from the NT+Res, NT-Res, MB, and ST-Res treatments and similarly high I_1 (99.9 and 110.3 mm/h) resulting from the RT and ST+Res treatments (Table 1). The overall range was only 37.8 mm/h after wheat as compared with 246.1 mm/h after sorghum. Greater uniformity of I_1 after wheat probably resulted from greater surface coverage provided by wheat as compared to that provided by sorghum, even though some residues were incorporated by tillage or removed before the infiltration measurements were made. The I_f was lower for all treatments after wheat than after sorghum, and ranged from 2.7 mm/h for the MB treatment to 9.2 mm/h for the NT+Res

treatment after wheat. These treatments resulted in the lowest and highest amounts of surface residues, respectively. However, in general, there were no consistent trends related to soil loosening by tillage or surface cover remaining at the time of simulated rainfall. The overall lower I_f after wheat than after sorghum probably resulted from different soil conditions (Tables 2 and 3) that are discussed later as well as different cropping and tillage histories and different slope aspects on the two areas.

The γ coefficients for the first rain showed no trends that appeared to be related to tillage method, residue amount, or residue type (sorghum vs. wheat). For example, the overall lowest γ value was 0.012 for the NT+Res treatment after sorghum, while the highest was 0.055 for the same treatment after wheat.

The initial I_i for the second rain after sorghum was similarly low (29.0 to 34.0 mm/h) for the MB, RT, and NT-Res treatments; intermediate (49.6 and 59.5 mm/h) for the ST-Res and ST+Res treatments; and highest (73.2 mm/h) for the NT+Res treatment (Table 1). As expected, these I_i rates were lower than for the first rain, except for the NT+Res treatment. The reason for the latter is uncertain, but could be related to the overall lower sediment loss, bulk density change, and random roughness change (Table 2), which suggests that there was less soil movement on the plots and possibly less clogging of pores by migrating soil particles.

The I_f on Area 1 for the second rain was lower than for the first rain for all treatments, except for the NT+Res treatment for which it was similar for the two rains (Table 1). Again, more stable soil conditions possibly contributed to the similar I_f for the NT+Res treatment for the two rains.

On Area 2, I_i for the second rain varied relatively little (27.7 to 48.1 mm/h) for the different treatments, with all, as expected, being

considerably lower than for the first rain (Table 1). The I_f rates for the second rain did not differ greatly (5.9 mm/h or less) from those for the first rain, except that it was much higher for the ST+Res treatment for the second rain, with the reason for this not being apparent.

As for the first rain, γ coefficients showed no consistent trends that appeared to be related to tillage method, residue amount, or residue type. Also, in many cases, the γ values for the second rain differed considerably from those for the first rain.

Soil measurements

Data in Tables 2 and 3 are for measurements made on Areas 1 and 2, respectively, in association with the infiltration measurements. For Area 1, the mean weight diameter (MWD) of dry and water stable aggregates was highest with the MB treatment and similarly low for the NT-Res and NT+Res treatments before applying water. After applying water, MWDs of dry aggregates generally were higher than before applying water with the largest increases occurring for the NT-Res and NT+Res treatments. For water stable aggregates, MWD increases occurred for the NT-Res and NT+Res treatments, but were relatively constant for the other treatments, and differences among treatments after applying water were not significantly different ($P = 0.05$).

Surface random roughness was greatest for the MB treatment and similarly low for the NT-Res and NT+Res treatments. The simulated rainfall resulted in the largest decrease in random roughness for the MB treatment followed in decreasing order by the ST-Res, ST+Res, RT, NT-Res, and NT+Res treatments. After rainfall, random roughness was similarly high (10.3 and 9.5 mm) for the MB and ST+Res treatments and similarly low (6.0 to 6.8 mm) for the remaining treatments. Random roughness before applying water had trends similar to those for dry aggregate MWD with the changes during water application being

greatest for those treatments (MB and ST+Res) that had the highest dry aggregate MWD before applying water.

Surface residue cover was similarly low where most residues were incorporated by tillage (MB and RT treatments) or mechanically removed (ST-Res and NT-Res treatments). However, although the percent cover was significantly higher for the ST+Res and NT+Res treatments, the percent cover was less than 10%, indicating that much of the surface was not protected by residues on Area 1, which undoubtedly contributed to the general lack of response of water infiltration to treatments for which surface residues were in place.

Soil pH was or tended to be lower for the MB and RT treatments than for the remaining treatments. However, although pH differences were significant, the values differed relatively little and it is doubtful whether pH per se played a significant role in affecting water infiltration.

Soil bulk density was directly affected by tillage methods, with all treatments involving soil disturbance by tillage resulting in lower bulk densities than the NT-Res and NT+Res treatments. After applying water, bulk densities increased for those treatments involving tillage, but they remained lower than for the NT-Res and NT+Res treatments that experienced little change during the rainfall event. Trends in soil porosity, which were calculated from the measured bulk densities and an assumed particle density of 2.65 Mg/m^3 , followed the bulk density trends, except that they were in an opposite direction.

During the first rain on Area 1, sediment loss was significantly higher from the MB treatment plots than from the remaining plots for which the differences were not significant. However, numerically, sediment loss was least from the NT+Res treatment plots. It was again numerically least from

the NT+Res treatment plots and highest from the MB treatment plots during the second rain. High sediment loss from the MB plots is attributed to the lack of surface residues and greater change in random roughness, with the latter indicating a greater breakdown of aggregates that provided soil materials for transport from the plots.

Before the first rain, surface soil (0 to 10 cm) water content was lower on MB treatment plots than on other plots, apparently because of increased drying by evaporation of the tillage-loosened soil. Water content differences for the 0- to 1.2-m profile were not significantly different.

Soil organic matter concentration was lower for treatments involving inversion (MB) or mixing (RT) tillage than for the remaining treatments. Lower concentrations with the MB and RT treatments resulted from subsurface materials having lower organic matter concentrations being deposited on or mixed with the surface soil.

For Area 2, MWD of dry aggregates before applying water was greatest with the MB treatment; intermediate and similar with the RT, ST-Res, and ST+Res treatments; and similarly low with the NT-Res and NT+Res treatments (Table 3). After applying water, the trends remained the same. However, the MWD decreased slightly with the MB treatment, but increased with all other treatments.

Before applying water, the MWD of water stable aggregates was lower with the NT-Res and NT+Res treatments than with other treatments (Table 3). Differences among treatments were not significant after applying water. The MWD remained relatively constant with the NT-Res and NT+Res treatments, but decreased with the remaining treatments during the rainstorm. Overall, the MWD of water stable aggregates was lower on Area 2 than on Area 1.

Surface random roughness before applying water on Area 2 was highest with the MB treatment, which was followed in decreasing order by the ST+Res, ST-Res, RT, NT+Res, and NT-Res treatments (Table 3). After applying water, the random roughness trends were in the same order, but roughness decreased most with the MB treatment and least with the NT+Res treatment. Random roughness values, both before and after applying water, were similar on both areas for given treatments, even though surface cover by residues varied considerably for the treatments.

Surface cover by residues with all treatments was higher on Area 2 than on Area 1. On Area 2, cover ranged from 9.9% with the MB treatment to 68.4% with the NT+Res treatment (Table 3). Residue removal on the ST-Res and NT-Res treatment plots resulted in cover percentages similar to that on the MB treatment plot (differences not significant).

Soil pH differences among treatments were not significant at the $P = 0.05$ level on Area 2 (Table 3). For all treatments, pH was lower on Area 2 than on Area 1. The reason for this difference is not definite, but may be related to the distance to an outdoor beef cattle feeding operation that may be contributing airborne substances that affect pH to the surrounding areas. This operation is about 0.2 km from Area 1 plots and about 1.5 km from Area 2 plots.

As expected, bulk densities were lower on plots loosened by tillage than on no-tillage (NT-Res and NT+Res) plots, with the lowest bulk density resulting from the RT treatment (Table 3). Bulk densities were higher after than before applying water for all treatments, except the NT+Res treatment for which it decreased slightly. The reason for this decrease is not known. Soil porosity trends followed bulk density trends, but in an opposite direction.

Sediment losses on Area 2 were similar to those on Area 1 for the same treatments, with the greatest loss occurring from the MB treatment plot and the least from the NT+Res plot (Table 3). Second rain losses were lower than first rain losses for all treatments.

Soil water contents determined before applying water were not significantly different ($P = 0.05$ level) among tillage treatments at the 0- to 10-cm depth, but were significant at the 0- to 1.2-m depth (Table 3). However, since differences at the 0- to 10-cm depth were similar for all treatments, it is doubtful that differences at the greater depth had a major impact on water infiltration. The reason for differences among treatments at the 0- to 1.2-m depth is not apparent.

Soil organic matter concentrations differed significantly among treatments on Area 2, with the lowest concentration resulting from the MB treatment and the highest resulting from the ST+Res treatment. For all treatments, organic matter concentrations were higher on Area 1 than on Area 2, with the higher concentrations on Area 1 possibly being related to the closeness to the cattle feeding operation, as mentioned in regard to soil pH.

Infiltration-soil factor relationships

In an attempt to better understand the effects of the measured soil factors on the infiltration parameters, multiple regression analyses were used to establish relationships among the infiltration and soil variables. Data from both areas were combined for the analyses. Results for the analyses involving infiltration parameters and soil factors are shown in Table 4.

For the first rain, I_1 was related significantly only to soil organic matter concentration. This is surprising in view of the fact that the

Table 4. Infiltration parameter-soil factor relationships for Pullman soil based on multiple regression analyses, Bushland, Texas.

Rainfall event	Infiltration parameter ^{1/}	Soil factor(s) ^{2/}	Intercept	Coef.	R ²	F
First	I _i	OM	13.66	+4.722*	0.346	0.044
		OM	656.61	+0.595(7)**		
	I _f	MWD (wet, after)		-11.575(3)***	0.995	0.0002
		BD (after)		-159.160(1)***		
		POR (after)		-276.841(5)**		
		RR (before)		-2.035(4)***		
		RR (after)		+2.405(6)**		
		ESP		-19.816(2)***		
		MWD (wet, after)	1.716	-0.003(6)**		
	γ	BD (before)		-0.226(3)**	0.990	0.0001
		BD (after)		-0.388(2)***		
		POR (before)		-0.695(1)***		
		POR (after)		-0.966(4)***		
		RR (before)		-0.003(5)***		
		RR (after)		-0.003(5)***		
Second	I _i	MWD (wet, after)	1058.325	-37.013(2)*	0.542	0.0299
		ESP		-65.381(1)*		
	I _f	H ₂ O (0-10 cm depth)	-31.194	+1.091(3)*	0.568	0.069
		Sediment loss (first rain)		-178.483(2)*		
		Sediment loss (second rain)		+249.415(1)*		
	γ	OM	0.104	-0.001(2)**	0.729	0.0028
		RR (after)		-0.005(1)**		

^{1/} See text for description of parameters.

^{2/} See text for description of soil factors.

^{3/} Levels of significance: *--0.05; **--0.01; ***--0.001. Values in parenthesis indicate relative importance of the soil factor--1-highest, higher values are less important.

different tillage treatments also had a major effect on MWD of dry aggregates, random roughness, surface residue cover, bulk density, and porosity, which, in most cases, exhibited their maximum differences among treatments before water application was started.

In contrast to I_1 , I_f for the first rain was related significantly, in order of importance, to bulk density (after) (after the rain), soil ESP, MWD of water stable aggregates (after), random roughness (before) (before the rain), porosity (after), random roughness (after), and organic matter concentration. In this case, bulk density (after) and organic matter concentration had the greatest and least effects, respectively, on I_f . The indication that bulk density (after) negatively affects I_f is as expected. However, difficult to understand is the indication that MWD of water stable aggregates (after) and porosity (after) negatively affect I_f . For MWD, a possible explanation is that low values indicated a more stable soil condition that contributed to greater I_f rates than a system of larger aggregates that tended to disintegrate to a greater extent during water application and, hence, contributed to greater soil sealing and lower I_f rates. Since bulk density and porosity are negatively related, there is no apparent reason why porosity should negatively affect I_f , and this indication may be due to a limitation of the multiple regression procedure. However, deleting porosity from the analysis resulted in bulk density (after), random roughness (before and after), and ESP also being found to be non-significant with regard to their effects on I_f (results not shown). The effects of organic matter concentration, random roughness (before and after), and ESP were in the direction (positive or negative) as expected.

For the first rain, γ was related significantly, in order of importance, to porosity (before), bulk density (after), bulk density

(before), porosity (after), random roughness (before), and MWD of water stable aggregates (after). Since low γ values are indicative of a more stable soil surface condition, the negative relationship between γ and the above variables seems desirable. However, as indicated in the discussion relative to I_f for the first rain, the results regarding negative responses to both bulk density and porosity seem contradictory, with no apparent explanation for this being available. Deleting porosity from the analysis resulted in no soil factors being significantly related to γ (results not shown), which seems unreasonable.

For the second rain, I_f was related negatively, in order of importance, to soil ESP and MWD of water stable aggregates (after) (measured after the first rain). The response to ESP is as expected and a possible reason for the negative response to MWD is as discussed for I_f for the first rain.

The I_f for the second rain was significantly related ($P = 0.069$), in order of importance, to sediment loss (second rain), sediment loss (first rain), and soil water content at the 0- to 10-cm depth. Although significant, the contribution of soil water content to second rain I_f is questionable because the water content was determined before the first rain. The response to sediment loss during the first rain is as expected, while that for the second rain is questionable. A possible explanation is that the second rain removed some fine particles that clogged pores from the surface and, hence, permitted greater water infiltration.

The γ coefficient for the second rain was related, in order of importance, negatively to random roughness (after the first rain) and to organic matter concentration. Since low γ values indicate a more stable surface condition than high γ values, these trends are as expected.

Relationships among soil factors

Results of multiple regression analyses involving the soil factors evaluated in association with the infiltration determination are shown in Table 5. These analyses were performed to determine which soil factor or factors had a significant effect on a given soil factor. The independent variables for a given analyses were limited to those soil factors that had a possible causal effect on the dependent variable.

Sediment loss during the first rain was not significantly ($P = 0.05$ level) related to any measured soil factor. Loss during the second rain was related, in order of importance, to loss during the first rain and to soil water content at the 0- to 10-cm depth. The relationship between sediment loss for the two rains was expected because treatments having large losses during the first rain undoubtedly would have larger losses during the second rain. Although significant, the influence of soil water content measured before the first rain on sediment loss during the second rain is questionable, and may be a limitation of regression analyses.

The MWD of dry aggregates (before) (measured before the first rain) was significantly related to the MWD of water stable aggregates (before) and to soil ESP. This indicates that substances causing water stable bonding of soil particles as well as sodium increase the stability of dry soil aggregates. The MWD of dry aggregates (after) (after the first rain) was not significantly related to any measured soil factor.

The MWD of water stable aggregates (before) was significantly related, in order of importance, to bulk density (before) and to soil pH. However, the nature of the effect of bulk density on MWD of water stable aggregates is unclear. A possible reason for the indicated bulk density effect is related to the difference in depth of sampling for the two soil factors. Samples for

Table 5. Relationships among soil factors^{1/} determined before or after simulated rainfall on Pullman soil, Bushland, Texas.

Dependent variable	Independent variable(s)	Intercept	Coef. ^{2/}	R ²	F
Sediment loss (first rain)	None signif.	--	--	--	--
Sediment loss (second rain)	H ₂ O (0-10 cm depth)	0.132	-0.003(2)**		
	Sediment loss (first rain)		+0.700(1)***	0.969	0.0001
MWD (dry) (before)	MWD (water stable) (before)	-115.429	+12.186(1)***		
	ESP		+7.616(2)*	0.745	0.0021
MWD (dry) (after)	None signif.	--	--	--	--
MWD (water stable) (before)	pH	2.354	+0.579(2)*		
	Bulk density (before)		-4.039(1)**	0.720	0.0032
MWD (water stable) (after)	ESP	24.589	-1.569***	0.943	0.0001
Bulk density (before)	Porosity (before)	2.597	-2.530***	0.976	0.0001
Bulk density (after)	Porosity (after)	2.741	-2.819***	0.917	0.0001
Porosity (before)	Bulk density (before)	1.015	-0.386***	0.976	0.0001
Porosity (after)	Bulk density (after)	0.935	-0.325***	0.917	0.0001
Random roughness (before)	MWD (dry) (before)	5.095	+0.427***	0.843	0.0001
Random roughness (after)	Random roughness (before)	2.680	+0.465***	0.840	0.0001

Table 5 cont'd. Relationships among soil factors^{1/} determined before or after simulated rainfall on Pullman soil, Bushland, Texas.

Dependent variable	Independent variable(s)	Intercept	Coef. ^{2/}	R ²	F
ESP	H ₂ O (0-10 cm depth)	21.648	+0.010(3)*		
	H ₂ O (0-1.2 m depth)		-0.005(2)*		
	pH		-0.984(1)***	0.991	0.0001

^{1/} See text for description of soil factors.

^{2/} Levels of significance: *--0.05; **--0.01; ***--0.001. Values in parenthesis indicate relative importance of the soil factor--1-highest, higher values are less important.

bulk density were obtained at a 0- to 15-cm depth, while those for MWD were obtained at a 0- to 2.5-cm depth. As a result, tillage that loosened soil and decreased the bulk density possibly also brought more stable aggregates to the surface where they were subsequently sampled for MWD determination. Although Unger and Fulton (1988) showed that the MWD of water stable aggregates obtained at a depth of 0 to 10 cm was higher on no-tillage than on tillage areas of the Pullman soil, no detailed measurements of the MWD of water stable aggregates by small depth increments (less than 7.5 cm) have been made for this soil. Results in Tables 2 and 3 indicate that aggregates from a shallow depth (0 to 2.5 cm) of no-tillage plots are less water stable than aggregates obtained from a larger (0 to 10 cm) depth increment, as reported by Unger and Fulton (1988).

