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A Semi-Annual Progress Report (Jan-June, 1989)

Title: Improving Rain Penetration and Reducing Soil Erosion in Dryland Farming

Project Identification Number: C7-036

by

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ISRAEL

During 1989 the following objectives were accomplished and manuscripts were written (see Appendix).

1) Slope and Phosphogypsum Effects on Runoff and Erosion*

ABSTRACT

The effect of slope on runoff and erosion has been studied mainly in stable soils. Loamy soils from semiarid regions have unstable structures and tend to seal during a rainstorm. The permeability of the seal is sensitive to water quality. The effect of slope angle (5 - 30%) and addition of phosphogypsum (PG), which changes the water quality, on the infiltration rate (IR), runoff and erosion from an unstable sandy loam soil material (Typic Rhodoxeralf) was studied using a rain simulator. Increasing the slope slightly reduced the amount of runoff and increased the final infiltration rate. The increase in final IR was due to seal erosion. The PG application increased the permeability of the seal, tripled the final IR of the soil sample and decreased the volume of runoff by 50%. Phosphogypsum application also reduced erosion by 60% at the gentlest slope angle. Change in slope angle from 5 to 25% doubled soil loss in the PG-treated soil samples but increased by seven-fold soil loss from the untreated soil samplers. Gypsum treatment releases electrolytes into the percolating and runoff water. Its effect on soil erosion is due to decreasing the fraction of runoff water, stabilizing the soil structure at the soil surfce, and increasing the rate of sediment deposition. The dramatic effect of PG in reducing erosion from steep slopes may be used in stabilizing soil structures on steep slopes.

* The manuscript will be published in Soil Sci. Soc. Am. J. (1989) Vol. 53 July-August issue (see Appendix A).

## 2) Slope, Aspect and Phosphogypsum Effects on Runoff and Erosion*

ABSTRACT

The effect of slope, aspect (windward and leeward sides), and phosphogypsum (PG) application on rain amount, runoff, and erosion from a grumusol soil (Typic Chromoxererts) was measured in small field plots (1 x 1.5 m) exposed to natural rainstorms. The amount of effective rain on the slopes, as measured with small raingauges with orifices in a plane parallel to the slope, increased slightly on the western (windward) aspect as slope increased to approx. 58% and decreased thereafter. On the leeward aspect the amount of effective rain dropped steadily to half of the meteorological rain at a slope of 100%. The amount of runoff was not affected by the slope on the western aspect and decreased sharply on the eastern aspect. PG application reduced runoff to about 25% of that in the control and soil losses to 1-3% of that in the control. The dramatic effect of PG on erosion increased with slope steepness.

PG releases electrolytes into the percolating and runoff water. It prevents dispersion of the particles at the surface, stabilizes the soil structure and reduces soil erosion.

* The manuscript was accepted for publication in Soil Sci. Soc. Am. J. (see Appendix B)

## 3) Water Infiltration as Affected by Soil Crust and Moisture Profile*

ABSTRACT

The effect of wetting front depth on the infiltration rate (IR) of the Calcic Haploxeralf and the Typic Chromoxerert soils was studied under field conditions using a rainfall simulator. In both soils the IR decreased more sharply when the wetting front was deeper but this difference becomes smaller as the rainstorm continued. The infiltration rate of the soils at the end of the rainstorm ($8x10^{-2}$ m) was $8.5x10^{-3}$, $6.3x10^{-3}$, and $5.0x10^{-3}$ m $h^{-1}$ for the Calcic Haploxeralf soil prewetted with water at amount equivalent to 0, $3x10^{-2}$, and $2x10^{-1}$ m, respectively, and $1.5x10^{-3}$, and $1.0x10^{-3}$ m $h^{-1}$ for the Typic Chromoxerert soil prewetted with water at amount equivalent to 0, and $2x10^{-1}$ m, respectively. When the dry soil surface was covered with mulch, however, the steady state value of the IR was $3.5x10^{-2}$ m $h^{-1}$ for both soils. The high permeability of the soils during the rainstorm in the presence of mulch, and the similar low steady state IR values for the various prewetting treatments suggest that the moisture regime in the profile had a negligible effect on the IR in the presence of soil crust.

* The manuscript was accepted for publication in Soil Science (see Appendix C)

## 4) Effect of PAM and Gypsum Application on Rain Infiltration and Runoff

ABSTRACT

Seals, formed at the soil surface during rainstorms, reduce rain penetration resulting in runoff and erosion. The effect of surface application of anionic polyacrylamide (PAM) at rates of 10, 20 and 40 $kg.ha^{-1}$ on the infiltration rate (IR) of two soils, a loess (Calcic Haploxeralf) and a grumusol (Typic Chromoxerert), during simulated rainstorms, was studied. The interaction between PAM and electrolyte concentration at the soil surface was determined under a simulated rainfall of distilled water or tap water, and by spreading gypsum. Electrolytes in the soil solutions, which flocculate the soil clay prior to cementation by the polymer, enhanced aggregate stability and greatly reduced water losses. Complete drying of the polymer-soil surfaces improved the binding action of the polymer.