As for bulk density, the nature of the effect of pH on the MWD of water stable aggregates is unclear. However, since the effect is positive and pH and MWD were higher on Area 1 than on Area 2 (Tables 2 and 3), the greater MWD on Area 1 may be related to the nearness of the plots to the cattle feeding operation and, hence, on conditions that affected pH and not on pH per se.

The MWD of water stable aggregates (after) was related negatively to soil ESP. This effect is attributed to the dispersing effect of sodium on soil aggregates. With higher ESP, the MWD of water stable aggregates was lower.

Since porosity was calculated from bulk density and an assumed constant particle density (2.65 Mg/m^3), the close relationships between bulk density and porosity for the before and after water application conditions are obvious (Table 5). Somewhat surprising is the fact that bulk density (or porosity) determined before water application had no significant effect on bulk density (or porosity) after water application.

Surface random roughness (before) was positively related to the MWD of dry aggregates. This was expected because dry aggregates cause the roughness measured by the random roughness procedure. (The procedure eliminates oriented roughness such as ridge roughness resulting from tillage.) Random roughness (after) was related only to random roughness (before), which also was expected because the water application was inadequate to eliminate the initial roughness resulting from the tillage treatments.

Soil ESP was related, in order of importance, to pH, soil water content (0- to 1.2-m depth), and soil water content (0- to 10-cm depth). Since there is no clear-cut relationship between pH and ESP (Richards, 1954), the reason for the significant negative response to pH in this study is unclear. Also unclear is the reason for a negative response of ESP to soil water content at the 0- to 1.2-m depth because both average ESP and average water content were higher on Area 2 than on Area 1. It was anticipated that an increased water content would result in a lower ESP due to leaching of salt. However, the increased water content possibly resulted in salt transport to and accumulation at the surface due to greater evaporation of soil water. This would also help explain the positive effect of soil water content at the 0- to 10-cm depth on ESP.

Bushland, Texas -- Study 2

Dry Aggregate Size Effects on Water Infiltration and Surface Roughness

Soil aggregates have a major influence on water infiltration. Fine aggregates tend to move with water, become re-oriented on the surface, and, hence, form a dense layer at the surface that restricts water infiltration. In contrast, large aggregates, if sufficiently stable, resist movement by water, are resistant to close packing, and, hence, provide for channels through the surface layer that allow more rapid infiltration of water. In this study, we determined the influence of dry aggregate size on the infiltration of simulated rainfall under laboratory (in a greenhouse) conditions.

METHODS AND MATERIALS

The aggregates for this study were obtained in August 1987 from Area 2 of Study 1 at Bushland, Texas. At the time of sampling, the area was in fallow after winter wheat that was harvested in June 1987. The soil was a Pullman silty clay loam.

For the study, surface soil (0- to about a 3-cm depth) was obtained from the MB (moldboard plus disk tillage), RT (rotary tillage), ST-Res (sweep tillage with residues removed), and NT-Res (no-tillage with residues removed) treatment plots that had been prepared for the simulated rainfall tests under field conditions.

The soil obtained was sufficient to provide an adequate amount of soil of each aggregate size to make the tests under the laboratory conditions. After sampling, the soil was air-dried, then sieved with a rotary sieving apparatus having sieve openings of 0.42, 0.84, 2.0, 6.4, and 18.3 mm (Chepil, 1962). Soil particles >18.3 mm, but <76.2 mm, were also obtained, but simulations were not made involving these large aggregates (clods).

For the infiltration tests, different size aggregates were placed on top of pea-sized gravel covered with cheesecloth in metal containers (boxes) that were subsequently rotated under the rotating disk type rainfall simulator (Morin et al., 1967). Inside dimensions of the boxes were 30.0 cm wide, 50.0 cm long, and 12.0 cm deep. The gravel depth was 75 mm and the soil depth was 25 mm, leaving a free-board of 20 mm. The boxes were constructed in such a manner that runoff across the surface and percolation through the soil could be determined individually. Splash from the surface was calculated from the water application, runoff, and percolation rates. To minimize the possible delay in percolation water from draining from the boxes, the gravel was wetted with water before placing the aggregates in the boxes.

Before starting the rainfall simulations, height elevation readings relative to a constant reference elevation were made at 60 points on the soil surface so that roughness of the surface could be determined. A similar set of readings was made after applying the water.

Water was applied to four boxes of soil simultaneously. A fifth box, having the same dimensions as other boxes and covered with a wire mesh, was used to determine the water application rate. The disk on the rainfall simulator was designed to apply water at about a 49-mm/h rate. Stored rainwater was used for the simulations. The water was of the same quality (EC of 0.0039 S/m and sodium concentration of 0.196 mg/kg) as the water used for Study 1. The soil ESP averaged 15.2 mg/kg.

The turntable on which the boxes were placed made one revolution each 4 min and 10 s. Rotation of the boxes as well as the changing pattern of water application by the rainfall simulator resulted in uniform distribution of water on the surface, based on visual observations.

For a given run, water was applied until runoff and percolation rates became relatively constant. This generally occurred from 1.5 to 2.0 h after starting water application. The water infiltration parameters (I_i , I_f , and γ) were calculated from the measured data on water application rate, time, and percolation.

RESULTS AND DISCUSSION

Infiltration

Results of the infiltration measurements on dry-sieved Pullman soil are given in Table 6. For the <0.42-mm aggregates, surprisingly high I_i values were obtained, based on analyses of the data. These high values, however, are unrealistic due to the small sized aggregates and the nature of the soil, and apparently resulted from the method of determining I_i . Because of the sharp decline in infiltration after wetting of the aggregates, the analyses indicated a high intercept. The generally high γ values indicate that the surfaces for all treatments were unstable and that infiltration greatly decreased during the simulations. This lends support to the explanation for the indicated high I_i . The I_f for <0.42-mm aggregates was highest for the NT-Res treatment and lowest for the RT treatment. However, differences among treatments were relatively small.

For the 0.42- to 0.84-mm aggregates, infiltration data for the RT treatment were inadvertently lost. For the remaining treatments, I_i and I_f were similar for the ST-Res and NT-Res treatments, and both were higher than for the MB treatment. The low γ value for the MB treatment indicated that the aggregates were relatively stable. This was indicated also by the rather small difference between I_i and I_f for this treatment. However, even so, the I_f was lower for the MB treatment than for the other treatments.

Table 6. Infiltration parameters for aggregates of different sizes of dry-sieved Pullman soil as affected by tillage treatments, Bushland, Texas.

Aggregate size	Treatment ^{1/}	Infiltration parameters ^{2/}			
		I _i	I _f	γ	R ²
<u>mm</u>					
< 0.42	MB	150.25	6.53	-0.061	0.935
	RT	120.82	4.99	-0.049	0.866
	ST-Res	143.30	5.73	-0.050	0.943
	NT-Res	155.37	7.36	-0.049	0.959
0.42 - 0.84	MB	16.51	7.69	-0.014	0.120
	RT	<u>3/</u>	--	--	--
	ST-Res	49.70	11.91	-0.035	0.924
	NT-Res	43.79	11.95	-0.032	0.680
0.84 - 2.0	MB	28.93	3.86	-0.039	0.935
	RT	28.78	5.40	-0.029	0.806
	ST-Res	27.03	8.37	-0.039	0.732
	NT-Res	28.16	7.80	-0.040	0.512
2.0 - 6.4	MB	37.44	2.30	-0.029	0.918
	RT	42.33	5.08	-0.004	0.763
	ST-Res	49.02	2.30	-0.029	0.871
	NT-Res	31.38	4.37	-0.022	0.823
6.4 - 18.3	MB	28.72	3.14	-0.022	0.229
	RT	49.87	2.47	-0.025	0.643
	ST-Res	38.89	1.29	-0.018	0.361
	NT-Res	28.63	1.93	-0.021	0.166

^{1/} Tillage treatments: MB--moldboard + disk, RT--rotary, ST-Res--sweep with residues removed, NT-Res--no-tillage with residues removed.

^{2/} See text for description of parameters.

^{3/} Data for this treatment were inadvertantly lost.

The I_i for 0.84- to 2.0-mm aggregates was similar for all treatments, but I_f was lowest for the MB treatment and highest for the ST-Res treatment. The I_f for the NT-Res treatment was slightly lower than for the ST-Res treatment. Although the change between I_i and I_f was greatest for the MB treatment and least for the ST-Res treatment, these treatments had identical γ values, which indicates that the γ values alone do not fully explain the changes that occur during the infiltration process.

For the 2.0- to 6.4-mm aggregates, I_i was highest for the ST-Res treatment and lowest for the NT-Res treatment. However, I_f was equally low for the MB and ST-Res treatments; it was highest for the RT treatment. Again, differences between I_i and I_f for the different treatments were not fully explained by the γ values.

For the largest aggregates (6.4-18.3 mm), I_i was highest for the RT treatment and similarly low for the MB and NT-Res treatments. The MB and the ST-Res treatments resulted in the highest and lowest I_f , respectively. Differences among the γ values were slight.

Except for the high I_i values for the smallest aggregates and the lower I_i for the MB treatment than for other treatments for 0.42- to 0.84 mm aggregates, differences in I_i among treatments and among aggregate sizes were relatively small, ranging from a low of 27.03 for the ST-Res treatment for 0.84- to 2.0-mm aggregates and a high of 49.87 for the RT treatment for the 6.4- to 18.3-mm aggregates. Overall, there were no consistent trends for any treatment or aggregate size with regard to I_i .

The highest I_f values were obtained with the 0.42- to 0.84-mm aggregates, with generally similar and somewhat smaller values being obtained with the 0.84- to 2.0- and the <0.42-mm aggregates. Generally smaller I_f values were obtained for all treatments for the two largest aggregate sizes.

Although there were no consistent trends due to treatments, it appears that aggregates in the 0.42- to 2.0-mm range are most effective for maintaining favorable I_f rates. [The finer aggregates (<0.42-mm) also resulted in fairly high I_f rates, but these could clog pores if mixed with larger aggregates.] A favorable I_f rate with the 0.42- to 2.0-mm aggregates is not surprising because this size represents the natural soil aggregates that seemingly would be most stable. Larger materials apparently are clods comprised of smaller particles, which disintegrated during the simulated rainfall event and resulted in the lower I_f rates. Greater disintegration of the larger aggregates was reflected in the greater changes in surface elevation and surface roughness that occurred during the rainfall events. (See Table 5 and related discussion, next Section.)

Surface Roughness and Roughness Change

As expected because of the method of preparing the aggregates for the rainfall simulations, mean surface elevations before applying water varied little among treatments and aggregate sizes, except that mean elevations increased slightly for the 6.4- to 18.3-mm aggregates as compared to those for the smaller aggregates (Table 7). This increase is attributed to the method of measuring the surface elevations, which involved pins coming in contact with the surface. The pin diameter was 3.2 mm, which was larger than most aggregates in the four smaller size ranges. For larger aggregates, the pins apparently did not fully enter the spaces between the aggregates, thus tending to result in the higher mean readings.

As for elevations, standard deviations (SD) of the elevations, which were used as a measure of surface roughness, varied only slightly among treatments and aggregate sizes, except that they increased with increasing aggregate size for the two largest aggregate sizes (Table 7). This again was expected

Table 7. Mean surface elevations and surface roughness (SD of elevations) before and after applying simulated rainfall to dry-sieved Pullman soil, Bushland, Texas.

Time of measurement and treatment ^{1/}	Aggregate size - mm									
	< 0.42		0.42-0.84		0.84-2.0		2.0-6.4		6.4-18.3	
	Mean	SD ^{2/}	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Before										
MB	46.3	0.15	46.3	0.18	46.2	0.17	46.2	0.18	46.6	0.33
RT	46.3	0.19	46.6	0.18	46.3	0.22	46.3	0.23	46.4	0.32
ST-Res	46.3	0.16	46.2	0.22	46.3	0.14	46.3	0.26	46.5	0.31
NT-Res	46.5	0.21	46.3	0.18	46.2	0.20	46.3	0.24	46.8	0.29
Ave.	46.4	0.18	46.4	0.19	46.3	0.18	46.3	0.23	46.6	0.31
After										
MB	46.1	0.16	46.0	0.26	45.8	0.18	45.8	0.24	46.1	0.27
RT	46.2	0.23	46.2	0.19	45.8	0.22	45.7	0.22	45.9	0.25
ST-Res	46.2	0.12	46.0	0.21	45.8	0.23	45.7	0.18	46.0	0.26
NT-Res	46.3	0.23	46.0	0.28	45.7	0.27	45.7	0.26	46.2	0.21
Ave.	46.2	0.19	46.1	0.24	45.8	0.23	45.7	0.23	46.1	0.25
Change										
MB	-0.2	+0.01	-0.3	+0.08	-0.4	+0.01	-0.4	+0.06	-0.5	-0.06
RT	-0.1	+0.04	-0.4	+0.01	-0.5	0.00	-0.6	-0.01	-0.5	-0.07
ST-Res	-0.1	-0.04	-0.2	-0.01	-0.5	+0.09	-0.6	-0.08	-0.5	-0.05
NT-Res	-0.2	+0.02	-0.3	+0.10	-0.5	+0.07	-0.6	+0.02	-0.6	-0.08
Ave.	-0.2	+0.01	-0.3	+0.05	-0.5	+0.04	-0.6	0.00	-0.5	-0.07

^{1/} MB--moldboard + disk, RT--rotary, ST-Res--sweep with residue removed,
NT--no-tillage.

^{2/} Standard deviation of elevation readings.

because the larger aggregates result in a rougher surface than smaller aggregates.

Surface elevations after applying water varied little due to treatments and aggregate sizes (Table 7). Likewise, there were no major differences among treatments and aggregate sizes in surface roughness after applying water.

Surface elevations decreased in all cases due to water application, with the average decreases ranging from 0.2 cm for the smallest aggregates to 0.5 or 0.6 cm for the three largest aggregate sizes (Table 7). These changes in elevation were expected and resulted from settling of the soil (collapse) and disintegration and/or dispersion of the aggregates, especially for the larger-sized aggregates. There were no consistent trends in elevation decrease due to treatments.

Not expected were the average increases in surface roughness (SD) due to water application for the three smallest aggregate sizes. Possible reasons for these increases are soil rilling due to water flow across the surface, uneven settling of the soil, and indentations of the surface due to raindrop impact. For these sizes of aggregates, it is doubtful that non-uniform aggregate stability affected surface roughness. Average roughness did not change for the 2.0- to 6.4-mm size range of aggregates.

For the four smallest sizes of aggregates, roughness increased in each case for aggregates from the MB and NT treatment plots, decreased or did not change for those from the RT treatment plots, and was variable for those from the ST plots. Because an increase in roughness for small-sized aggregates apparently is associated with an increased movement (rilling) or uneven consolidation of the soil, the increases for the MB treatment soil possibly resulted from moldboard plowed soil having surface aggregates that were less

water stable than those of other tillage treatments that did not invert the surface soil (RT and ST). However, based on this assumption, it is not apparent why the roughness increased for aggregates from the NT treatment plots.

In contrast to the average surface roughness increase for the small aggregate sizes, roughness decreased for the largest aggregate size in all cases. There was little difference among treatments in roughness decrease for aggregates in the 6.4- to 18.3-mm size range. However, decreases for the MB and ST treatments were similar to those of the RT and NT treatments, respectively. The decreases in roughness for surfaces composed of large aggregates are attributed to aggregate disintegration due to water application.

Bushland, Texas -- Study 3

Soil Type and Tillage Method Effects on Water Infiltration

Initial plans called for making simulated rainfall infiltration measurements in the field on soils other than the Pullman soil at Bushland. However, because of travel distances involved, it was deemed impractical to make such off-location determinations. Consequently, two soils having characteristics different from those of the Pullman were selected and sampled for determining the infiltration parameters under laboratory (in a greenhouse) conditions. The objectives of this study were to determine the influence of soil type and tillage method on the infiltration parameters. Various soil parameters associated with water infiltration also were measured to aid in interpreting the infiltration results.

METHODS AND MATERIALS

The soils used for this study were Sherm silty clay loam (fine, mixed, mesic Torreritic Paleustoll) from near Etter, Texas, and Olton clay loam (fine, mixed, thermic Aridic Paleustoll) from near Lubbock, Texas. Etter and Lubbock are about 100 and 200 km, respectively, from Bushland, Texas.

Treatments that had been imposed on the field areas were no-tillage (NT), sweep tillage (ST), and sweep plus disk tillage (ST+DT) for the Sherm soil and no-tillage (NT), lister tillage (LT), and lister tillage plus planting (LT+P) for the Olton soil. The Sherm soil was used for a winter wheat-grain sorghum rotation, and was in fallow after wheat when it was sampled in May 1988 (wheat was harvested the previous July). The Olton soil was used for grain sorghum the two most recent years and was sampled in April 1988.

The soils were sampled at a depth of 0 to 10 cm and air-dried before applying the simulated rainfall using the equipment as described for

Study 2. A difference in procedure was that a 51-mm soil layer over gravel was used rather than a 25-mm layer as used for Study 2 for the infiltration determinations. In addition to using the disk in the simulator that provided for a water application rate of about 49 mm/h, simulations also were made with a disk that provided for an application rate of about 25 mm/h. Water used for the simulations was stored rainwater having the same quality as used for Studies 1 and 2.

In addition to the determinations made in connection with the rainfall simulations, other determinations made were organic matter, particle size distribution (Day, 1965), pH, and water stable aggregate size distribution on the bulk soil before the rainfall simulations; bulk density and porosity after the simulations; and surface elevation and roughness before and after the simulations. Procedures for these determinations were the same as those used in Study 1, except that bulk density was determined on soil packed in the boxes and surface elevation and roughness determinations were the same as used in Study 2.