Treatments with PAM under the optimal conditions increased the final IR of the loess form 2.0 to 23.3 $mm.h^{-1}$ and increased rain intake of an 80 mm rainstorm from 12.3 to 65.0 mm. PAM treatment of the grumusol increased the final IR from 3.0 in the control to 29.1 $mm.h^{-1}$ and the rain intake from 22.8 to 60.8 mm. As soils from semi-arid regions are unstable, form crusts and produce much runoff (50%) during rainstorms, the use of PAM to reduce runoff should be considered.

* The manuscript was sent for publication in J. of Soil Science (Appendix D).

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Appendix 1

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D. Warrington and I. Shainberg, Inst. of Soils and Water, ARO, The Volcani Center, POB 6, Bet Dagan, Israel; M. Agassi and J. Morin, Soil Erosion Research Stn., Emek Hefer, Israel. Contribution no. 2240-E, 1987 series, from the ARO, The Volcani Center, Bet Dagan, Israel. Received 4 Mar. 1988. *Corresponding author.

Published in Soil Sci. Soc. Am. J. 53:000–000 (1989).

# Effect of Slope and Phosphogypsum on Runoff and Erosion

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D. Warrington, I. Shainberg,* M. Agassi and J. Morin

## ABSTRACT

The effect of slope on runoff and erosion has been studied mainly in stable soils. Loamy soils from semiarid regions have unstable structures and tend to seal during a rainstorm. The permeability of the seal is sensitive to water quality. The effect of slope angle (5–30%) and addition of phosphogypsum (PG), which changes the water quality, on the infiltration rate (IR), runoff and erosion from an unstable sandy loam soil material (Typic Rhodoxeralf) was studied using a rain simulator. Increasing the slope slightly reduced the amount of runoff and decreased the final infiltration rate. The increase in final IR was due to seal erosion. The PG application increased the permeability of the seal, tripled the final IR of the soil sample and decreased the volume of runoff by 50%. Phosphogypsum application also reduced erosion by 60% at the gentlest slope angle. Change in slope angle from 5 to 25% doubled soil loss in the PG-treated soil samples but increased by seven-fold soil loss from the untreated soil samples. Gypsum treatment releases electrolytes into the percolating and runoff water. Its effect on soil erosion is due to decreasing the fraction of runoff water, stabilizing the soil structure at the soil surface, and increasing the rate of sediment deposition. The dramatic effect of PG in reducing erosion from steep slopes may be used in stabilizing soil structures on steep slopes.

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The rapid drop in the IR of soils during rainstorms is mainly due to seal formation on the soil surface. Breakdown of the soil structure and formation of a seal are enhanced by the impact energy of the raindrops and the low concentrations of electrolytes in rainwater (Agassi et al., 1981, 1985a). Agassi et al. (1981) proposed that seal formation was due to two complementary mechanisms: (i) physical disintegration of soil aggregates caused by the impact of water drops; and (ii) chemical dispersion which depends on the soil exchangeable sodium percentage (ESP) and on the electrolyte concentration of the applied water. When water of high salinity was used, chemical dispersion was largely prevented and a seal with high permeability was formed mainly by the physical mechanism.

The water erosion process requires a slope. Level land is eroded slowly because the runoff velocity is slow. As the slope increases, runoff velocity and erosion also increase. The effect of slope on the IR and runoff is complicated when considering unstable soils which tend to seal (Poesen, 1986). Since the seal may be eroded, it is possible that, with an increase in slope and seal erosion, the soil IR may increase and runoff decrease. Poesen (1986) found that increasing the slope resulted in greater IRs and lower runoff, and that shear strength of the seal decreased with an increase in slope. He concluded that the decrease in runoff with increase in slope was mainly due to increased splash and sheet erosion which removed the seal. Other processes which may reduce runoff with an increase in slope are: (i) a decrease in the number of raindrop impacts per unit surface area; (ii) a decrease in the normal component of drop impact force; and (iii) the occurrence of a thin film of water—through which the compactive force of the raindrops can be increased—being reduced (Poesen, 1986).