RESULTS AND DISCUSSION

Infiltration

Results of the infiltration measurements on Sherm and Olton soils are given in Table 8. At the 25-mm/h application rate on Sherm soil, I_i and I_f were highest with the NT treatment and similar for the ST and ST+DT treatments. The explanation for the unusually high I_i for the NT treatment is the same as for the small aggregates of Pullman soil. (See Study 2 results.) However, there is no apparent reason why it differed so greatly from that for the ST and ST+DT treatments. The high γ value for the NT treatment supports the contention that the soil changed drastically during

Table 8. Infiltration parameters for Sherm and Olton soils as affected by tillage treatment and simulated rainfall rate, Bushland, Texas, Study 3.

Soil and application rate (mm/hr)		Infiltration parameter ^{2/}			
	Treatment ^{1/}	I _i	I _f	γ	R ²
Sherm					
25	NT	147.70	10.48	-0.081	0.904
	ST	37.53	5.11	-0.072	0.700
	ST+DT	38.13	4.90	-0.056	0.755
49	NT	13.83	5.07	-0.013	0.584
	ST	-- ^{3/}	--	--	--
	ST+DT	7.61	2.75	-0.008	0.095
Olton					
25	NT	29.93	9.70	-0.044	0.465
	LT	38.94	4.76	-0.066	0.769
	LT+P	20.00	3.98	-0.034	0.504
49	NT	136.71	7.78	-0.046	0.873
	LT	-- ^{3/}	--	--	--
	ST+P	2.26	1.21	-0.008	0.124

^{1/} Tillage treatments: NT--no-tillage, ST--sweep, ST+DT--sweep + disk, LT--lister, LT+P--lister + planting.

^{2/} See text for description of parameters.

^{3/} Data too erratic among replications to obtain meaningful parameter values.

the rainfall event. However, I_f for the NT treatment was more than double that for the other two treatments.

At the 49-mm/h application rate on Sherm soil, both I_i and I_f with NT were almost double that for the ST+DT treatment. The γ value was lowest for the ST+DT treatment, even though the percent change in infiltration was greater for that treatment than for the NT treatment. The lower I_i and I_f values with the 49-mm/h application rate than the 25-mm/h rate were expected because of the greater energy provided by the 40-mm/h rainfall. However, the low γ values at the 49-mm/h rate were not expected, and no plausible explanation for the low values is available.

For the Olton soil at the low application rate, I_i was highest with the LT treatment and lowest with the LT+P treatment. The I_f remained lowest with the LT+P treatment, but was highest with the NT treatment. There was no definite trend in γ values as related to changes in infiltration (I_i as I_f) during the rainstorms.

At the 49-mm/h application rate on Olton soil, an unusually high I_i was obtained for the NT treatment (same explanation as for < 0.42-mm aggregates in Study 2; also for Sherm soil, this study). Associated with this treatment was a high γ value, but the I_f for the NT treatment still was much higher than for the ST+P treatment, which resulted in a very low (-0.008) γ value.

Factors seemingly associated with the higher infiltration rates, especially I_f , with the NT than for the other treatments on both soils were higher organic matter concentrations, lower bulk densities, and higher aggregate stability (Tables 9 and 10). Higher organic matter would tend to protect the surface and, along with greater aggregate stability, would result in a soil surface more resistant to aggregate dispersion and surface sealing

Table 9. Tillage and water application rate effects on various measured parameters of Sherm soil.

Determination	Water application rate ^{1/}					
	25-mm/h			49-mm/h		
	NT ^{2/}	ST	ST+DT	NT	ST	ST+DT
Organic matter conc.--g/kg	27.1a ^{3/}	21.4b	17.6c	--	--	--
Sand conc.--g/kg	285b	319a	276b	--	--	--
Silt conc.--g/kg	485a	405b	514a	--	--	--
Clay conc.--g/kg	230ab	276a	210b	--	--	--
pH	6.70b	7.00a	6.48c	--	--	--
Bulk density--Mg/m ³	1.38b	1.46a	1.46a	1.37a	1.45a	1.44a
Porosity--m ³ /m ³	0.48a	0.45b	0.45b	0.49a	0.45a	0.46a
Elevation--cm						
Before	46.6	46.7	46.6	46.3	46.5	46.3
After	46.6	46.7	46.6	46.4	46.5	46.3
Change	0.0	0.0	0.0	+0.1	0.0	0.0
Roughness, SD--cm						
Before	0.16	0.18	0.16	0.21	0.20	0.25
After	0.17	0.17	0.15	0.19	0.20	0.23
Change	+0.01	-0.01	-0.01	-0.02	0.00	-0.02
Water stable aggregates,	2.1a	1.71b	0.87c	--	--	--
MWD--mm						

^{1/} Application rate of simulated rainfall.

^{2/} Tillage treatments: NT--no-tillage, ST--sweep, ST+DT--sweep + disk.

^{3/} Row values followed by the same letter or letters are not significantly different at the 0.05 level of probability.

Table 10. Tillage and water application rate effects on various measured parameters of Olton soil, Bushland, Texas, Study 3.

Determination	Water application rate ^{1/}					
	25-mm/h			49-mm/h		
	NT ^{2/}	ST	ST+DT	NT	ST	ST+DT
Organic matter conc.--g/kg	12.4a ^{3/}	13.1a	0.91b	--	--	--
Sand conc.--g/kg	285b	293b	327a	--	--	--
Silt conc.--g/kg	513a	485a	405b	--	--	--
Clay conc.--g/kg	202b	222ab	268a	--	--	--
pH	7.70a	7.65a	7.55b	--	--	--
Bulk density--Mg/m ³	1.58b	1.60b	1.76a	1.57b	1.70a	1.79a
Porosity--m ³ /m ³	0.41a	0.39a	0.34b	0.41a	0.36b	0.32b
Elevation--cm						
Before	46.4	46.5	46.7	46.4	46.6	46.6
After	46.5	46.7	46.7	46.4	46.6	46.6
Change	+0.1	+0.2	0.0	0.0	0.0	0.0
Roughness, SD--cm						
Before	0.14	0.16	0.14	0.15	0.23	0.17
After	0.17	0.19	0.13	0.15	0.20	0.19
Change	+0.03	+0.03	-0.01	0.00	-0.03	+0.02
Water stable aggregates,	1.6a	1.1b	0.9b	--	--	--
MWD--mm						

^{1/} Application rate of simulated rainfall.

^{2/} Tillage treatments: NT--no-tillage, LT--lister, LT+P--lister + planting.

^{3/} Row values followed by the same letter or letters are not significantly different at the 0.05 level of probability.

than soil having less organic matter and less stable aggregates. The value of a less dense soil is that it results in lower soil porosity, which provides more channels for water flow through the soil.

Soil Parameters

Data from the Sherm and Olton soil parameter determinations are presented in Tables 9 and 10, respectively. Because tillage treatments on the soils differed, except for no-tillage, data for each soil will be discussed separately.

Sherm silty clay loam

Organic matter (OM) concentration was highest for soil from the NT treatment plots and lowest for soil from the ST+DT treatment plots (Table 9). Higher OM concentrations in near-surface soil from no-tillage areas than in adjacent tillage areas has been reported for the Pullman soil (Unger, 1989), which is similar to the Sherm soil. No-tillage retains crop residues (organic materials) on the surface while tillage incorporates such residues with the soil.

As compared to the ST and ST+DT treatments, NT resulted in intermediate concentrations of sand, silt, and clay in the Sherm soil (Table 9), but all differences from other treatments were not significant. The ST treatment resulted in the highest sand and clay concentrations and the lowest silt concentration. The reason for the differences is not clear, but may be related to silt and clay migration due to rainfall or irrigation and subsequent mixing of the soil when the tillage operations were performed.

Soil pH was highest with the ST treatment and lowest with the ST+DT treatment (Table 9). The reason for these differences is not apparent.

Soil bulk density following water application at both rates was significantly lower for the NT treatment than for the ST and ST+DT

treatments, for which they were identical with the low application rate and similar with the high application rate (Table 9). Densities differed very little as a result of the water application rates. Lower bulk densities with the NT treatment are attributed to the higher OM concentration, which minimized soil reconsolidation during the simulated rainfall events. Because porosity was calculated from bulk density and an assumed particle density of 2.65 Mg/m^3 , trends in porosity were inversely proportional to bulk density trends, with the reason for porosity differences due to the NT treatment being the same as for the bulk density treatment.

Surface elevations before applying water differed only slightly due to tillage treatments for soils prepared for water application at the two rates (Table 9). The differences were 0.3 cm or less in all cases. Water application at either rate had a minor effect on elevation change. Surface roughness was little affected by soil from the different tillage areas before water application, except that roughness was slightly higher for soil from the ST+DT area in boxes prepared for water application at the 40-mm/h rate. The reason for this increase relative to that for the same treatment at the lower application rate is not apparent. Water application at both rates caused minor changes in roughness in all cases.

The mean weight diameter (MWD) was highest for the NT treatment soil and lowest for the ST+DT treatment soil (Table 9). Because OM influences water stable aggregation (Kemper and Koch, 1966), the higher MWD for the NT soil undoubtedly is a reflection of the higher OM concentration of the NT soil.

Olton clay loam

The OM concentration in Olton soil was significantly lower with the LT+P treatment than with the NT and LT treatments (Table 10). For the LT+P treatment, the planting operation apparently moved the higher OM

concentration soil away from the surface, thus resulting in the lower OM concentration with that treatment. The overall lower OM concentration in Olton soil than in Sherm soil is attributed to past cropping practices (the Olton soil is frequently used for cotton), whereas the Sherm primarily is used for grain crop (wheat or sorghum) production.

For the Olton soil, the sand, silt, and clay concentrations were not significantly different with the NT and LT treatments, but sand and clay concentrations tended to be lower and silt concentration tended to be higher with the NT than with the ST treatment (Table 10). The LT+P treatment resulted in the highest sand and clay concentrations and the lowest silt concentrations. As for the Sherm soil, the differences probably resulted from particle migration due to rainfall and subsequent soil mixing when tillage was performed on the LT and LT+P treatment plots.

Soil pH was lower on the LT+P treatment area than on the other two areas, for which it was not significantly different (Table 10). The results indicate that no-tillage may be causing an increase in pH of the Olton soil under present management practices as compared to that where lister tillage is used.

Bulk density (Table 10) after water application at a 25-mm/h rate was lower for the NT and LT treatments than for the LT+P. This difference is attributed to the difference in OM concentration for these treatments. Water application at the 49-mm/h rate did not affect the bulk density of soil from the NT treatment area, but increased it for soils from the LT and LT+P treatment areas as compared to that for the 25-mm/h application rate. The higher application rate apparently contributed to the greater reconsolidation of soil from the LT and LT+P treatment areas. The porosity trends were inversely proportional to the bulk density trends, as indicated for the Sherm soil.

Surface elevations were little or not affected by tillage treatments or water application rates (Table 10). Surface roughness varied slightly before applying water at a 25-mm/h rate, but increased somewhat ($SD = 0.03$ mm) for the NT and LT treatments and decreased 0.01 cm for the LT+D treatment. The reason for this differential response is not apparent. Before applying water at a 49-mm/h rate, roughness was greater with the LT treatment than with the other treatments, and it decreased 0.03 cm with the LT treatment during the rainfall event. It did not change for the NT treatment, but increased 0.02 cm for the LT+P treatment. Again, the reason for these differential responses is not apparent.

The MWD of water stable aggregates was higher with the NT treatment than with the LT and LT+P treatments, for which it was not significantly different (Table 10). The higher MWD of the NT soil is attributed in part to the higher OM concentration. However, OM concentrations for the NT and LT treatment soils were similar, yet the NT treatment soil had a higher MWD than the LT treatment soil. The reason for this inconsistency is not apparent.

Israel -- Study 1

Aggregate Size and Stability Effect on Water Infiltration and Surface Roughness.

Soil aggregates have a major influence on water infiltration. Fine aggregates tend to disintegrate faster than large aggregates. Unstable aggregates disintegrate and produce a sealing layer which reduces the infiltration capacity of the soil. Also, large aggregates leave the surface with high roughness which results in a large surface water storage capacity. To evaluate the influence of aggregates, the following tests were made under laboratory conditions:

- a. Aggregate stability of soils from Israel under low energy drop impact.
- b. Aggregate stability under simulated rainfall.
- c. Aggregate stability of Pullman soil from Bushland, Texas, under low energy drop impact.

(a) Aggregate stability of soils from Israel under low energy drop impact

METHODS AND MATERIALS

A laboratory drip-type rainfall simulator has been built to measure the energy index of aggregate stability. This procedure for the single size, multi-drop rain simulator for aggregate stability measurement improves the procedure using a single drop on a single aggregate.

The stability of aggregates resulting from different tillage methods on two soils was measured in order to characterize and compare the tillage methods and the soils. The soils and tillage practices were:

1. Loess soil:

- a. Traditional tillage: two passes of disks, then rolling and drilling.
- b. Minimum tillage: Light chiseling and direct drilling.

2. Gromosol soil:

- a. Traditional tillage: plow, disking, rolling and drilling.
- b. Minimum tillage: disking two passes and drilling.

Aggregates of two soil types were studied. The locations and characteristics of areas from which the samples were taken are summarized in Table 11.

Air dry soil samples were sieved (nine fractions) so that the aggregate stability of each fraction could be determined. This procedure uses many aggregates spread in one layer under the rain. The simulator was constructed using a 450 x 750 x 2 mm closed stainless steel water chamber placed in a variable height raindrop tower. Rain drops fell from 1000 hypodermic needles arranged in a spacing of 20 x 20 mm to form a droplet size of 2.53 mm diameter. Rainfall intensity was controlled by a peristaltic pump. The water used was distilled with resin filters. The aggregate samples were spread over a fine net attached to a funnel, 300 x 500 mm, located under the simulator. The aggregates eroded from the net tray were collected from the funnel outlet and dried in an oven at 105°C for 48 h to obtain dry weight.

The energy from a 1.0-m free fall height was 8.00 J/m²/m (Epema and Riezebos, 1983). The rainfall intensities were between 30 to 60 mm/h for the various experiments. Two fans were slowly rotated to move the drops out of vertical lines. The simulated rain was applied to the aggregate samples

Table 11. Soil types and annual precipitation of the working locations,
Israel.

Ruhama location (two sites)

Average annual precipitation: 330 mm

Loess soil: Sand 370 g/kg, Silt 470 g/kg, Clay 160 g/kg

C.E.C. - 15 cmol/kg, O.M. - 2.0 g/kg, E.C. - 3 dS/m

Sde-Yoav location

Average annual precipitation: 450 mm

Gromosol soil: Sand - 240 g/kg, Silt - 280 g/kg, Clay - 480 g/kg

C.E.C. - 38 cmol/kg, O.M. - 7.0 g/kg, E.C. - 1 dS/m

in five replications, and the samples of the eroded material were taken every 2 min.

RESULTS AND DISCUSSION

Samples of the two soils were mechanically analyzed and the results are given in Table 12. Figure 3 shows the comparison of the aggregate size distribution of the two soils where traditional tillage was used.

The results show that the Loess soil has a much higher percentage of small aggregates than the Gromosol soil. In the Loess soil, accumulated percentage of aggregates up to 4 mm is 65%, while for the Gromosol it is only 36%. The fraction of 4 to 12.5 mm is 16% and 35%, respectively, and for the fraction above 12.5 mm, it was 20 and 29%, respectively. The results also show that there is little difference in aggregate size distribution resulting from traditional and minimum tillage practices.

The results of the drip-type rainfall simulation experiments are given in Table 13. Increasing aggregate size increased the aggregate stability. More energy was needed to destroy large aggregates than small aggregates, or, with the same rain intensity, more time is needed to destroy larger aggregates (Fig. 4). A comparison involving the same applied energy to Loess and Gromosol soils shows that for 1- to 2-mm and for 4- to 6.5-mm aggregates, the Loess soil is more stable than the Gromosol soil. For 9.5- to 12-mm aggregates, the Gromosol seems to be more stable, but the differences are small. Extrapolation of the results for 100% aggregate destruction shows that 130 J are needed to destroy the fine aggregates of the Gromosol soil, while 150 J are needed in the case of the Loess soil. A typical Mediterranean rain has kinetic energy of 29 J/mm/m^2 . We can see that after 5 mm of rain, the upper soil layer of fine aggregates will be

Table 12. Mechanical analysis of Loess and Gromosol soils under traditional and minimum tillage, Israel.

Loess and Gromosol soils, traditional tillage

	Size range, mm								
	<1	1-2	2-4	4-6.5	6.5-8	8-9.5	9.5-12.5	12.5-25	>25
<u>Percent in size range</u>									
Loess soil 1	42	7	15	5	3	4	4	10	10
Gromosol	12	9	15	13	6	5	11	17	12

Loess soil, traditional and minimum tillage

	Size range, mm									
	<0.5	.5-1	1-2.5	2.5-4	4-6.5	6.5-8	8-9.5	9.5-12.5	12.5-25	>25
<u>Percent in size range</u>										
Loess soil 2, traditional	20.7	10.1	8.6	14.3	8.1	2.8	3.9	6.2	14.0	11.3
Loess soil 2, minimum	24.5	13.7	10.6	15.0	7.5	2.4	3.1	4.3	8.6	10.3

Fig. 3. Aggregate distribution by weight for Loess and Gromosol soils, Israel.

Table 13. Accumulated percentage of eroded aggregates at different sizes for Loess and Gromosol (Grom) soil in Israel. Rain depth and kinetic energy comparison (sorted for the exact rain depth).