The objectives of this work were to study the effect of slope and PG application on the IR of rain water, runoff, and erosion from a sandy loam soil which has an unstable structure and tends to seal. The effect of changing the water quality was also investigated. Phosphogypsum spread over the soil surface increases the electrolyte concentration in the rainwater, prevents soil dispersion and crust formation, increases rain penetration, and maintains larger aggregates at the soil surface (Kazman et al., 1983). The reduced amount of runoff and the larger particles at the soil surface should reduce erosion. The beneficial effects of PG in reducing erosion from slopes of various steepness were assessed in this study.

## MATERIALS AND METHODS

A sandy loam soil material from the coastal plain of Israel was used in this study. The clay, silt, and sand components of the soil material were 18, 7, and 75%, respectively, of the whole. The CEC was 11.7 cmol, kg$^{-1}$, the ESP was 2.2, and the organic matter content was 0.5%. The saturated hydraulic conductivity and the initial IR of the saturated soil material, as measured with a mist with intensity of 150 mm h$^{-1}$, were approximately 100 mm h$^{-1}$.

Disturbed samples were collected, air dried, crushed to pass a 4-mm sieve, and thoroughly mixed. Layers of the soil material, 2 cm deep, were packed into perforated metal boxes, 30 by 30 cm, over an 8-cm layer of coarse sand. The sand allowed free drainage of water to an outlet pipe set in the base of the box. The boxes were placed in a rainfall simulator (Morin et al., 1967) on a supporting framework which could be inclined at slope angles to the horizontal in the range 0 to 30%.

Seven slope angles were examined (5, 7.5, 10, 15, 20, 25, and 30%) for both untreated soil samples and for soil samples treated with PG ground to <1 mm and spread over the soil surface at a rate equivalent to 5 ton ha$^{-1}$. The PG, a by-product of the phosphate fertilizer industry, has a dry composition of: $CaSO_4$, 97%; $MgSO_4$, 1%; $P_2O_5$, 0.6%; fluorapatite and $SiO_2$, 1.4%.

The samples were first saturated with tap water from the base, after which PG was applied to the treated trays. The samples were then subjected to simulated rainfall with an intensity of 40 mm h$^{-1}$ for 90 min. Distilled water was used to simulate rainwater. Typical mechanical parameters of the applied rain were: median raindrop diameter, 1.9 mm; median drop velocity, 6.02 m s$^{-1}$; and total kinetic energy, 470 J h$^{-1}$ m$^{-2}$. As soon as runoff was observed to commence, samples were collected at regular intervals. The volume of runoff and the mass of the soil it carried were measured. The volume of the effluent was measured at 2-min intervals and the IR was calculated.

Curves were fitted to the infiltration data using the NLIN procedure of SAS (SAS Institute, 1982, p. 15–37) for the Hortonian type equation:

$$I_t = I_f + (I_i - I_f)\exp(-p\,g\,t) \qquad [1]$$

where $I_t$ = the infiltration rate at time $t$
$I_i$ = initial infiltration rate
$I_f$ = the final infiltration rate
$p$ = rainfall intensity
$g$ = a constant

## RESULTS AND DISCUSSION

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### Effects of slope angle and PG on infiltration and runoff.

The effects of slope angle (5 and 25%) and the PG treatment on the IR and soil loss are illustrated in Fig. 1. It is evident from the rapid drop in the IR of the untreated soil (Fig. 1a), that the Typic Rhodoxeralf is very susceptible to surface sealing. A similar observation was made by Ben Hur et al. (1985), who found that soils with moderate (15–20%) clay percentage and low content of organic matter are most susceptible to crusting. The impact of the raindrops, combined with a low concentration of electrolytes in the water, caused the IR of the soil to fall from the initial rate of approximately 100 mm h$^{-1}$ to a final IR of 2.9 mm h$^{-1}$ and 4.5 mm h$^{-1}$ for the 5 and 25% slopes, respectively, following 25 to 30 mm of rainfall. The infiltration curves for the other slopes ranged between those of the 5 and 25% slopes. The final IR and runoff percentages for the seven slopes are presented in Fig. 2. Differences between slopes ≤15% are insignificant. As slope angle increased to 20% and over, there was a significant increase in the final IR. The increase in final IR is associated with increase in soil erosion (Fig. 1 and 3). A sharp increase in soil loss occurred only at slopes ≥15% (Fig. 3). Our results are in agreement with those of Poesen (1986), except that he used artificial mixtures of sand and silt to prepare crust-prone sediments, and those mixtures were more susceptible

to sealing than our soil samples.

The IRs of soil samples treated with PG dropped much less rapidly than those of the untreated soil samples. The drop began after a greater cumulative rainfall, and the final IR were higher (Fig. 1). Also, in the case of the untreated soil samples, the final IR was established after 25 to 30 mm of rain had fallen, compared with 60 mm of rain for the PG-treated soil samples. It has been shown (Gal et al., 1984) that PG reduces surface sealing by raising the electrolyte concentration in the solution at the soil surface, thus reducing the dispersion of the soil aggregates and the soil clays and preventing the formation of the "washed-in" layer. Thus, the crust forms more slowly on the surface of soil treated with PG, and is more permeable than the crust of untreated soil, reducing the rate of runoff.

As slope angle increased, the final IR of the PG-treated soil samples also increased (Fig. 2). The effect of slope angle on the properties of the seal, as determined by the final IR, was similar in both treated and untreated soil samples, in spite of the fact that PG-treated soils are less susceptible to sealing and are less erodible than untreated soil. A possible explanation is that mechanical disintegration of soil aggregates caused by the impact of raindrops, which is the main mechanism that operates in PG-treated soils, is quite sensitive to the slope angle.

There was no obvious relationship between slope angle and either the total amount of water infiltrating into the untreated soil sample or runoff percentage during the storm (Fig. 2). Cumulative infiltration and, hence, the amount of runoff are affected by the rate of seal formation, time to ponding, and changes in the FIR. The interaction of these relationships does not produce a simple trend in cumulative infiltration and the resulting changes in the amount of runoff as a function of slope are small. In the case when PG is added to the surface, a definite relationship (linear correlation coefficient of $r = 0.73$) between slope angle and cumulative infiltration exists with a decrease in runoff as the slope angle increases.

It is evident from Fig. 2 that PG is very effective in increasing the final IR of the soil and decreasing the total runoff. PG treatments increased the final IR by a factor of 2.7 and decreased the amount of runoff from 66% in the control to 29% in the treated soil sample (average of the seven slopes). The effect on crop production of doubling the fraction of rain that penetrates into the soil by PG treatment in semiarid areas has been evaluated in other studies (e.g., Agassi et al. 1985b). The effect of PG treatments on soil loss is discussed in the following section.

## Effect of slope angle and PG on soil loss

Soil loss as a function of rain depth is presented in Fig. 1b. Both the effect of slope and the effect of the PG treatment are very pronounced. Increase in slope angle from 5 to 25% resulted in soil losses increasing by 700% for the untreated soil samples and 200% for the PG-treated soil samples. The relationship between the total amount of soil loss during the storm and slope angle is shown in Fig. 3. The following observations should be noted: (i) The rapid increase in soil erosion of untreated soil samples does not occur until the slope increases above 10%. At slopes > 10%, rapid increases in soil erosion take place. (ii) Only a small increase in soil loss occurred between the 25 and 30% slopes.

Soil losses were not greatly affected by slope angle at the gentle slope range. At low slopes, and therefore low overland flow velocities, detachment of sediment from the soil surface is due to rainfall detachment alone. As rainfall detachment is relatively insensitive to slope (Rose, 1985; Walker et al., 1977), there is only a slight increase in erosion with increasing slope at slopes below a critical level. The results obtained in our study suggest that the range at which rainfall is the main agent of sediment detachment and at which surface flow acts simply to transport and not generate sediment, is at slopes gentler than 10%. As the slope angle increases above 10%, the velocity of overland flow exceeds the critical value, rills are formed, and erosion is generated by surface and rill flow. At slopes greater than 25%, the increase in the amount of soil loss with slope angle was slowed down (Fig. 3). This suggests that some form of limit is being approached, possibly reduced availability of erodible sediments. However, it is also possible that this is an artifact which results from the setup of the soil trays. The very intensive rill erosion that took place at the 30% slope (see Fig. 4), and the lowering of the soil surface below the edge of the trays, caused sediment precipitation at the outlet and lower soil loss values. As there was more confidence in soil loss data at the 25% slope, these data are presented in Fig. 1 and are considered in the following discussion.

Treatment with PG reduces soil loss dramatically (Fig. 1 and 3). The effect of PG in reducing erosion increases with increase in slope angle. At the 5% slope, the amount of soil loss from the untreated and treated soil samples was, respectively, 0.935 and 0.414 kg $m^{-2}$, and the treatment ratio (the ratio between soil loss from soil samples treated with PG to soil loss from untreated soil samples) was 0.443 (Table 2). At the 25% slope, the amount of soil loss from the untreated and treated soil samples was, respectively, 6.7 and 0.8 kg $m^{-2}$, and the treatment ratio was 0.12. The effect of PG on erosion should be compared with its effect on runoff. Treatment with PG decreased runoff at the 5% slope from 65 to 32% (treatment ratio of 0.49), and at the 25% slope from 65 to 23% (treatment ratio of 0.35). Whereas the effect of PG on runoff depends only slightly on slope, the effect of PG treatment on soil loss is more pronounced as the slope angle increases. This finding indicates that PG treatment on steep soils reduces runoff to 35% of the control but reduces erosion to 12% of the control. Thus, PG also reduces the concentration of sediments in the runoff volume.