K.E. ^{1/} (J/mm)	(mm)	Size range - mm					
		1-2		4-6.5		9.5-12.0	
		Loess	Grom.	Loess	Grom.	Loess	Grom.
----- Accumulated percentage -----							
14.30	1.79			2.36			
14.37	1.80	7.53					
14.95	1.87		14.78		2.06		
16.53	2.07					1.16	
16.97	2.12						1.09
28.60	3.57			8.77			
28.75	3.59	33.09					
29.91	3.74		47.48				
29.91	3.74				11.09		
33.07	4.13					5.79	
33.93	4.24						3.79
42.90	5.36			23.07			
43.12	5.39	52.19					
44.86	5.61				29.33		
44.86	5.61		64.06				
49.60	6.20					16.24	
50.90	6.36						13.78
57.19	7.15			37.09			
57.50	7.19	64.23					
59.81	7.48				45.01		
59.81	7.48		74.21				
66.13	8.27					28.30	
67.86	8.48						27.45
71.49	8.94			49.12			
71.87	8.98	72.51					
74.77	9.35		81.64				
74.77	9.35				56.95		
82.67	10.33					39.45	
84.83	10.60						40.66

^{1/} K.E.--kinetic energy.

Fig. 4. Destruction of aggregates vs. kinetic energy for Loess and Gromosol soils, Israel. (Numbers = aggregate size, L = Loess, G = Gromosol.)

completely destructed. For large aggregates, approximately 200 J, equal to approximately 65 mm of natural rainfall, was needed for 100% disintegration.

(b) Aggregate stability under simulated rainfall.

The rate of decrease of infiltration rate under rainfall is a measure of the stability of the surface, which disintegrates under rain drop impact to produce a sealing layer. To evaluate these effects, laboratory experiments of aggregate stability under rainfall simulation were performed by using a Rotating-Disk type rainfall simulator (Morin et al., 1967).

METHODS AND MATERIALS

The experiments were carried out on Loess soil aggregate samples. The soil sample was sieved, and the fraction of 2 to 4 mm was packed in 300 x 500 x 100 mm metal boxes in a 20-mm layer on top of 80 mm of coarse sand. The boxes were placed on a rotating table under the rain simulator, with treatments replicated four times. Measurements of water percolating from the bottom of the boxes were made every 5 min. Rain at an intensity of 34 mm/h was applied until final infiltration rate was achieved. Four runs were made for each soil, the first rain on freshly packed boxes and successive rains after 1, 4, and 8 d of drying. The analysis of the results were made using the infiltration equation of Morin and Benyamini (1977), namely, Eq. [1]. The amount of kinetic energy applied is calculated from the value of $29.0 \text{ J/mm of rain/m}^2$, and multiplied by the mm of rainfall received (or applied).

RESULTS AND DISCUSSION

The calculated experimental results (infiltration equation parameters, calculated infiltration results, and rainfall kinetic energy) are given in Table 14 and Fig. 5. The results show that the kinetic energy needed to reach the final infiltration rate (I_f) is much higher than the kinetic energy needed for separate aggregates to be disintegrated. The results also show that initial infiltration (I_i) rates are high for the first run when there is original aggregation in the surface. For later runs, I_i rates are low. The γ parameter is low for the first run and high for the other runs.

When using "drip-tower" systems, separate aggregates lie on a 1-mm net, while under simulated natural rainfall, the aggregates are supported next to each other. In the latter case, eroded material may accumulate among the aggregates so that the soil appears more stable than where separate aggregates are used.

The "drip-tower" system gives a comparative kinetic energy for aggregate stability measurements. The Gromosol soil is known to be more stable than Loess soil, but according to the findings, the same size aggregates show higher stability for the Loess soil than for the Gromosol soil. However, from Table 12, it is clear that the Loess soil has a higher percentage of fine material than the Gromosol soil so that for the total mixture, the Gromosol is more stable.

(c) Aggregate stability of Pullman soil under low energy drop impact

Aggregate stability measurements of Pullman soil from the Bushland location were carried out, using the drip-type rainfall simulator in the same routine as described in Section a. The results show that aggregates of

Table 14. Calculated infiltration parameters for laboratory infiltration experiment on 2-4 mm aggregate size (Part 1) and calculated data (Part 2), Israel.

Part 1. The infiltration equation parameters:

Parameter	First rain	Drying days		
		1	4	8
I_i mm/h	83.1	19.8	17.2	23.2
I_f mm/h	5.3	3.2	3.5	1.8
γ 1/h	0.125	0.158	0.263	0.290
r	0.928	0.840	0.981	0.944

Part 2. Calculated infiltration rate (I_t) as a result of rainfall depth and kinetic energy [KE (J/mm = 29)]:

		Drying days			
K.E. ^{1/}	mm rain				
J	(pt)	1st rain	1	4	8
0	0	83.1	19.8	17.2	23.2
145	5	46.9	10.7	7.2	6.8
290	10	27.6	6.6	4.5	3.0
435	15	17.2	4.8	3.8	2.1
580	20	11.7	3.9	3.6	1.9
725	25	8.7	3.5	3.5	1.8
870	30	7.1	3.3	3.5	1.8
1015	35	6.3	3.3	3.5	1.8
1160	40	5.8	3.2	3.5	1.8
1305	45	5.6	3.2	3.5	1.8
1450	50	5.5	3.2	3.5	1.8
1595	55	5.4	3.2	3.5	1.8
1740	60	5.3	3.2	3.5	1.8

^{1/} K.E.--kinetic energy.

Fig. 5. Infiltration rate vs. kinetic energy for Loess soil, Israel.

Pullman soil (Fig. 6) are more stable than those of the Israeli soils (Fig. 4). The differences between the various sizes of aggregates are minor. The aggregate size of 8 to 9.5 mm has only one replication, so the result is not reliable. The large aggregates had the highest stability. For other aggregate sizes, there was not much difference in stability. For most of them, 100 J of applied energy was needed to cause a 50% weight loss. For Israeli soils, 50 J was needed to lose the 50%. Rainfall parameters in Bushland, Texas, have to be taken into consideration when trying to apply these results.

Fig. 6. Cumulative relative erosion vs. kinetic energy for Pullman soil, Bushland, Texas. (Aggregate sizes are in mm.)

Israel -- Study 2

Infiltration and Runoff as Influenced by Different Tillage Methods and Crop Residue on Two Soil Types.

Study 2 was a field study pertaining to the following subjects:

- a. Aggregate size distribution and stability and organic matter.
- b. Surface water storage due to roughness.

(a) Aggregate size distribution and stability and organic matter

Aggregate size distribution is affected by tillage methods. Aggregate distribution in the soil surface, on the other hand, controls the water infiltration characteristics. Hence, the infiltration capacity of the soil is influenced by the tillage practices used.

Surface roughness is controlled by the aggregate size distribution and the final contact of the implements used. Surface roughness influences the water storage capacity of the soil surface. The storage capacity equals the volume of the surface depressions.

Aggregates tend to disintegrate to finer particles and to reorganize on the surface and form a sealing layer. Large aggregates are more stable than small ones, and the sealing effect is delayed. Crop residues used as a soil cover protect the surface from the drop impact. They also are a source of organic material for improving aggregate stability.

It has been found, and is known from agricultural experience, that Loess soil is very unstable. It is difficult to increase the stability of such soil, and it may be more useful to increase surface storage while fine aggregates remain at the surface. Then, when rainfall occurs, with intermittent breaks, time is available for the ponded water to infiltrate and new storage is developed for the next rainfall event.

METHODS AND MATERIALS

General

Infiltration studies were conducted at two sites, the first one was the Ruhama location with the dominant Loess soil and the second was the Sde-Yoav location with the dominant Gromosol soil. (The soil characteristics are in Table 11).

The cultivated fields consisted of long commercial plots that had received different tillage operations. Infiltration experiments were carried out in the field, with the Rotating Disk type rainfall simulator, on plots of 2 x 2 m (wetting area) with a measuring frame of 1.22 x 1.22 m (1.5 m²) in the center. The frame is equipped with a runoff collector, and runoff water is pumped out and measured with time. Runoff measurements are made every 1 to 5 min. The constant rain intensity minus the runoff rate gives the infiltration rate values.

Rain was applied until steady infiltration rate was achieved (final infiltration rate) on a freshly cultivated surface (first rain), and after 1 or 7 d of drying (second rain). The treatments were replicated three times. The first rain had nine replications. The infiltration parameters (I_f , I_1 , and γ) for a storm were obtained from the determined values of I_f , p , and t using nonlinear regression analysis of Eq. [1] (Morin and Benyamini 1977). Distilled water was used as in the laboratory experiments. Treatments involving different tillage methods were imposed by using commercial and special cultivation implements.

Ruhama location (Traditional tillage and minimum tillage with wheat residue)

A set of experiments using a Rotating Disk type rainfall simulator, with 35 mm/h rain intensity, was conducted to measure the effect of a stubble

mulch on traditional and minimum tillage areas on infiltration decay rates.

Tillage treatments were:

1. Traditional tillage: two passes with a disk, then a roller and a drill.
2. Minimum tillage: direct drilling with a chisel drill. Wheat residue which covered the surface was as follows:
 - a. Stubble mulch of 700 kg/ha
 - b. Stubble mulch of 700 kg/ha and 1000 kg/ha of loose added straw
 - c. Stubble mulch of 700 kg/ha and 3000 kg/ha of loose added straw
 - d. Stubble mulch of 1500 kg/ha and 3000 kg/ha loose added straw

(supplementary irrigation conditions). The different mulch treatments reflect the actual field situation for long period evaluation.

Increasing the amount of surface cover increases water infiltration into the soil, in spite of the low aggregate stability. As a result of these findings, a large quantity of mulch was left in the field after harvesting. Minimum tillage operation was carried out in plots of 0.10 ha each for wheat seeding. This resulted in a very high amount of green vegetation, mainly weeds. Use of the mulch system required the use of herbicides, which are expensive and may cause soil pollution problems.

RESULTS AND DISCUSSION

Infiltration equation parameters and surface storage results are given in Table 15. The correlation coefficients (r) for the calculated and the measured results are fairly high. The r was lowest for the second rain after 1 d of drying. When the amount of mulch was very high, the r was lower after 1 and 7 d of drying than for the first application. We can only explain it by the irregularity of the field surface.

Table 15. Calculated infiltration parameters for traditional and minimal tillage methods, with different amounts of residue left or added to the surface, Israel.

Drying days ^{1/}	Tillage treatment ^{2/}	Infiltration parameters ^{3/}				SD
		I_i	I_f	γ	r	
0	Trad. 700	93.00	9.00	0.041	0.893	2.70
1		11.30	4.50	0.046	0.776	1.20
7		46.40	9.00	0.066	0.860	2.28
0	Trad. 1500	140.00	26.00	0.056	0.984	5.40
1	+3000	35.50	9.00	0.067	0.769	4.35
7		61.00	9.00	0.091	0.900	2.85
0	Min. 700	138.00	14.00	0.050	0.964	1.80
1		18.00	7.00	0.131	0.719	2.30
7		72.00	8.00	0.091	0.938	1.94
0	Min. 700	141.00	23.00	0.051	0.994	3.00
1	+1000	27.40	9.50	0.065	0.831	2.00
7		93.00	9.00	0.100	0.930	2.40
0	Min. 1500	90.00	37.00	0.047	0.992	1.50
1	+3000	47.00	16.00	0.100	0.619	5.22
7		59.00	20.00	0.051	0.750	4.10

^{1/} The first rain was applied on a freshly cultivated plot, the 2nd rain after 1 d of drying or the 2nd rain after 7 d of drying.

^{2/} Treatments:

Traditional tillage and 700 kg/ha residue--Trad. 700,
 Traditional tillage and 700 kg/ha + 1500 kg/ha loose straw--Trad, 700 + 1500,
 Minimum tillage and 700 kg/ha residue--Min. 700,
 Minimum tillage and 700 kg/ha residue + 1000 kg/ha loose straw--Min 700
 + 1000,
 Minimum tillage and 1500 kg/ha residue + 3000 kg/ha loose straw--Min 1500
 + 3000,

^{3/} I_i - initial infiltration rate (mm/h)

I_f - final infiltration rate (mm/h)

γ - soil stability coefficient (1/mm)

r - correlation coefficient

SD - standard deviation (mm/h)

Standard deviations (SD) of the differences between the calculated and measured infiltration rates, in mm/h of infiltrated rain, were the largest in the first rains when the soil was fresh tilled. In the later rains, the deviation values were smaller.

Surface roughness was defined as the surface storage of water that the roughness can hold prior to overland flow out of a unit area. The amount of surface storage is described by the volume of water per unit area or by mm of water.

Infiltration rate decreased with time (or with rainfall depth) during rainfall application. The γ parameter in Eq. [1] describes the rate of infiltration change due to the sealing process (crust formation). This parameter describes aggregate stability, which is the result of particle distribution and arrangement at the soil surface. The γ parameter (Table 15) was lowest for the first rain in all treatments. Differences in the γ parameter for the first rain were very small, with average values of 0.049 and a SD of 0.005. The standard error was 10%. The γ for each treatment was much higher after 1 d (the surface was wet) and higher after 7 d (the surface was dry, but without aggregation). Final infiltration values were the highest in the first rain and decreased to lower values after 1 d. For some treatments, the I_f value did not change much from the 1 d to 7 d or was even higher. The traditional tillage showed the minimum I_f for the first rain (9 mm/h) and after 1 d (4.5 mm/h), while the maximum value was obtained with minimum tillage and the maximum straw mulch.

Increasing infiltration in low aggregate stability soils needs a different approach. This idea is given in Section b.

(b) Surface water storage due to roughness

As we saw earlier, it is difficult to change aggregate stability in order to maintain high infiltration rate throughout the rainy season. Leaving large aggregates on the surface is not recommended in this area, since the dwarf wheat species are sown only to a depth of 2 cm. One way to increase the amount of infiltrated water and reduce runoff without changing aggregate stability is to increase surface storage.

Usually, the pattern of storms in the southern part of Israel is high intensities for short periods and low intensities for longer periods that might come alternately. Creating depressions on the surface will concentrate the rain water and let it infiltrate according to soil infiltrability. Intervals during the storm while infiltration takes place gives storage for the next rain pulse, which again fills the depressions.

METHODS AND MATERIALS

A pitting machine has been developed to create small surface depressions in the soil. The machine has rolling wings, 10 x 20 cm, attached to a shaft, which rotates slower than the speed of a towing tractor. This results in holes or puddles 10 cm wide, 20 cm long, and a maximum of 20 cm deep. A row of 6 m with 5 to 6 wings per 1 m is pulled behind a drill. This setup will create the right size depressions. The passes over the seeded field of wheat may cause loss of one row, but the wheat compensates with tillers so that no reduction in yield occurs (as we will show later). The effect of the pitting compares favorably with traditional tillage that farmers use in this region.

The tillage treatments evaluated were:

1. Traditional tillage: disking and wheat sown.
2. Pitting tillage: disking, wheat sown and pitting.

This study examined the influence of the above tillage methods on the following parameters:

1. Surface storage and its changes with amount of applied rain.
2. Soil water content.
3. Water infiltrated into the soil.
4. Wheat yield.

Measuring Pit Storage Changes

To measure the change in the storage capacity of the pits over the growing season, two hillsides were chosen that had been prepared in the following way: first, traditional tillage had been applied, and then pits were made on half of the field by driving the tractor with the pitter up and down the hill. All other cultivations had been made across the slope.

Pit volume was measured by using a large sheet of thin, soft plastic that was spread over the site, and gently pressed into the pits around the clods of soil, so that it was molded to the shape of the pits. Water from a measuring cylinder was poured on the plastic sheet until over flow started. The volumes of all pits divided by the area gave the storage of the pitted plot. Volumes were measured at the beginning of the rainy season and twice more throughout the season, each time after substantial rains. At the second measurement, wheat plants were very small and soft. The final measurement provided some difficulties, as the wheat was big and dry, so that it could only be cut by a sharp knife.

Soil Water Content

Soil samples were taken both on the pitted and an adjacent unpitted field. A prodrometer (a scaled metal probe with a wider cone, a penetrometer) was first used to determine the average depth of moist soil. Three soil samples were taken at the top, middle, and bottom of the hills to a depth of 90 cm, and at 15-cm intervals. The samples were dried in an oven, and the water content determined.

A rain gauge was placed at the foot of the hills, and records kept of the date and amount of rain occurring for the duration of the experiment.

Simulated Rain Experiments

The effects of simulated rainfall on pitting tillage were studied. Simulated rains, using the Rotating Disk type simulator, were conducted on the two tillage areas four times during the growing season. Those were in addition to the natural rainfall. The simulated rain was on a slope of 2%.

At the end of the simulated rain, the water was allowed to disappear from the surface. In the moment the rain was renewed, runoff was measured until steady readings had been reached. From this experiment, actual surface storage was calculated.

Profile-meter Measurements

A profile-meter was built in order to measure the surface roughness. A unit 50 cm long with 25 fiber-glass pins 3 mm in diameter running between two bars in holes 3.5 mm in diameter was constructed to measure the curvature of the surface in 2-cm spacing.

RESULTS AND DISCUSSION

Rainfall

The record of the rains of Ruhama region are presented in Table 16. Three locations were checked: Kibbutz Ruhama and the two working locations, about 4 km apart in a triangular form. From Table 16, we can see that rainfall amounts changed in short distances, from 232 to 287 mm of rain in the year 1988-89.

Pit Volume

Experiments have been done in order to define the best configuration to achieve maximum volume and minimum reduction of wheat stand. Three configurations were studied:

1. Five puddle driving fast (about 12 to 15 km/h).
2. Five puddle driving slow (about 5 km/h).
3. Six puddle driving slow (about 5 km/h).

We randomly selected 24 sites of 1 m^2 (12 on each of the hills) so as to have four sites of each of the three treatments spread up the hills. The results of pit number and the volume variation according to the amount of rainfall are summarized in Table 17.

Results of the experiments show that five puddles fast driving gave the maximum storage volume throughout the growing season. The volume of the pits decreased in time by 35%, but still gave storage that varied from about 5 mm of surface storage to about 3 mm at the end of the season. (The detailed experiment is not included here.)

Table 16. Rainfall recorded at Ruhama Station, 1988-89, Israel.

Date	Rain (mm)	Date	Rain (mm)
29/10/88	18.00	8/2/89	1.30
30/10/88	3.30	10/2/89	10.30
9/11/88	0.60	11/2/89	27.00
11/11/88	7.80	12/2/89	11.50
18/11/88	14.00	13/2/89	2.00
19/11/88	1.80	18/2/89	5.00
27/11/88	0.60	21/2/89	3.00
6/12/88	6.00	22/2/89	2.70
13/12/88	5.60	9/3/89	2.20
14/12/88	5.50	13/3/89	2.70
18/12/88	1.30	14/3/89	15.00
19/12/88	21.50	15/3/89	9.30
24/12/88	25.00	16/3/89	3.80
25/12/88	16.00	27/3/89	2.00
26/12/88	17.70		
27/12/88	1.20		
2/1/89	17.50	total	260.1
3/1/89	16.00		
8/1/89	3.20		
9/1/89	1.80		
10/1/89	2.50		
11/1/89	5.30		
15/1/89	12.00		
16/1/89	0.90		
20/1/89	27.00		
21/1/89	20.00		
23/1/89	0.70		
27/1/89	6.00		
28/1/89	1.30		

Table 16 cont'd. Ruhama rainfall, 29/11/88 to 21/4/89, Israel.^{1/}

<u>Date</u>	North fields	South east field
	<u>(mm)</u>	<u>(mm)</u>
16/12/88	11.5	7.5
20/12/88	20.0	9.5
28/12/88	54.0	53.0
4/1/89	30.0	26.5
11/1/89	6.0	6.0
13/1/89	5.0	4.0
23/1/89	60.0	44.0
1/2/89	8.0	4.0
14/2/89	54.5	50.0
19/2/89	3.5	5.0
19/3/89	32.0	20.0
29/3/89	3.0	3.0
Total	287.5	232.5

^{1/} Partial (recorded only during experimental period).

Table 17. Effect of wings on pitting machine and speed of operation on puddle numbers and volumes, Israel.

	<u>Treatment^{1/}</u>		
	5p fast	5p slow	6p slow
	<u>Puddles per 1 m² plot</u>		
Hill 1	7.25	5.25	7.75
Hill 2	7.25	5.75	7.50
	<u>Volume of puddles (mm)</u>		
North fields (hill 1)			
<u>Date</u>			
01/12/88	4.27	3.98	4.24
01/01/89	3.81	3.00	3.84
20/04/89	2.69	2.30	2.75
% change	35.3	42.56	35.7
North fields (hill 2)			
<u>Date</u>			
25/01/89	5.66	4.61	3.89
20/04/89	4.47	3.95	2.95
% change	22.7	16.0	24.8

^{1/} Treatments were: 5 p fast--five wings on machine, fast operation;
 5 p slow--five wings on machine, slow operation;
 6 p slow--six wings on machine, slow operation.

Change in Pit Storage

From Table 17, it can be seen that on hill no. 1, there was a decrease in pit water storage over the season (after 287 mm rain) of approximately 35.4% in the five puddle-fast (fast driving) and six puddle-slow (slow driving) plots. In the five puddle-slow plot, the storage reduction was 42.5%.

The plots on hill no. 2 also showed a reduction in storage over the season (after 98 mm rain), with again similar reductions in both five puddle-fast and six puddle-slow (22.7% and 24.7%), but a much lower reduction (15.0%) in the volume of five puddle-slow plots. If we look at the volumes of water that the different treatments held, it is seen that the five puddle-fast and six puddle-slow plots held similar volumes on the first hill, with much less being held in the five puddle-slow. On the second hill, more water was again held in the five puddle-fast plots, but less was held in the six puddle-slow than in either of the five puddle-fast or five puddle-slow plots. Variation in volumes that the different plots held within the same treatment is partially due to the position of the plots on the hill. As the slope of the hill became less towards the bottom, more water could be held. It appears from these results that the five puddle-fast plots hold, on average, more water than either of the other two plots over the growing season, and that the volume of these pits can be expected to decrease by about 35% by the end of the winter rains. Therefore, the five puddle-fast treatment appears to be the best out of the three that were tested.

Soil Water

Results for soil water are given in Table 18, which takes into consideration the position of the measured area according to the position in hill slope - top, in the middle, and bottom of the slope. From these

Table 18. Soil water contents (%) during the rainy season, Israel.

	Sample depth (cm)					
	0-15	15-30	30-45	45-60	60-75	75-90
North fields, 29/12/88						
Top pitted	20.57	20.34	19.86	14.77	12.40	12.73
Top unpitted	20.86	20.86	20.53	16.68	13.23	13.85
Middle pitted	21.40	21.80	22.25	19.56	13.74	13.80
Middle unpitted	21.97	21.68	21.12	15.35	15.02	15.64
Bottom pitted	20.50	19.74	19.38	17.17	12.18	12.75
Bottom unpitted	20.12	19.93	18.87	12.26	11.15	13.50
North fields, 6/1/89						
Top pitted	21.59	21.84	21.62	20.77	17.23	16.16
Top unpitted	19.42	19.58	19.76	19.50	14.97	13.95
Middle pitted	23.36	23.02	22.79	21.74	19.22	16.94
Middle unpitted	22.89	22.61	22.40	20.19	15.32	16.97
Bottom pitted	20.55	19.35	20.06	19.17	15.89	13.88
Bottom unpitted	20.34	20.12	20.33	17.79	14.71	12.86
North fields, 15/2/89						
Top Pitted	21.81	21.66	22.58	21.33	21.07	20.45
Top Unpitted	20.60	20.83	21.20	20.70	19.68	15.38
Middle Pitted	24.24	23.80	22.39	22.16	21.86	21.35
Middle Unpitted	22.55	22.07	22.64	21.50	21.11	21.41
Bottom Pitted	23.30	21.83	21.47	20.86	21.40	21.52
Bottom Unpitted	20.78	20.89	20.79	19.52	19.76	19.61

results, it can be seen that at the beginning of the season, there was very little difference in soil water content between the pitted and unpitted profiles. However, this changed as the season progressed. On 6 January 1989 after 30 mm of rain, there was considerably more water in the top and middle of the pitted area than in the unpitted one. In the top of the pitted area at the depth of 45 to 60 cm, the water content was 20.77%, while in the unpitted area at the top, the water content at the same depth was 19.50%, giving a difference of 1.27%, or 6.1% more water in the pitted than in the unpitted area. In greater depths, the difference was higher. The water penetrated deeper and earlier in the pitted tillage area on the top and middle slope positions. There was not a large increase in water content due to treatments at the bottom of the hill. After 164 mm of rain on 15 February, there was considerably more water in the pitted than in the unpitted area, particularly at the lower depths and at all positions on the hill.

At the 75- to 90-cm depth for the top pitted area, the water content was 20.45%, For the top unpitted area, it was only 15.38%, giving a difference of 5.06%, or 24.74% more water in the pitted than in the unpitted area. The differences at other positions were not so large. These results indicate that pitting the surface increases the water content of the soil, particularly in the middle and top of the hill, thus making more water available to plants during the growing season.

Prodometer

A quick way to evaluate the depth of water penetration into soil is the prodrometer technique. The maximum depth that a 100-cm long rod can be pushed into the soil is approximately the depth of the wetting front. A summary of

results using the prodrometer in the different tillages and the position on the slope is given in Table 19. Each measurement is an average of 10 pushings with the standard deviation (SD) also given.

A comparison of soil water content results and prodrometer results shows a fairly good correlation between the depth to which the prodrometer could be pushed into the soil and the point where the soil water content dropped to approximately 15 or 16%. Soil water content for the top of the pitted area on the 29 December 1988 dropped off sharply to about 15% at the 45- to 60-cm depth. The prodrometer results for this date show a reading of 52 cm, which is in fact in the range where the water content decreased. For the bottom of pitted area on the 6 January 1989, the soil water content dropped off sharply to about 16% at the 60- to 75-cm depth. The prodrometer results for this date show a reading of 62 cm, which again is in the range where the water content decreased. The results show that using the prodrometer gives a good indication of the average depth of moist soil. Based on the prodrometer readings, water penetrated deeper on pitted than on unpitted areas.

Rainfall Simulation

Rainfall simulation experiments were carried out on the pitted and unpitted fields. Rain simulations, of 40 mm/h intensity, were made four times, 4 to 6 weeks apart in the season, with three replications each time. The results were calculated using the infiltration equation, Eq. [1]. The parameters and the variance are given in Table 20. The calculation used nonlinear regression analysis for the three replications of each case. The final infiltration rate (I_f), which was taken to the calculation, was the average of the three replications in each case. The results show that the

Table 19. Average depth of moist soil as determined with a prodrometer,
Israel.

Location and condition	Date							
	<u>29/12/88</u>		<u>06/01/89</u>		<u>15/02/89</u>		<u>20/04/89</u>	
	Depth	SD	Depth	SD	Depth	SD	Depth	SD
	----- cm -----							
Top pitted	52.2	5.9	61.3	5.2	100.0	-- ^{1/}	60.2	9.4
Top unpitted	52.5	3.5	62.6	4.3	81.9	2.6	45.3	5.4
Middle pitted	48.5	6.3	66.2	5.7	94.0	6.1	65.1	9.3
Middle unpitted	45.6	3.1	60.9	5.2	90.6	4.4	43.4	6.6
Bottom pitted	51.0	3.7	63.4	4.6	100.0	--	100.0	--
Bottom unpitted	48.0	5.7	58.2	3.4	100.0	--	61.4	9.9

^{1/} Depth is more than 100 cm.

Table 20. Parameters for the infiltration experiments in Ruhama under traditional and pitting tillage methods, Israel. (Rain intensity 40 mm/h.)

Area and rain event	Parameter			R^2	S.E.
	I_f (mm/h)	I_i (mm/h)	γ (1/mm)		
Control, first	4.8	103.0	0.079	0.950	0.034
Pits, first	4.8	120.8	0.076	0.911	0.046
Control, second	4.0	53.7	0.210	0.920	0.041
Pits, second	6.8	126.0	0.111	0.752	0.063
Control, third	10.4	59.1	0.116	0.976	0.023
Pits, third	14.6	435.0	0.140	0.979	0.051
Control, fourth	14.0	56.3	0.067	0.903	0.037
Pits, fourth	12.8	91.6	0.051	0.858	0.056

deviations between the replications were fairly small because, in most cases, the R^2 was high, with a low standard error.

Data for surface storage after each rain are presented in Table 21. Changes in calculated infiltration rates due to the two tillage methods with the amount of rain applied and the kinetic energy of the drop impact are given in Table 22. This is the potential infiltration capacity. It predicts the maximum rainfall intensity which can infiltrate into the soil without producing runoff. The potential amount of water infiltrated into the soil can be calculated by integrating the infiltration equation, Eq. [1] (Morin and Benyamini, 1977). When the rainfall intensity is less than the infiltration rate, all rain infiltrates into the soil. The results (Table 20) describing the infiltration equation parameters show that there is no difference between the control and the pitted areas in the beginning of the season. The infiltration parameters are similar, despite the fact that the surface storage of the pitted field is larger than the control (Table 21). However, comparing the final infiltration rates shows that for each period, the difference between the control and the pitted plots is not large. This means that the characteristics of the surface did not change as a result of the pitting, and that the surface storage is the only difference.

As the season progressed, considerable differences became apparent. Gamma (γ) values were the lowest at the last simulation. This occurred after a long period of warm temperatures (spring time) without substantial rain, which left the soil dry with cracks in the surface. The γ values were also small for the first rain simulation which came on dry uncrusted soil. The last rains resulted in differences due to tillage. For these rains, parameters for pitting were always higher than for the control.

Table 21. Surface storage and detention on the rainfall simulation plots using rainfall simulator technique, Israel.

Run	<u>Control plots</u>		<u>Fitted plots</u>	
	Site No.	Vol.(mm)	Site No.	Vol.(mm)
1	-- <u>1/</u>	--	6	4.5
	--	--	7	4.2
	--	--	AVG	4.35
2	8	0.6	11	4.1
	9	1.0	12	5.6
	10	1.2	13	3.9
	AVG	0.93	AVG	4.53
3	14	1.2	--	--
	15	2.1	--	--
	16	1.1	--	--
	AVG	1.47	--	--
4	20	1.6	25	5.5
	21	2.4	26	3.7
	22	1.7		
	AVG	1.9	AVG	4.6

1/ No data.

Table 22. Calculated infiltration rates from infiltration equation parameters, Israel.^{1/}

pt	KE	Treatment and period of measurement							
		C1	C2	C3	C4	P1	P2	P3	P4
0	0	103.0	53.7	59.1	56.3	120.8	126.0	435.0	91.6
5	140	71.0	21.4	37.7	44.3	84.1	75.2	223.4	73.9
10	280	49.4	10.1	25.7	35.6	59.0	46.1	118.3	60.1
15	420	34.8	6.1	18.9	29.5	41.9	29.4	66.1	49.5
20	560	25.0	4.7	15.2	25.1	30.2	19.7	40.2	41.2
25	700	18.4	4.3	13.1	21.9	22.1	14.2	27.3	34.8
30	840	14.0	4.1	11.9	19.7	16.7	11.1	20.9	29.9
35	980	11.0	4.0	11.2	18.1	12.9	9.2	17.7	26.0
40	1120	9.0	4.0	10.9	16.9	10.3	8.2	16.2	23.0
45	1260	7.6	4.0	10.7	16.1	8.6	7.6	15.4	20.7
50	1400	6.7	4.0	10.5	15.5	7.4	7.3	15.0	19.0
55	1540	6.1	4.0	10.5	15.1	6.6	7.1	14.8	17.6
60	1680	5.7	4.0	10.4	14.8	6.0	7.0	14.7	16.5
65	1820	5.4	4.0	10.4	14.5	5.6	6.9	14.6	15.7
70	1960	5.2	4.0	10.4	14.4	5.4	6.9	14.6	15.0
75	2100	5.1	4.0	10.4	14.3	5.2	6.8	14.6	14.5
80	2240	5.0	4.0	10.4	14.2	5.1	6.8	14.6	14.1
85	2380	4.9	4.0	10.4	14.1	5.0	6.8	14.6	13.8
90	2520	4.9	4.0	10.4	14.1	4.9	6.8	14.6	13.6
95	2660	4.9	4.0	10.4	14.1	4.9	6.8	14.6	13.4
100	2800	4.8	4.0	10.4	14.1	4.9	6.8	14.6	13.3
105	2940	4.8	4.0	10.4	14.0	4.8	6.8	14.6	13.2
110	3080	4.8	4.0	10.4	14.0	4.8	6.8	14.6	13.1
115	3220	4.8	4.0	10.4	14.0	4.8	6.8	14.6	13.0

^{1/} Calculated infiltration rates (mm/h) with rain depth (pt) and kinetic energy (KE) for control (C) and pitted (P) tillage methods in four periods of measurements (1-4). Calculated from the parameters in Table 20.

Infiltration was higher on treated plots for a given accumulated precipitation than for the control plots. For example, for the third period of simulated rain on the control plots (Table 22), the infiltration rate after 30 mm of rain was 11.9 mm/h, while on the pitted plots it was 20.9 mm/h for the same amount of rain. For each period, the final infiltration rate on pitted plots was higher than on control plots. A possible explanation for differences between treatments in final infiltration rates may be the deposition of eroded material at the bottom of the depressions, which resulted in ponded water that minimized the compacting effects of raindrop impact on the surface where infiltration was occurring. Because of the higher infiltration rates with pitting, the amount of infiltrated water is higher than with the control, and the effect lasts during the entire rainy season.

Calculated surface storage capacities from simulated rainfall experiments (Table 21) show higher storage in pitted than in control areas. The results for the control show an increase in storage with time (run), which may be due to the plants growing on the plots. On the pitted areas, the increase was less remarkable. At the beginning of the season when the soil was bare, the increase in storage was five-fold, but this dropped to slightly over a two-fold increase late in the season. Even this two-fold increase, however, indicated that the pitted soil holds more water than the unpitted soil, which is the main advantage of the system. With high storage capacity and high final infiltration rates, the amount of water infiltrated increases, which increases the water content of the soil profile.

Yield

Wheat yield measurements were made in commercial fields on Loess soil in regions around the location where the experiments were conducted. The effects of traditional tillage were compared to those of pitting tillage in 10 plots of about 40 ha each. Data are presented in Table 23. From the yield results, it is clear, with high confidence, that the pitting practice is increasing wheat yields in the dry regions of Loess soil.

Sde-Yoav location

A set of experiments using the Rotating Disk type rainfall simulator was carried out in the field. The experiments were designed to evaluate the influence of different tillage methods on the infiltration characteristics of the soil. The dominant soil in this region is a Gromosol. Traditional tillage practices were plowing, disking, rolling, and drilling. Minimum tillage was tested as the comparison method. Simulated rain at an intensity of 40 mm/h was applied on plots with 5% slope. The water applications were replicated three times.

The results of this set of experiments are summarized in Table 24. The data were analyzed by using the infiltration equation, Eq. [1], and the parameters are given in the Table 24(1). Solving the equation for the tillage conditions with the infiltration parameters gives the infiltration pattern for the different tillage methods (Table 24(2)) and in Fig. 7 and 8.

From Table 24, it can be seen that final infiltration rates with traditional tillage in the three drying periods are lower than those with minimum tillage. With traditional tillage, there were almost no differences in final infiltration rates among the different runs, while with minimum tillage, the differences were relatively large. The amount of rain needed

Table 23. Average wheat yields for 2 years with traditional and pitting tillage at 10 locations in the south of Israel.

Year	Treatment		Difference	SD	Diff. %
	Control	Pitting			
	----- kg/ha -----				
1987/88	3010	3253	243	24.7	8.08
1988/89	2155	2451	296	23.2	13.7

Table 24. Rainfall simulator infiltration equation parameters (1) and calculated infiltration rates with rain depth and kinetic energy for Sde-Yoav Gromosol soil (2), Israel (up to 100 mm rain).