The effect of PG on the micro-relief of the soil exposed to rain is presented in Fig. 4. Following a 60 mm rainstorm, the surface of the untreated soil at the 5% slope is smooth. An untreated soil will, at the beginning of a rainstorm, form pits as a result of the impact of the raindrops (Hardy et al., 1983). As the storm proceeds, a crust is formed, and runoff and erosion take place. Seal formation increases the resistance of the soil surface to further pitting, and the erosion removes the loose soil particles. The final result of these processes is the development of a smooth soil surface (Fig. 4a). Soil treated with PG continues to pit throughout the rainstorm, probably because the strength of the seal is not sufficient to resist the impact of the raindrops (Fig. 4b).

Increasing the slope angle increases the velocity of the water flowing over the soil surface. When the velocity and turbulence become large enough, rill formation takes place. In our study, easily discerned rills were formed along the entire length of the tray on slopes greater than 10%. On the 30% slope, at the end of the storm, rills were up to 0.75 cm deep and 2 cm wide (Fig. 4c). Phosphogypsum-treated soil did not develop rills even at the 30% slope (Fig. 4d).

The dramatic effect of PG on erosion and its dependence on slope angle may be explained as follows. According to Rose (1985) and Foster (1982), three processes affect sediment concentration in the runoff water continuously and simultaneously: (i) rainfall detachment of soil particles, in which raindrops splash soil particles from the soil surface into the water of overland flow; (ii) soil particle entrainment by overland flow (or runoff detachment); and (iii) sediment deposition, a continually occurring process owing to sediment settling out under gravity. This process depends on sediment size and fall velocity. The resultant sediment concentration is determined by the relative magnitude of these different rates.

Rainfall detachment is the main transport process at low slope angle (Walker et al., 1977). The effect of applying PG on rainfall detachment is relatively small, and soil losses are similar in treated and untreated soils.

The capacity of water to cause sheet erosion depends upon its velocity and turbulence which, in turn, depend upon the slope angle, the depth of the runoff water, the tortuosity of its path, and the roughness of the soil surface. As the size of the soil particles increases, it is more difficult for overland flow to lift the particles from the soil surface. Treatment with PG affects each of these factors; PG reduces the volume of runoff and maintains the roughness of the surface, thereby decreasing the velocity of overland flow. Phosphogypsum treatment also increases the electrolyte concentration in both the runoff water and the percolating water. Increasing the electrolyte concentration prevents aggregate dispersion (Agassi et al., 1981) and bigger particles are less erodible. Thus, it is concluded that erosion by overland flow is reduced effectively by PG treatment. Since overland flow becomes the dominant mechanism as the slope angle increases, it is to be expected that the effectiveness of PG increases as the slope angle increases.

The third process that affects the sediment concentration in the runoff water is sediment deposition. Sediment deposition depends on the size of the particles. In the PG treatment, the concentration of electrolytes in the runoff water is high and the clay particles flocculate and are deposited. Miller (1987), analyzing the effect of PG on sediment particle sizes in the runoff water, found for the control soils 15 to 30% clay and 60 to 75% silt, whereas PG-amended soils showed no clay in the runoff water. PG treatments always enhance sediment deposition.

## CONCLUSIONS

Seal formation at soil surfaces exposed to rainfall is due to two mechanisms: (i) breakdown of the soil aggregates caused by the impact of raindrops, and (ii) a physiochemical dispersion of the clay, which can then migrate and clog pores immediately beneath the surface. When PG was spread over the soil sample, it dissolved and prevented clay dispersion, tripled the final IR of the soil, and decreased the depth of runoff by 50%. PG application also reduced erosion by 60% at gentle slope angles.

Increasing the slope angle of the soil that was exposed to vertical rain from 5% to 30%, almost doubled the final IR of both treated and untreated soil samples, tripled soil erosion from PG-treated samples and increased by sevenfold soil loss from the untreated samples. The increase in final IR was attributed to seal erosion.

Phosphogypsum treatment and the release of electrolytes into the percolating and runoff solutions reduced soil erosion by the following mechanisms:

—Increasing the fraction of rain that penetrated into the soil, thus decreasing the depth of runoff water.

—Increasing the stability of the soil aggregates at the surface, thus detaching fewer soil particles by raindrop impact and overland flow.

—Maintaining a rough soil surface (compared with the smooth surface of the untreated soil), thus decreasing the velocity of the overland flow of runoff water.

—Maintaining a high concentration of electrolytes in the runoff water, thus enhancing the flocculation and deposition of the clay particles.

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Fig. 1. Effect of rainfall, phosphogypsum treatment (PG), and slope (5 and 25%) on (a) infiltration rate and (b) soil loss from a sandy loam (Typic Rhodoxeralf).

Fig. 2. Effect of slope and phosphogypsum treatment (PG) on the final infiltration rate and runoff percentage of a sandy loam soil under simulated rainfall (40 mm $h^{-1}$ for 1.5 h).

Fig. 3. Effect of slope and phosphogypsum treatment (PG) on soil loss from a sandy loam soil exposed to simulated rain (40 mm $h^{-1}$ for 1 h).

Fig. 4. Effect of slope and phosphogypsum treatment (PG) on the microrelief of soil surface exposed to 60 mm rain: a) control, 5%; b) PG, 5%; c) control, 30%, d) PG, 30%.

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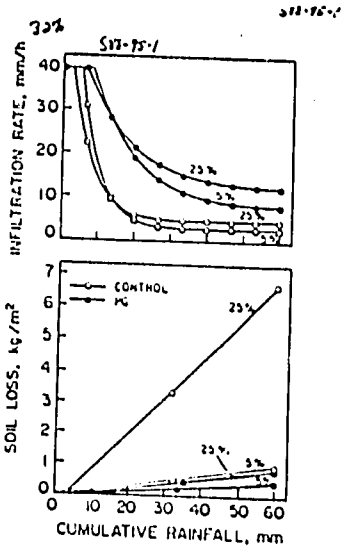
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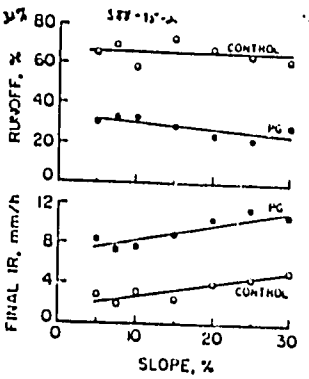
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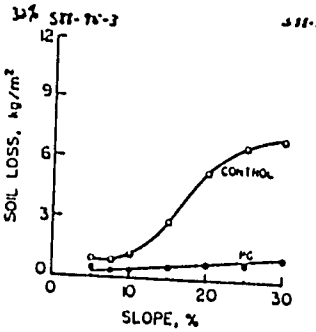
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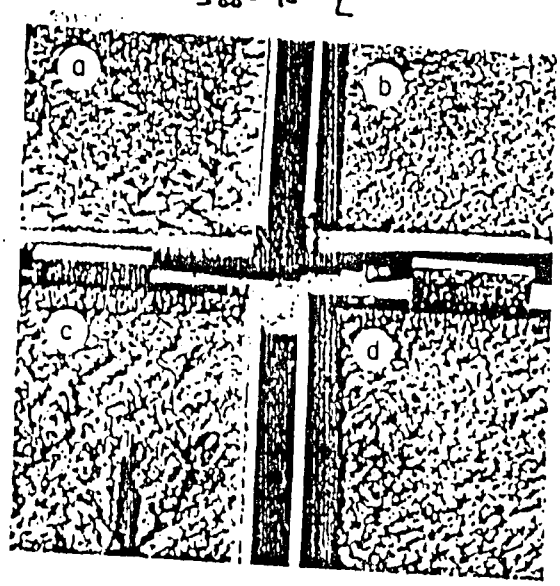

Appendix 2

LOESS

# SLOPE, ASPECT AND PHOSPHOGYPSUM EFFECTS ON RUNOFF AND EROSION

by

M. Agassi*, I. Shainberg and J. Morin

Author/Paper Documentation

M. Agassi and J. Morin, Soil Erosion Research Center, Emeq Hefer, Israel, and I. Shainberg, Institute of Soils and Water, ARO, The Volcani Center, P.O.B. 6, Bet Dagan, Israel. This work was supported by US-Israel CDR project C7-036.

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Abstract

The effect of slope, aspect (windward and leeward sides), and phosphogypsum (PG) application on rain amount, runoff, and erosion from a grumusol soil (Typic Chromoxererts) was measured in small field plots (1 x 1.5 m) exposed to natural rainstorms. The amount of effective rain on the slopes, as measured with small raingauges with orifices in a plane parallel to the slope, increased slightly on the western (windward) aspect as slope increased to approx. 58% and decreased thereafter. On the leeward aspect the amount of effective rain dropped steadily to half of the meteorological rain at a slope of 100%. The amount of runoff was not affected by the slope on the western aspect and decreased sharply on the eastern aspect. PG application reduced runoff to about 25% of that in the control and soil losses to 1-3% of that in the control. The dramatic effect of PG on erosion increased with slope steepness.