1. Infiltration parameters								
Traditional seed bed					Minimum tillage seed bed			
	I_f	I_i	γ	SD	I_f	I_i	γ	SD
First rain	2.5	280	-0.089	1.6	8.0	105.7	-0.064	3.2
2nd after 1d	2.0	40	-0.121	2.0	4.0	13.2	-0.11	2.9
2nd after 7d	2.0	86	-0.134	1.1	5.0	40	-0.087	2.4
2. Calculated infiltration rates								
		Traditional seed bed			Minimum tillage seed bed			
pt	KE ^{1/}	$I_t(0)$	$I_t(24h)$	$I_t(7d)$	$I_t(0)$	$I_t(24h)$	$I_t(7d)$	
0	0	280.0	40.0	86.0	105.7	13.2	40.0	
5	145	180.3	22.8	45.0	78.9	9.3	27.7	
10	290	116.5	13.3	24.0	59.5	7.1	19.7	
15	435	75.5	8.2	13.3	45.4	5.8	14.5	
20	580	49.3	5.4	7.8	35.2	5.0	11.1	
25	725	32.5	3.8	4.9	27.7	4.6	9.0	
30	870	21.7	3.0	3.5	22.3	4.3	7.6	
35	1015	14.8	2.6	2.8	18.4	4.2	6.7	
40	1160	10.4	2.3	2.4	15.6	4.1	6.1	
45	1305	7.6	2.2	2.2	13.5	4.1	5.7	
50	1450	5.7	2.1	2.1	12.0	4.0	5.5	
55	1595	4.6	2.0	2.1	10.9	4.0	5.3	
60	1740	3.8	2.0	2.0	10.1		5.2	
65	1885	3.4		2.0	9.5		5.1	
70	2030	3.0			9.1		5.1	
75	2175	2.9			8.8		5.1	
80	2320	2.7			8.6		5.0	
85	2465	2.6			8.4		5.0	
90	2610	2.6			8.3			
95	2755	2.6			8.2			
100	2900	2.5			8.2			

^{1/} Kinetic energy/mm rain = 29 J/mm

Fig. 7. Infiltration rate vs. rain depth for disk and minimum tillage methods for the Sde-Yoav Gromosol soil, Israel. Treatments are: dis1--first rain, disk tillage; min1--first rain, minimum tillage; dis2--second rain (after 24 h), disk tillage; min2--second rain (after 24 h), minimum tillage; dis7--third rain (after 7 days), disk tillage; min7--third rain (after 7 days), minimum tillage.

Fig. 8. Calculated infiltration rate vs. kinetic energy for Gromosol soil at Sde-Yoav, Israel, for disk (dis) and minimum (min) tillage. (0 is for 1st rain, 1 and 7 are after days of drying.)

for the infiltration rate to reach the final rate value is about 90 mm for the first rain for traditional tillage, about 45 mm for the second rain after 24 h, and 50 mm after 7 d of drying. For minimum tillage, the amounts were 100, 40, and 65 mm, respectively. It is clear that with minimum tillage, the amount of infiltrated rain is higher than with traditional tillage for the same amount of rain in each time. However, the infiltration capacity with the two tillage methods is relatively low. An examination of the aggregate stability data (Table 13) shows that the stability of the Gromosol is low compared to the stability of the Loess soil. Thus, it will also be an advantage to adopt the pitting technique to improve the infiltration capacity of the Gromosol soil. This technique is suitable for different crops, mainly when the soil is bare in the beginning of the winter. In fact, pitting tillage is being used by farmers in the Gromosol soil regions.

Israel -- Study 3

Computer Analysis of Rainfall Data Combined with Infiltration Data for Runoff Yield Prediction with Different Tillage and Cultivation Methods.

Morin and Benyamini (1988) showed that an analysis of rainfall data can be used as a tool for choosing appropriate tillage methods. The technique indicates the surface storage that is necessary for accepting rain storms in different climatic regions. It also indicates the tillage methods that will produce the needed surface storage.

METHODS AND MATERIALS

The procedure contains the following steps:

1. Analyzing the entire available record of rain storms according to equal rain intensities and duration of each intensity, and the total for the year, based on statistical calculations.
2. Developing infiltration curves for different rain conditions (first rain, second rain, or third rain) and soil conditions (soil types and tillage practice).
3. Combining information on rain storms and infiltration curves for different volumes of surface storage in order to select tillage methods that will provide the surface storage capacity needed to receive the runoff expected for the above conditions.

Analyses have been done for all the available rainfall records, which were received from the meteorological service in Israel, for the two sites of the project, Ruhama and Sde-Yoav. The meteorological stations which are related to our sites are Dorot station for Ruhama and Negba station for Sde-Yoav. Infiltration equation parameters, which were calculated from the field experiments described earlier, were developed for different tillage methods.

Combinations of rainfall analysis and infiltration parameters were used to produce synthetic data for all the records of rainfall. Analysis of runoff probabilities under a range of surface storage capacities give us the opportunity of selecting desired tillage methods. Because surface storage differs as a result of different tillage methods, we should be able to select the best tillage method for our purpose. Pitting or other basin tillage methods are giving us the opportunity to control soil surface storage in spite of the low aggregate stability of the two tested soils.

RESULTS AND DISCUSSION

The rainfall simulation field experiment provided the parameters of the infiltration equation for various conditions. The parameters, which describe the infiltration process of rain into the soil, depend on sealing of the soil surface. These parameters, together with the analyzed rainfall records, gave the expected runoff for each unit of rain storm. The analysis has been done for rains that exceeded 10 mm. An example of the calculation with the storm analysis and the runoff expected from three tillage methods is presented in Table 25.

Tables 26, 27, and 28 present the runoff calculations for the 42.9 mm rain storm which was analyzed above. Table 26 is for disk tillage, Table 27 is for minimum tillage with 700 kg/ha of stubble mulch, and Table 28 is for stubble mulch of 700 kg/ha + 1000 kg/ha of spread cut straw.

The calculations show the role of surface storage and different infiltration characteristics for controlling runoff. We can see that under disk tillage, even for 10 mm surface storage, there is some runoff. Under minimum tillage (Table 28), 1.81 mm of runoff occurred at 2 mm of surface storage. The results for minimum tillage with less straw (Table 27) show

Table 25. Rainstorm analysis - for 9 January 1990, Israel.^{1/}

Intensity, mm/h	Volume, mm	Percentage
0	2.72	6.34
1	2.59	12.38
2	0.20	12.86
3	0.81	14.75
4	0.70	16.39
5	2.00	21.05
6	4.98	32.66
7	1.87	37.01
9	1.04	39.43
12	2.18	44.52
14	1.74	48.58
16	1.67	52.46
17	1.61	56.21
19	5.74	69.59
24	3.26	77.18
27	2.78	83.65
32	3.46	91.72
35	3.55	100.00

Total volume	42.9 mm	

^{1/} Storm kinetic energy = 910.7 J/m^2 .

The maximum intensity for 30 min was 17.7 mm/h at segment 19 - 24.

Erosivity (R) = 16.12 J/mm-h.

Table 26. Runoff calculation for disk tillage, Israel.

Infiltration parameters		
$I_f(A)=$ 93	$I_f(A)=$ 9	$\gamma(A)=$ 0.041
$I_f(B)=$ 11.3	$I_f(B)=$ 4.5	$\gamma(B)=$ 0.046
$I_f(C)=$ 47	$I_f(C)=$ 9	$\gamma(C)=$ 0.066

Maximum surface storage and detention (S.D.M) in mm								
	0.0	0.5	1.0	2.0	5.0	10.0	15.0	20.0
Max. RF ^{1/}	2.71	2.21	2.12	2.12	2.12	0.28	0.00	0.00
at seg.	19	19	21	21	21	25	0	0
RF	17.75	14.42	12.42	8.77	5.28	0.28	0.00	0.00

^{1/} RF - Runoff (mm), Max. RF - Maximum runoff per segment, seg - segment of equal rain intensity.

Table 27. Runoff calculation for minimum tillage with 700 kg/ha mulch,
Israel.

Infiltration parameters								
$I_f(A)=$	138	$I_f(A)=$	14	$\gamma(A)=$	.05			
$I_f(B)=$	18	$I_f(B)=$	7	$\gamma(B)=$	.131			
$I_f(C)=$	72	$I_f(C)=$	8	$\gamma(C)=$	.091			
Maximum surface storage and detention (S.D.M) in mm								
	0.0	0.5	1.0	2.0	5.0	10.0	15.0	20.0
Max. RF ^{1/}	2.65	2.15	2.04	2.04	2.04	0.00	0.00	0.00
at seg.	19	19	21	21	21	0	0	0
RF	15.42	12.52	10.52	6.85	3.85	0.00	0.00	0.00

^{1/} RF - Runoff (mm), Max. RF - Maximum runoff per segment, seg - segment
of equal rain intensity.

Table 28. Runoff calculation for minimum tillage of 700 kg/ha + 1000 kg/ha mulch, Israel.

Infiltration parameters								
$I_i(A)=$	141	$I_f(A)=$	23	$\gamma(A)=$	.051			
$I_i(B)=$	27	$I_f(B)=$	9.5	$\gamma(B)=$	.065			
$I_i(C)=$	93	$I_f(C)=$	9	$\gamma(C)=$	.1			
Maximum surface storage and detention (S.D.M) in mm								
	0.0	0.5	1.0	2.0	5.0	10.0	15.0	20.0
Max. RF ^{1/}	1.99	1.49	1.49	1.49	0.00	0.00	0.00	0.00
at seg.	19	21	21	21	0	0	0	0
RF	7.11	5.09	3.09	1.81	0.00	0.00	0.00	0.00

^{1/} RF - Runoff (mm), Max. RF - Maximum runoff per segment, seg - segment of equal rain intensity.

that surface storage of 5 mm gave 3.85 mm runoff. Surface storage of 5 mm for the disk gave 5.28 mm runoff. This analysis describes the tool which was developed to predict the storage needs under different amounts of rainfall, and for choosing the most suitable tillage practice.

The runoff estimates that were developed from all the available rainfall records under different surface storage conditions are given in Tables 29 to 34 for Loess soil in the Ruhama region and in Tables 35 and 36 for Gromosol soil in the Sde-Yoav region. Annual runoff and maximum daily runoff in each year are related to the actual annual and the maximal rain storms.

The expected runoff is related to the storage that can be achieved on the soil surface. Illustrations of the results from the above analyses (Tables 29 to 34 and Fig. 9 to 12) show the most sensitive period for runoff and how different amounts of surface storage can reduce the expected runoff. Tables for the daily maximum runoff show that in the Loess region, the most sensitive months for runoff are November and December. In the Gromosol region, November, December, and January are the sensitive ones. In these periods, the grain fields usually are bare after seeding or with very small vegetation, so that increased surface storage is required. Increased surface storage results in reduction of runoff, and penetration of more water into the soil. As we saw earlier, pitting tillage can increase surface storage, thus reducing runoff and increasing crop yields.

The wheat committee in Israel is examining the pitting method in order to make recommendations. Their economic calculations show that the yield of wheat is increasing and the hectoliter weight (test weight) is increasing also. Results for 1987/88 show average increase in yield of 240 kg/ha with a hectoliter weight over 76 kg, which increases the payment per ton by \$26. The cost of the tillage is \$10/ha or equivalent to 50 kg/ha of wheat.

Table 29. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/} with a surface mulch of 700 kg/ha, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
53	58.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	104.4	2.0	0.8	0.2	0.0	0.0	0.0	0.0
56	217.3	9.4	5.4	2.9	0.0	0.0	0.0	0.0
57	85.3	2.2	1.7	1.2	0.0	0.0	0.0	0.0
58	105.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0
59	157.2	8.9	5.8	4.0	0.0	0.0	0.0	0.0
61	168.9	2.6	1.3	0.3	0.0	0.0	0.0	0.0
62	127.1	16.7	15.0	13.5	8.6	4.6	0.0	0.0
63	72.6	14.7	12.4	11.1	7.4	5.4	0.4	0.0
64	298.7	5.4	3.7	2.6	0.0	0.0	0.0	0.0
65	305.8	1.5	0.2	0.0	0.0	0.0	0.0	0.0
66	123.8	2.8	1.4	0.8	0.0	0.0	0.0	0.0
67	308.1	5.5	4.0	2.8	0.0	0.0	0.0	0.0
68	193.1	0.6	0.1	0.0	0.0	0.0	0.0	0.0
69	254.9	10.1	7.9	6.2	3.1	1.1	0.0	0.0
70	154.0	11.2	10.7	10.2	8.2	6.2	1.2	0.0
71	291.9	29.7	27.7	26.4	22.4	19.5	14.5	4.5
72	275.4	4.5	2.3	1.3	0.0	0.0	0.0	0.0
73	238.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0

- more -

Table 29 cont'd. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/}
with a surface mulch of 700 kg/ha, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
74	418.1	10.8	8.5	6.5	1.3	0.0	0.0	0.0
75	250.1	9.2	7.3	6.0	3.7	1.7	0.0	0.0
76	137.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
77	191.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0
78	258.0	11.4	10.4	9.6	7.6	5.6	0.6	0.0
79	184.6	0.9	0.2	0.0	0.0	0.0	0.0	0.0
80	378.1	48.1	41.1	35.3	16.9	11.0	2.1	0.0
81	118.4	4.6	3.8	3.3	1.3	0.0	0.0	0.0
82	203.9	2.7	1.5	1.0	0.0	0.0	0.0	0.0
84	89.7	4.9	4.4	3.9	1.9	0.0	0.0	0.0
85	113.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	97.2	3.2	1.4	0.6	0.0	0.0	0.0	0.0
87	314.6	2.9	1.7	1.0	0.0	0.0	0.0	0.0
88	282.5	10.6	7.1	5.0	0.4	0.0	0.0	0.0

^{1/} Data for 1960 and 1983 are missing.

Table 30. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/} with disk tillage, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
53	58.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	104.4	3.0	1.5	0.5	0.0	0.0	0.0	0.0
56	217.3	13.5	8.2	4.7	0.1	0.0	0.0	0.0
57	85.3	2.2	1.7	1.2	0.0	0.0	0.0	0.0
58	105.4	3.9	2.2	1.1	0.0	0.0	0.0	0.0
59	157.2	9.2	6.0	3.4	0.0	0.0	0.0	0.0
61	168.9	4.5	2.8	1.5	0.0	0.0	0.0	0.0
62	127.1	17.7	15.9	14.4	8.4	4.3	0.0	0.0
63	72.6	13.9	11.9	10.5	6.7	4.7	0.0	0.0
64	298.7	7.7	5.4	4.4	0.8	0.0	0.0	0.0
65	305.8	2.4	1.0	0.4	0.0	0.0	0.0	0.0
66	123.8	4.2	2.7	1.6	0.0	0.0	0.0	0.0
67	308.1	6.6	5.1	3.9	0.3	0.0	0.0	0.0
68	193.1	3.8	2.8	1.8	0.0	0.0	0.0	0.0
69	254.9	11.3	8.5	6.2	2.6	0.6	0.0	0.0
70	154.0	11.0	10.5	10.0	8.0	6.0	1.0	0.0
71	291.9	29.7	26.3	25.2	21.2	18.6	13.6	3.6
72	275.4	7.3	4.4	2.2	0.0	0.0	0.0	0.0
73	238.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0

- more -

Table 30 cont'd. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/}
with disk tillage, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
74	418.1	15.6	12.1	9.4	4.3	1.5	0.0	0.0
75	250.1	10.6	8.6	7.3	4.8	2.8	0.0	0.0
76	137.9	2.3	1.8	1.3	0.0	0.0	0.0	0.0
77	191.5	0.6	0.1	0.0	0.0	0.0	0.0	0.0
78	258.0	11.8	10.6	9.6	7.2	5.2	0.2	0.0
79	184.6	1.7	0.7	0.0	0.0	0.0	0.0	0.0
80	378.1	48.7	41.6	36.2	18.4	11.4	1.8	0.0
81	118.4	7.9	6.9	5.9	3.5	1.5	0.0	0.0
82	203.9	3.2	1.4	0.8	0.0	0.0	0.0	0.0
84	89.7	4.0	3.4	2.9	0.9	0.0	0.0	0.0
85	113.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	97.2	4.7	2.7	1.4	0.0	0.0	0.0	0.0
87	314.6	4.0	2.5	1.0	0.0	0.0	0.0	0.0
88	282.5	11.6	7.6	4.8	0.0	0.0	0.0	0.0

^{1/} Data for 1960 and 1983 are missing.

Table 31. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/} with
mulch of 700 kg/ha + 1000 kg/ha, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
53	58.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	104.4	1.0	0.5	0.0	0.0	0.0	0.0	0.0
56	217.3	6.6	3.7	1.7	0.0	0.0	0.0	0.0
57	85.3	1.8	1.3	0.8	0.0	0.0	0.0	0.0
58	105.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
59	157.2	6.7	4.9	3.4	0.0	0.0	0.0	0.0
61	168.9	0.9	0.4	0.0	0.0	0.0	0.0	0.0
62	127.1	13.8	12.3	11.1	7.1	3.1	0.0	0.0
63	72.6	12.8	10.6	9.2	6.1	4.1	0.0	0.0
64	298.7	2.4	1.4	0.9	0.0	0.0	0.0	0.0
65	305.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0
66	123.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67	308.1	1.1	0.1	0.0	0.0	0.0	0.0	0.0
68	193.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	254.9	7.1	6.1	5.1	2.8	0.8	0.0	0.0
70	154.0	9.8	9.3	8.8	6.8	4.8	0.0	0.0
71	291.9	28.4	26.9	25.8	21.8	19.0	14.0	4.0
72	275.4	2.3	1.1	0.5	0.0	0.0	0.0	0.0
73	238.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0

- more -

Table 31 cont'd. Annual runoff (mm) at Ruhama calculated for 1953-1988^{1/}
with mulch of 700 kg/ha + 1000 kg/ha, Israel.