PG releases electrolytes into the percolating and runoff water. It prevents dispersion of the particles at the surface, stabilizes the soil structure and reduces soil erosion.

## Introduction

Soils from semi-arid regions are characterized by poor structure and relatively high sodicity in the soil profile. A major consequence of the lack or non-stability of aggregation is the tendency of these soils to display rapid surface sealing during rainfall, which induces excessive runoff and soil erosion.

Breakdown of the soil structure and formation of a seal at the soil surface are enhanced by the impact energy of the raindrops and the low concentation of electrolytes in rainwater (Agassi et al., 1981, 1985a). Agassi et al. (1981) proposed that seal formation was due to two complementary mechanisms: (a) physical disintegration of soil aggregates caused by the impact of water drops; and (b) chemical dispersion which depends on the soil ESP (Exchangeable Sodium Percentage) and on the electrolyte concentration of the applied water. When water of high electrolyte concentration was used, chemical dispersion was largely prevented and a seal with high permeability was formed, mainly by the physical mechanism.

The beneficial effect of surface application of phosphogypsum (PG) in maintaining high rain penetration, reducing runoff and preventing soil loss has been demonstrated in the laboratory (Agassi et al., 1982, 1985b; Kazman et al., 1983; Warrington et al., 1989). When PG is spread over the soil, it dissolves and releases electrolytes which prevent clay dispersion. By preventing clay dispersion, surface-applied PG increased the permeability of the seal, tripled the final infiltration rate of a typic Rhodoxeralf, reduced the amount of runoff by 50%, and reduced erosion to 10-40% of that in the control (Warrington et al., 1989). The objectives of this work were

i) to study the effect of slope and aspect (windward and leeward sides), on rain amount, runoff and erosion from a grumusol soil in small field plots (1.5 $m^2$) exposed to natural rainstorms. ii) To study the effect of PG spread over different slopes and aspects on runoff and erosion.

## Materials and Methods

### Geography

The experimental sites were located in the northern Negev of Israel near Kibbutz Bet Qama. The soil type was grumusol (typic chromoxererts) with clay, silt and sand contents of 48%, 25% and 27%, respectively. The cation exchange capacity (CEC) of the soil samples ranged around 37 cmole(+)$kg^{-1}$ and the ESP around 18. The $CaCO_3$ content was 13.4%.

Annual rainfall at the site is approx. 265 mm, with a coefficient of variation of 38%. The meteorological rain is measured with raingauges whose orifices are horizontal. However, the intensity at which a given rain flux is intercepted on the ground depends on the angle of incidence (Sharon, 1980). It is greatest when rain falls normal to a surface, whence it decreases to zero for rain falling parallel to it, such as vertical rain falling near a wall. The angle of incidence depends on the position (i.e., aspect and inclination) of the sloping ground, relative to the direction from which rain is falling. Thus, for a given direction of rain, the proportion of rain actually intercepted on the ground will vary with aspect or inclination or both. It is this quantity that is significant in rain-dependent processes taking place at soil surfaces.

Dominant wind direction during rainfall varies in the region, but at least 50% of the rain comes from a narrow section of only $\pm 20-25^{o}$ around

the azimuth of 240° (dominantly west-southwest winds) (Sharon et al., 1988). As a result of the prevailing wind, rain falls mostly at a considerable inclination. Resultant angles of 40°-60° (measured from the vertical) have been found in storms with wind speed of 10 m/s (Sharon, 1980). As a result, the effective depth of rainfall that is actually incident on the windward and leeward side of sloping ground, also deviates widely from measurements made in conventional raingauges with a horizontal orifice.

Runoff plots and instrumentation

Runoff plots (1.0-m wide and 1.5-m long) were constructed at two sites, 2 km apart. One site was on natural wadi wall (Plate 1). The prevailing aspect of the slopes at the site was toward southwest. The runoff plots were constructed on natural consolidated undisturbed slopes of 12%, 31.5% and 65%. The soil at this site is quite variable, with ESP ranging between 10 and 20, thus another site, on a nearby roadcut, was chosen (Plate 2). Slopes of 8.7%, 57.7% and 100% were constructed at this site on the western (windward) and eastern (leeward) aspects. Well-mixed undisturbed soil from the wadi wall was used to form the uppermost 5-cm layer in these slopes (Plate 2).

Raingauges were of the small-orifice (=6.4 $cm^2$) type. The gauges on the slopes were inclined, with the orifices on a plane parallel to the soil surface. Runoff water together with the suspended solids in the runoff water were collected in containers. After each rainstorm rain, runoff water, and the suspended solids in the runoff water were measured. Two soil treatments were applied: bare untreated (control) and PG spread over the

soil surface at the rate equivalent to 5 ton $ha^{-1}$. The soil surface at the undisturbed slopes was cultivated just to break the previous crust and then smoothed by hand. Each treatment was replicated three times; thus the number of plots at the roadcut site was 3 slopes x 2 treatments x 2 aspects x 3 replicates = 36 plots, and at the wadi site it was, 3 slopes x 2 treatments x 3 replicates = 18 plots.