Year	Rain (mm)	Surface storage (mm)						
		0	0.5	1	3	5	10	20
74	418.1	6.9	4.9	2.9	0.0	0.0	0.0	0.0
75	250.1	6.8	5.3	4.3	2.3	0.3	0.0	0.0
76	137.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
77	191.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
78	258.0	10.3	9.8	9.3	7.3	5.3	0.3	0.0
79	184.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	378.1	43.2	36.7	31.1	15.1	9.7	1.9	0.0
81	118.4	2.2	1.7	1.2	0.0	0.0	0.0	0.0
82	203.9	1.8	1.3	0.8	0.0	0.0	0.0	0.0
84	89.7	3.6	3.1	2.6	0.6	0.0	0.0	0.0
85	113.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	97.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
87	314.6	1.7	0.9	0.4	0.0	0.0	0.0	0.0
88	282.5	7.3	4.5	2.6	0.0	0.0	0.0	0.0

^{1/} Data for 1960 and 1983 are missing.

Table 32. Maximum daily runoff (mm) at Ruhama calculated for 1953-1988^{1/}
with mulch of 700 kg/ha, Israel.

Hy ^{2/}	Storm date			Daily rain (mm)	Surface storage (mm)						
	Day	Month	Year		0	0.5	1	3	5	10	20
1	20	1	53	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	5	12	54	30.8	1.8	0.8	0.2	0.0	0.0	0.0	0.0
3	5	1	56	37.3	6.0	4.0	2.3	0.0	0.0	0.0	0.0
4	13	3	57	28.3	2.2	1.7	1.2	0.0	0.0	0.0	0.0
5	20	1	58	15.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
6	19	1	59	64.3	7.6	5.5	4.0	0.0	0.0	0.0	0.0
7	17	11	60	15.4	1.0	0.5	0.0	0.0	0.0	0.0	0.0
8	14	12	61	29.3	8.9	7.9	6.9	3.9	1.9	0.0	0.0
9	11	2	63	44.6	14.7	12.4	11.1	7.4	5.4	0.4	0.0
10	29	2	64	58.4	4.6	3.6	2.6	0.0	0.0	0.0	0.0
11	22	3	65	37.8	0.7	0.2	0.0	0.0	0.0	0.0	0.0
12	21	3	66	12.7	2.8	1.4	0.8	0.0	0.0	0.0	0.0
13	25	3	67	22.6	5.5	4.0	2.8	0.0	0.0	0.0	0.0
14	20	2	68	13.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	30	10	68	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	7	11	69	31.1	11.2	10.7	10.2	8.2	6.2	1.2	0.0
17	7	12	70	14.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
18	18	11	71	28.1	2.1	1.6	1.1	0.0	0.0	0.0	0.0
19	15	1	73	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

- more -

Table 32 cont'd. Maximum daily runoff (mm) at Ruhama calculated for
1953-1988^{1/} with mulch of 700 kg/ha, Israel.

Hy ^{2/}	<u>Storm date</u>			Daily rain (mm)	<u>Surface storage (mm)</u>						
	Day	Month	Year		0	0.5	1	3	5	10	20
20	31	1	74	66.0	3.8	3.3	2.8	0.8	0.0	0.0	0.0
21	22	11	74	33.0	6.7	6.2	5.7	3.7	1.7	0.0	0.0
22	21	12	75	18.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	23	4	77	33.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0
24	3	1	78	39.2	10.6	10.1	9.6	7.6	5.6	0.6	0.0
25	31	10	78	24.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0
26	6	12	79	62.8	24.7	20.7	17.2	6.2	3.9	0.0	0.0
27	30	10	80	14.8	4.3	3.8	3.3	1.3	0.0	0.0	0.0
28	28	11	81	31.6	2.0	1.5	1.0	0.0	0.0	0.0	0.0
29	15	1	84	41.0	4.9	4.4	3.9	1.9	0.0	0.0	0.0
30	14	2	85	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	18	12	85	16.4	2.8	1.4	0.6	0.0	0.0	0.0	0.0
32	2	11	86	39.0	2.9	1.7	1.0	0.0	0.0	0.0	0.0
33	23	2	88	61.5	10.0	7.0	5.0	0.4	0.0	0.0	0.0

^{1/} Data for 1960 and 1983 are missing.

^{2/} Hydrological year.

Table 33. Maximum daily runoff (mm) at Ruhama calculated for 1953-1988^{1/}
for disk tillage, Israel.

					Surface storage (mm)							
Storm date				Daily rain (mm)								
Hy ^{2/}	Day	Month	Year		0	0.5	1	3	5	10	20	
1	20	1	53	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2	5	12	54	30.8	2.5	1.5	0.5	0.0	0.0	0.0	0.0	
3	5	1	56	37.3	5.6	3.6	2.1	0.1	0.0	0.0	0.0	
4	13	3	57	28.3	2.2	1.7	1.2	0.0	0.0	0.0	0.0	
5	20	1	58	15.0	1.7	1.2	0.7	0.0	0.0	0.0	0.0	
6	19	1	59	64.3	6.2	4.6	3.1	0.0	0.0	0.0	0.0	
7	17	11	60	15.4	2.0	1.5	1.0	0.0	0.0	0.0	0.0	
8	14	12	61	29.3	10.0	9.0	8.0	4.0	1.8	0.0	0.0	
9	11	2	63	44.6	13.9	11.9	10.5	6.7	4.7	0.0	0.0	
10	29	2	64	58.4	7.0	5.4	4.4	0.8	0.0	0.0	0.0	
11	22	3	65	37.8	1.4	0.9	0.4	0.0	0.0	0.0	0.0	
12	21	3	66	12.7	4.2	2.7	1.6	0.0	0.0	0.0	0.0	
13	25	3	67	22.6	6.6	5.1	3.9	0.3	0.0	0.0	0.0	
14	20	2	68	13.2	2.7	2.2	1.7	0.0	0.0	0.0	0.0	
15	30	10	68	12.2	1.0	0.5	0.0	0.0	0.0	0.0	0.0	
16	7	11	69	31.1	11.0	10.5	10.0	8.0	6.0	1.0	0.0	
17	7	12	70	14.0	1.7	0.1	0.0	0.0	0.0	0.0	0.0	
18	18	11	71	28.1	2.8	2.3	1.8	0.0	0.0	0.0	0.0	
19	15	1	73	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

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Table 33 cont'd. Maximum daily runoff (mm) at Ruhama calculated for
1953-1988^{1/} for disk tillage, Israel.

				Surface storage (mm)							
Storm date				Daily rain (mm)							
Hy ^{2/}	Day	Month	Year		0	0.5	1	3	5	10	20
20	31	1	74	66.0	6.5	6.0	5.5	3.5	1.5	0.0	0.0
21	22	11	74	33.0	7.8	7.3	6.8	4.8	2.8	0.0	0.0
22	21	12	75	18.7	2.3	1.8	1.3	0.0	0.0	0.0	0.0
23	23	4	77	33.4	0.6	0.1	0.0	0.0	0.0	0.0	0.0
24	3	1	78	39.2	10.2	9.7	9.2	7.2	5.2	0.2	0.0
25	31	10	78	24.6	0.9	0.4	0.0	0.0	0.0	0.0	0.0
26	6	12	79	62.8	24.3	20.5	17.0	6.7	4.7	0.0	0.0
27	30	10	80	14.8	6.5	6.0	5.5	3.5	1.5	0.0	0.0
28	28	11	81	31.6	2.2	1.3	0.8	0.0	0.0	0.0	0.0
29	15	1	84	41.0	3.9	3.4	2.9	0.9	0.0	0.0	0.0
30	14	2	85	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	18	12	85	16.4	3.9	2.4	1.4	0.0	0.0	0.0	0.0
32	2	11	86	39.0	2.9	1.9	0.9	0.0	0.0	0.0	0.0
33	23	2	88	61.5	9.0	6.0	4.0	0.0	0.0	0.0	0.0

^{1/} Data for 1960 and 1983 are missing.

^{2/} Hydrological year.

Table 34. Maximum daily runoff (mm) at Ruhama calculated for 1953-1988^{1/}
for mulch of 700 kg/ha + 1000 kg/ha, Israel.

Hy ^{2/}	Storm date			Daily rain (mm)	Surface storage (mm)						
	Day	Month	Year		0	0.5	1	3	5	10	20
1	20	1	53	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	5	12	54	30.8	1.0	0.5	0.0	0.0	0.0	0.0	0.0
3	5	1	56	37.3	5.2	3.2	1.7	0.0	0.0	0.0	0.0
4	13	3	57	28.3	1.8	1.3	0.8	0.0	0.0	0.0	0.0
5	20	1	58	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	19	1	59	64.3	6.7	4.9	3.4	0.0	0.0	0.0	0.0
7	17	11	60	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	14	12	61	29.3	6.9	5.9	5.1	3.1	1.1	0.0	0.0
9	11	2	63	44.6	12.8	10.6	9.2	6.1	4.1	0.0	0.0
10	29	2	64	58.4	1.9	1.4	0.9	0.0	0.0	0.0	0.0
11	22	3	65	37.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	21	3	66	12.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	25	3	67	22.6	1.1	0.1	0.0	0.0	0.0	0.0	0.0
14	20	2	68	13.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	30	10	68	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	7	11	69	31.1	9.8	9.3	8.8	6.8	4.8	0.0	0.0
17	7	12	70	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	18	11	71	28.1	1.5	1.0	0.5	0.0	0.0	0.0	0.0
19	15	1	73	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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Table 34 cont'd. Maximum daily runoff (mm) at Ruhama calculated for
1953-1988^{1/} for mulch of 700 kg/ha + 1000 kg/ha, Israel.

					Surface storage (mm)							
Storm date				Daily rain (mm)								
Hy ^{2/}	Day	Month	Year		0	0.5	1	3	5	10	20	
20	31	1	74	66.0	1.5	1.0	0.5	0.0	0.0	0.0	0.0	
21	22	11	74	33.0	5.3	4.8	4.3	2.3	0.3	0.0	0.0	
22	21	12	75	18.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23	23	4	77	33.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
24	3	1	78	39.2	10.3	9.8	9.3	7.3	5.3	0.3	0.0	
25	31	10	78	24.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
26	6	12	79	62.8	22.3	18.5	15.1	4.8	2.8	0.0	0.0	
27	30	10	80	14.8	2.2	1.7	1.2	0.0	0.0	0.0	0.0	
28	28	11	81	31.6	1.8	1.3	0.8	0.0	0.0	0.0	0.0	
29	15	1	84	41.0	3.6	3.1	2.6	0.6	0.0	0.0	0.0	
30	14	2	85	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
31	18	12	85	16.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	
32	2	11	86	39.0	1.7	0.9	0.4	0.0	0.0	0.0	0.0	
33	23	2	88	61.5	7.3	4.5	2.6	0.0	0.0	0.0	0.0	

^{1/} Data for 1960 and 1983 are missing.

^{2/} Hydrological year.

Table 35. Annual runoff (mm) at Sde-Yoav calculated for 1959-1988^{1/}, Israel.

Year	Rain (mm)	Surface storage (mm)							
		0	0.5	1	3	5	10	20	40
60	94.3	17.1	11.9	9.8	5.7	3.2	0.0	0.0	0.0
61	259.4	60.4	45.1	37.0	19.6	11.8	3.9	0.0	0.0
62	98.4	7.8	4.5	3.0	0.0	0.0	0.0	0.0	0.0
63	104.7	28.5	23.8	21.1	13.3	7.8	1.0	0.0	0.0
64	382.6	88.6	70.9	61.0	35.3	21.6	7.9	0.0	0.0
65	437.6	110.7	88.0	75.1	45.8	28.6	10.6	0.0	0.0
66	138.8	25.8	20.3	17.3	11.7	7.7	2.5	0.0	12.1
67	501.3	187.2	155.0	138.4	106.5	91.1	60.8	32.2	0.0
68	283.7	86.1	70.0	60.3	40.7	32.5	22.5	6.2	0.0
69	311.1	85.4	71.4	61.8	40.6	27.7	10.7	0.0	0.0
70	134.0	52.3	43.5	37.6	25.1	17.1	9.0	0.0	0.0
71	359.9	94.3	80.2	70.8	50.3	38.9	29.8	19.8	0.0
72	325.4	77.4	62.5	51.1	32.3	20.6	5.1	0.0	0.0
73	314.8	102.0	83.3	70.5	42.8	29.1	11.6	0.0	0.0
74	533.2	150.3	114.9	92.8	49.7	38.9	23.8	8.1	4.9
75	470.4	170.3	147.0	133.3	104.0	86.4	62.0	34.0	0.0
76	137.1	16.1	11.0	8.6	3.2	0.0	0.0	0.0	0.0
77	475.9	146.0	120.3	102.5	68.2	48.3	25.4	1.5	19.8
78	346.0	135.6	117.1	103.7	76.5	66.5	56.0	39.8	0.0

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Table 35 cont'd. Annual runoff (mm) at Sde-Yoav calculated for 1959-1988^{1/},
Israel.

Year	Rain (mm)	Surface storage (mm)							
		0	0.5	1	3	5	10	20	40
79	330.5	114.6	97.8	85.6	59.9	45.1	22.3	6.0	0.0
80	481.9	181.6	157.4	139.7	96.0	78.4	50.2	18.7	0.0
81	289.6	66.0	50.5	41.6	25.6	14.3	1.9	0.0	0.0
82	296.5	67.5	54.6	44.4	23.3	14.5	1.5	0.0	0.0
83	588.8	141.3	103.8	81.6	41.0	26.8	9.5	0.0	0.0
84	189.4	65.6	56.8	50.1	31.0	18.6	4.5	0.0	0.0
85	301.0	85.4	74.1	67.1	52.0	45.4	30.4	6.8	0.0
86	285.6	78.7	64.5	54.0	35.5	27.5	16.2	6.2	0.0
88	534.1	208.2	181.3	164.4	129.3	106.1	73.5	47.9	8.2

^{1/} Data for 1960 and 1983 are missing.

Table 36. Maximum daily runoff (mm) at Sde-Yoav calculated for 1959-1988^{1/},
Israel.

				Surface storage (mm)								
Storm date				Daily rain (mm)								
Hy ^{2/}	Day	Month	Year		0	0.5	1	3	5	10	20	40
1	23	3	60	24.5	13.9	11.3	9.8	5.7	3.2	0.0	0.0	0.0
2	14	2	61	47.2	20.1	17.3	15.3	10.9	8.9	3.9	0.0	0.0
3	19	2	62	28.0	4.8	3.0	2.0	0.0	0.0	0.0	0.0	0.0
4	12	2	63	30.5	16.4	13.3	11.1	5.3	1.8	0.0	0.0	0.0
5	9	12	63	40.5	24.5	21.0	19.3	15.2	11.2	4.5	0.0	0.0
6	10	1	65	51.3	22.5	21.2	20.2	16.2	12.8	7.8	0.0	0.0
7	3	2	66	23.7	14.7	12.7	11.6	9.5	7.5	2.5	0.0	0.0
8	19	12	66	81.0	57.1	53.5	51.7	49.1	47.1	42.1	32.1	12.1
9	23	11	67	62.5	28.3	26.6	25.6	23.2	21.2	16.2	6.2	0.0
10	19	3	69	44.0	19.4	18.3	17.8	15.8	13.8	8.8	0.0	0.0
11	21	1	70	55.8	21.7	20.3	19.3	16.0	14.0	9.0	0.0	0.0
12	12	4	71	81.1	49.6	46.9	44.9	38.7	34.8	29.8	19.8	0.0
13	28	12	71	36.0	17.0	15.2	13.8	11.5	9.5	4.5	0.0	0.0
14	16	1	73	45.0	29.6	27.2	25.2	18.4	14.6	9.6	0.0	0.0
15	16	1	74	66.0	37.8	33.9	31.3	25.7	23.1	18.1	8.1	0.0
16	5	12	74	90.5	61.3	56.8	54.6	47.1	42.0	34.9	24.9	4.9
17	24	2	76	27.5	11.9	9.7	8.2	3.2	0.0	0.0	0.0	0.0
18	29	12	76	59.6	30.9	26.4	23.9	18.5	16.5	11.5	1.5	0.0
19	15	12	77	105.0	77.2	70.0	65.4	57.5	54.8	49.8	39.8	19.8

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Table 36 cont'd. Maximum daily runoff (mm) at Sde-Yoav calculated for 1959-1988^{1/},
Israel.

Hy ^{2/}	<u>Storm date</u>			Daily rain (mm)	<u>Surface storage (mm)</u>							
	Day	Month	Year		0	0.5	1	3	5	10	20	40
20	12	12	78	49.5	29.2	26.8	25.5	23.0	21.0	16.0	6.0	0.0
21	1	3	80	78.9	41.3	37.2	35.0	30.0	28.0	23.0	13.0	0.0
22	26	3	81	25.0	13.2	11.7	10.9	8.9	6.9	1.9	0.0	0.0
23	14	2	82	46.2	24.3	19.6	15.9	8.9	6.5	1.5	0.0	0.0
24	27	2	83	31.0	17.7	16.9	16.4	14.4	12.4	7.4	0.0	0.0
25	12	11	83	45.0	21.8	19.0	16.5	10.8	8.4	3.4	0.0	0.0
26	16	10	84	44.9	27.7	26.7	25.8	23.8	21.8	16.8	6.8	0.0
27	9	2	86	41.0	29.5	27.9	26.4	23.2	21.2	16.2	6.2	0.0
28	17	2	88	86.0	58.7	54.3	51.4	46.0	43.2	38.2	28.2	8.2

^{1/} Data for 1960 and 1983 are missing.

^{2/} Hydrological year.

Fig. 9. Annual calculated runoff from actual storms above 10 mm under different tillage methods, Ruhama location, Israel. (The values for treatments are surface storage in mm.)

Fig. 10. Daily calculated runoff from actual maximum daily rainfall for different tillage methods, Ruhama location, Israel. (The values for treatments are surface storage in mm.)

Fig. 11. Annual calculated runoff from actual storms above 10 mm under different conditions for Sde-Yoav location, Israel. (The values for different conditions are surface storage in mm.)

Stubble mulch also reduces runoff (by increasing the infiltration characteristics) but use of stubble mulch in Israel is limited because of weeds and plant diseases. This analysis is a tool for evaluation of the surface storage volume needed and, hence, a valuable tool for selecting appropriate tillage methods for conserving water and improving crop yields.

GENERAL DISCUSSION

Measurements made with a rainfall simulator under field conditions in Israel and at Bushland, Texas, revealed that the type of tillage performed influences water infiltration and runoff, and, consequently, soil erosion. Other determinations made on the same soils in conjunction with the infiltration measurements indicated that different tillage methods resulted in soil surface conditions that differed with respect to aggregate stability, aggregate size distribution, organic matter concentration, residues on the surface, and surface roughness, all of which appeared related to water infiltration. Although aggregate stability was involved, results for a given soil were variable and there was no conclusive evidence that it was the dominant factor affecting infiltration. However, that aggregate stability was involved was indicated by the γ values which were lower for studies at Bushland, Texas (Table 1), than for the study in Israel at Ruhama (Table 15). Low γ values indicate greater aggregate stability and higher surface water storage capacity than high values. Other measurements (Israel--Study 1) showed that the Pullman soil from Bushland (Fig. 6) was more stable than the soil from Israel (Fig. 4).

Separation of Loess and Gromosol soils into different sizes of aggregates showed that the Loess soil had a higher percentage of fine aggregates than the Gromosol soil. For the Loess soil, the effect of tillage (traditional or minimum) was slight. Stability determinations on single-size aggregates spread in one layer under a laboratory rainfall simulator showed that stability increased with increasing aggregate size. The 1- to 2- and 4- to 6.5-mm aggregates were more stable for the Loess soil, while the 9.5- to 12-mm aggregates appeared most stable for the Gromosol. For a given size range, aggregates were more stable for the Loess soil. However, because the

Loess soil had more fine aggregates than the Gromosol, a mixture of all aggregates was more stable for the Gromosol than for the Loess soil.

A factor that apparently had a major influence on aggregate stability of different soils was organic matter concentration. The concentrations ranged from 18.9 to 34.2 g/kg for Area 1 and from 13.5 to 14.9 g/kg for Area 2 for the Pullman soil for different tillage treatments, but was only 2.0 g/kg for the Loess and 7.0 g/kg for the Gromosol soil. The relatively high organic matter concentration of Pullman soil contributed to the higher stability (higher mean weight diameter--MWD) for most tillage treatments after the simulated rainfall than before the rainfall, especially on Area 1 (Table 2). On Area 2, the MWD increased in most cases for dry aggregates, but was variable for water stable aggregates (Table 3).

Surface residues are recognized for their value in protecting the soil surface against the impact of falling raindrops, and, hence, for minimizing aggregate dispersion and surface sealing, which can result in reduced infiltration. In Israel, increasing amounts of surface residues increased I_f for all rains (initial and after 1 or 7 d of drying--Table 5). However, on the Pullman soil at Bushland, Texas, there was no close relationship between I_f and surface cover provided by crop residues. At Bushland, the measurements were made on dryland (non-irrigated) field areas with naturally-occurring residues from grain sorghum (Area 1) and winter wheat (Area 2) crops. On Area 1, surface cover ranged from only 1.6 to 9.6% (Table 2), and a response to cover was unlikely. Cover ranged from 9.9 to 68.4% (Table 3) on Area 2, and an infiltration response to surface cover seemed possible. The I_f rate was higher for the NT+Res treatment (68.4% cover) than for the NT-Res treatment (15.6% cover). However, the ST-Res treatment with 11.5% cover had a higher I_f rate than the ST+Res treatment with 63.1%

cover. The reason for these unexpected results is not obvious. On the Pullman soil, especially where residues amounts are low, as after dryland grain sorghum, soil loosening by sweep tillage (ST+Res or ST-Res treatments, Area 1--Table 1) was effective for increasing water infiltration. These results are in agreement with runoff results obtained from field-size watersheds on Pullman soil at Bushland, Texas. Greater infiltration (less runoff) with sweep tillage where residue amounts are low is attributed to disruption of the surface crust, roughening of the soil surface, and formation of depressions to temporarily store water on the surface, thus providing more time for infiltration.

Where surface residues are limited and the soil aggregates are highly unstable, as for the Loess soil in Israel, soil pitting was found effective for reducing runoff and increasing soil water contents. Maximum water storage volume throughout the growing season resulted from using a pitting machine having five pit-forming wings per 1 m of width and operating the machine at a fast forward speed (12 to 15 km/h). Wheat yields increased with increasing amounts of stored water (Table 23).

A computer model was used to analyze rainfall records from 1953 to 1988 to determine the amount of surface storage that is needed to minimize runoff. Such an analysis is effective for evaluating surface storage requirements and, hence, a valuable tool for selecting appropriate tillage methods for conserving water and improving crop yields. Once selected, use of a rainfall simulator is an efficient technique for determining whether a selected tillage method performs satisfactorily under field conditions.

CONCLUSIONS

Studies conducted at Bushland, Texas, and in Israel led to the following conclusions:

1. Use of different tillage methods leads to different surface conditions that affect water infiltration as determined through use of a rainfall simulator.
2. Soil aggregate size distribution and stability affect water infiltration, but were not the dominant factors for the soils evaluated.
3. Besides aggregate size distribution and stability, other factors affecting infiltration included organic matter concentration, crop residues on the surface, and surface roughness.
4. Aggregate stability increases with aggregate size for Loess and Gromosol soils in Israel.
5. For a given size range of aggregates, those for the Loess soil are more stable than those for the Gromosol soil.
6. The Loess soil has more fine aggregates than the Gromosol soil. Consequently, a mixture of all aggregate sizes is less stable for the Loess than for the Gromosol soil.
7. The Pullman soil at Bushland, Texas, is more stable than either the Loess or the Gromosol soil in Israel.
8. Infiltration increases with increasing amounts of surface residues for the Loess soil in Israel, but no definite trends in infiltration as related to surface residues were apparent for the Pullman soil at Bushland, Texas.
9. Where residues are limited, as after dryland grain sorghum at Bushland, Texas, loosening of the soil by sweep tillage increases water infiltration.

10. Where residues are limited and the soil is highly unstable, as for the Loess soil in Israel, pitting the soil to create depressions for temporary water storage on the surface increases water infiltration, water storage in the soil, and crop yields.
11. An analysis of rainfall data related to the amount of surface storage capacity that is needed to minimize runoff provides an effective method of selecting tillage methods appropriate for conserving water and, hence, increasing crop yields.

REFERENCES

- Agassi, M., I. Shainberg, and J. Morin. 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. Soil Sci. Soc. Am. J. 45:848-851.
- Allmaras, R. R., R. E. Burwell, and R. F. Holt. 1967. Plow-layer porosity and surface roughness from tillage as affected by initial porosity and soil moisture at tillage time. Soil Sci. Soc. Am. Proc. 31:550-556.
- Allmaras, R. R., R. E. Burwell, W. E. Larson, and R. F. Holt. 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. U.S. Dept. Agric. Conserv. Res. Rep. No. 7. U.S. Gov't. Print. Office, Washington, DC.
- Armbrust, D. V., J. D. Dickerson, E. L. Skidmore, and O. G. Russ. 1982. Dry soil aggregation as influenced by crop and tillage. Soil Sci. Soc. Am. J. 46:390-393.
- Benyamini, Y. 1981. The behavior of bare soils under rainfall application. Ph.D. Thesis, The Hebrew University, Rehovot, Israel. (Hebrew)
- Burwell, R. E. and W. E. Larson. 1969. Infiltration as influenced by tillage-induced random roughness and pore space. Soil Sci. Soc. Am. Proc. 33:449-452.
- Chepil, W. S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Sci. Soc. Am. Proc. 26:4-6.
- Cogo, N. P., W. C. Moldenhauer, and G. R. Foster. 1983. Effect of crop residue, tillage-induced roughness, and runoff velocity on size distribution of eroded soil aggregates. Soil Sci. Soc. Am. J. 47:1005-1008.

- Day, Paul R. 1965. Particle fractionation and particle-size analysis.
In C. A. Black (ed-in-chief) Methods of Soil Analysis, Part I.
Agronomy 9:545-567.
- DeBoodt, M. L., L. De Leenheer, and D. Kirkham. 1961. Soil aggregate
stability indexes and crop yields. Soil Sci. 91:138-146.
- Dexter, A. R., J. K. Radke, and J. S. Hewitt. 1983. Structure of a tilled
soil as influenced by tillage, wheat cropping, and rainfall. Soil Sci.
Soc. Am. J. 47:570-575.
- Eigel, J. D. and I. D. Moore. 1983. Effect of rainfall energy on
infiltration into a bare soil. Proc. National Conf. on Advances in
Infiltration. Dec. 1983, Chicago, IL. pp. 188-200.
- Epema, G. F., and H. Th. Riezebas. 1983. Fall velocities of water drops at
different heights as a factor influencing erosivity of simulated rain.
Catena Supplement 4:1-17.
- Falayi, O. and J. Bouma. 1975. Relationships between the hydraulic
conductance of surface crusts and soil management in a Typic Hapludalf.
Soil Sci. Soc. Am. Proc. 39:957-963.
- Gumbs, F. A., and B. P. Warkentin. 1976. Bulk density, saturation water
content and rate of wetting of soil aggregates. Soil Sci. Soc. Am. J.
40:28-33.
- Hadas, A., D. Wolf, and I. Meirson. 1978. Tillage implements-soil
structure relationships and their effect on crop stands. Soil Sci.
Soc. Am. J. 42:632-637.
- Hillel, D. 1960. Crust formation in loessial soil. Trans. VIIth Int.
Soil Sci. Congr., Madison, WI. pp. 330-337.
- Jones, O. R., and V. L. Hauser. 1975. Runoff utilization for grain
production. pp. 277-283. In Proc. Water Harvesting Symp., Phoenix,
Arizona, March 1974. U.S. Dept. Agric. ARS W-22.

- Kemper, W. D., and W. S. Chepil. 1965. Size distribution of aggregates. In C. A. Black (ed-in-chief) Methods of Soil Analysis, Part I. Agronomy 9:499-510.
- Kemper, W. D., and E. J. Koch. 1966. Aggregate stability of soils from the western United States and Canada--measurement procedure, correlations with soil constituents. U.S. Dept. Agric. Tech. Bull. 1355. U.S. Gov't. Print. Office, Washington, DC.
- Lindstrom, M. J., and C. A. Onstad. 1984. Influence of tillage system on soil physical parameters and infiltration after planting. J. Soil Water Conserv. 39:149-152.
- Lindstrom, M. J., W. B. Voorhees, and C. A. Onstad. 1984. Tillage system and residue cover effects on infiltration in northwestern Corn Belt soils. J. Soil Water Conserv. 39:64-68.
- McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 58:185-189.
- Moore, I. D. 1981. Effect of surface sealing on infiltration. Trans. ASAE 24:1546-1561.
- Morin, J., and Y. Benyamini. 1977. Rainfall infiltration into bare soils. Water Resour. Res. 13:813-817.
- Morin, J., and Y. Benyamini. 1988. Tillage method selection based on runoff modeling. p. 251-254. In P. W. Unger, W. R. Jordan, T. V. Sneed, and R. W. Jensen (eds.) Challenges in dryland agriculture--A global perspective, Proc. Int. Conf. on Dryland Farming, August 1988, Amarillo/Bushland, Texas.
- Morin, J., Y. Benyamini, and A. Michaeli. 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. J. Hydrology 52:321-335.

- Morin, J., and C. B. Cluff. 1980. Runoff calculation on semiarid watersheds using Rotadisk Rainulator. *Water Resour. Res.* 16:1085-1903.
- Morin, J., S. Goldberg, and I. Seginer. 1967. A rainfall simulator with a rotating disk. *Trans. ASAE* 10:74-79.
- Morin, J., and H. S. Jarosch. 1977. Runoff rainfall analysis for bare soils. Pamphlet 164, 21 pp. The Volcani Center Scientific Publications, Bet-Dagan, Israel.
- Morin, J., E. Rawitz, W. B. Hoogmoed, and Y. Benyamini. 1984. Tillage practices for soil and water conservation in the semiarid zone. III. Runoff and modeling as a tool for conservation tillage design. *Soil Tillage Res.* 4:155-164.
- Parker, J. J., and H. M. Taylor. 1965. Soil strength and seedling emergence relations. I. Soil type, moisture tension, temperature, and planting depth effects. *Agron. J.* 57:289-291.
- Rawitz, E., and A. Hazan. 1978. The effect of stabilized hydrophobic aggregate layer properties on soil water regime and seedling emergence. *Soil Sci. Soc. Am. J.* 42:787-793.
- Rawitz, E., J. Morin, W. B. Hoogmoed, M. Margolin, and H. Etkin. 1983. Tillage practices for soil and water conservation in the semiarid zone. I. Management of fallow during the rainy season preceding cotton. *Soil Tillage Res.* 3:211-231.
- Richards, L. A. (ed-in-chief). 1954. Diagnosis and improvement of saline and alkali soils. U.S. Dept. Agric., Agric. Handbook No. 60. U.S. Gov't. Print. Office, Washington, DC.
- Sloneker, L. L., and W. C. Moldenhauer. 1977. Measuring the amounts of crop residue remaining after tillage. *J. Soil Water Conserv.* 32:231-236.

- Taylor, H. M. 1962. Seedling emergence of wheat, grain sorghum, and guar as affected by rigidity and thickness of surface crusts. Soil Sci. Soc. Am. Proc. 26:431-433.
- Unger, P. W. 1984. Tillage effect on surface soil physical conditions and sorghum emergence. Soil Sci. Soc. Am. J. 48:1423-1432.
- Unger, P. W., and L. J. Fulton. 1988. Tillage effects on soil conditions of the upper root zone. p. 171-176. In Proc. Int. Soil Tillage Res. Org., 11th Int. Conf., Edinburgh, Scotland, July 1988.
- Unger, P. W. 1989. Organic matter, pH, and nutrient distribution in no- and conventional-tillage soil. p. 296. Agronomy Abstr., Am. Soc. Agron., Madison, WI.
- Wustamidin, and L. A. Douglas. 1985. Aggregate breakdown in relation to raindrop energy. Soil Sci. 139:239-242.

F. Description of cooperation

Prior to initiation of the research covered by this report, Dr. Yoram Benyamini had spent about 16 months at the USDA Research Laboratory at Bushland, Texas. During this time, he constructed a rotating disk rainfall simulator similar to one that was already in use in Israel. By using similar equipment, it was possible to directly compare results obtained on the different soils for the studies covered by this report.

Where a particular type of equipment was available only in one country, as the low energy rainfall simulator built in Israel, cooperation among the scientists led to Pullman soil from Bushland being shipped to Israel for analysis. This work showed the relative stabilities of aggregates of the different soils, which helped interpretation of the infiltration data.

Exchange of visits by scientists from the two countries was a major form of cooperation. By observing firsthand the soil conditions, equipment and facilities used, etc. in each others countries, a better understanding of the overall project was possible, which led to more meaningful discussions of the results obtained and, consequently, in the preparation of the final report.

G. Main achievements of the research

Main achievements of the research covered by this report were the findings that:

1. Different tillage methods result in different distributions in sizes and stabilities of the resultant soil aggregates, which subsequently affects water infiltration and storage of the water for subsequent use by crops. However, aggregate size distribution and stability do not fully account for differences in infiltration. Other factors affecting water infiltration include soil organic matter concentration, crop residues on the soil surface, and surface roughness (or depressions for temporary storage of water on the surface).
2. Aggregates of different sizes differ in stability, with stability generally increasing with increases in aggregate size. There are also differences in stabilities of aggregates from different soils, but of the same size. For example, for the same size range, aggregates of the Loess soil were more stable than those of the Gromosol soil, both from Israel. For a mixture of all aggregates, the Loess soil is less stable than the Gromosol soil because the Loess soil has a higher percentage of small aggregates. Consequently, tillage that results in fine aggregates should be avoided when possible. However, other factors are also involved, and infiltration generally was higher with tillage that retained some residues on the surface than with moldboard tillage that resulted in more large aggregates, but incorporated most residues with the soil.

3. When residues are limited, as after a dryland grain sorghum crop, infiltration is enhanced by tillage that disrupts the surface crust, roughens the soil surface, or provides for temporary storage of water on the surface. Loosening of the soil by sweep tillage was effective for the Pullman soil at Bushland, Texas. For the Loess soil in Israel, which is highly unstable, surface pitting was effective for increasing infiltration, soil water storage, and crop yields.
4. Analyses of long-term rainfall records with computer models revealed the amount of surface storage capacity that is needed to minimize runoff. By knowing the capacity needed, tillage methods can be selected that eliminate runoff from most storms. Use of the rainfall simulator is an efficient method of assessing the suitability of different tillage methods for minimizing runoff and, hence, their effectiveness for increasing soil water storage and crop yields.

H. Publications

Unger, P. W., Y. Benyamini, O. R. Jones, and J. Morin. 1988. Tillage and crop residue effects on water infiltration. p. 520-522. In P. W.

Unger, W. R. Jordan, T. V. Sneed, and R. W. Jensen (eds.) Challenges in dryland agriculture--A global perspective. Proc. Int. Conf. in Dryland Farming, August 1988, Amarillo/Bushland, Texas.