## Results and Discussion

Measurements for the present study were conducted during the 1987/88 rainy season. Observations from five (disturbed soil) and six (undisturbed soil) consecutive rain storms from January to March 1988 totaled about 240 mm. Earlier storms are not presented, because plots were not prepared yet.

A complete listing of rainfall, runoff and soil losses for each storm is presented in Tables 1 and 2. The season sum of rainfall, runoff and erosion is presented in Figures 1-3.

### Rain measurements

The depth of rain measured with standard raingauges with horizontal orifices at the wadi and roadcut sites (consolidated and disturbed surfaces, respectively) was 240 and 249 mm, respectively. The amount of effective rain on the slopes, as measured with inclined raingauges with orifices on a plane parallel to the soil surface is presented in Tables 1 and 2 (for each of the single storms) and in Figure 1 (for the total season rainfall). It is evident that the effective rain is a function of both the slope and the aspect of the sites. Since the dominant wind direction

during rainstorms is from the west-southwest (azimuth of 240°, Sharon et al., 1988), the amount of incident rain is higher on the western than on the eastern aspect. The maximum amount of incident rain on the western aspect was at the intermediate slope (57.5%) and the effective rain decreased as the slope increased further to 100%. It is at the moderate slope that the incident rain was probably perpendicular to the soil surface. At slopes less or greater than the moderate slope, the effective rain decreases. At the leeward slope (eastern aspect) the amount of effective rain decreased continuously with increase in slope. At slopes of 57.5% and 100%, the effective rain dropped to 0.77 and 0.50 of the meteorological rain. In this study experimental runoff and erosion are related to the effective rain as measured with the inclined raingauges (Fig. 1).

Runoff measurements

The amounts of runoff (mm) as a function of slope and treatment for each storm at the two sites and the two aspects are presented in Tables 1 and 2. The fraction of runoff (from effective rain) as a function of slope is presented in Fig. 2. The following characteristics should be noted:

1) On western-aspect slopes the effect of gradient on the percent of runoff was small. Whereas on the consolidated surfaces the percent of runoff increased with an increase in slope, in the plots with disturbed soil surfaces the percent of runoff decreased with an increase in slope. Averaging runoff percentage for both surfaces, the percent of runoff in the control was about 60 percent of the effective rain. The high runoff (and low rain penetration) was due to seal formation at the soil surface (Agassi

et al., 1981). The impact of raindrops, combined with the low concentration of electrolytes in the water and the inherent low stability of the soil structure, caused the IR of a similar grumusol to drop to low final IR values of 2-3 $mm.h^{-1}$ (Agassi et al., 1985a) and a high percent of runoff was obtained.

With an increase in slope, runoff is expected to increase because surface storage decreases. However, with an increase in slope, soil erosion also increased and the seal at the soil surface was eroded. A high rate of seal erosion leads to an increase in rain infiltration and decreased runoff (Warrington et al., 1989). The net effect of the two opposing processes was that runoff was affected only slightly by slope.

2) The effect of treatment with PG on runoff percentage was very pronounced (Fig. 2). The percent of runoff in the PG treatments was approx. 15, about one-fourth of that in the control. It was already shown (Agassi et al., 1982, 1985 a, b, and Gal et al., 1984) that PG reduces surface sealing by raising the electrolyte concentration in the solution at the soil surface, thus reducing the dispersion of soil clays and preventing the formation of the "washed in" layer. Since the seal forms more slowly on soil surface treated with PG and is more permeable, runoff in PG-treated soil surfaces is reduced. As in the control, the effect of slope on runoff from PG-treated surfaces was small.

3) The difference in runoff from a natural slope ("consolidated") and that from a disturbed or cultivated soil layer was small (Fig. 2). Since seal formation determines the rate of rain penetration and seal is formed at the surfaces of both disturbed and consolidated soils, the properties of the soil underneath the surface affect only slightly the rate of rain

penetration, and thus the difference in runoff between the soils at the two sites is small.

4) The amount of effective rain on the leeward side of the dominant wind (eastern aspect) decreased with slope (Fig. 1). On this slope the percent of runoff (from effective rain) decreased sharply from $7^{o}$ x 70 at 8.5% slope to approx. $2^{o}$ x 20 at 100% slope (Fig. 2). The low values of runoff from the steep slope suggest that the seal was not fully developed on the eastern aspect. In a study of the effect of impact energy of raindrops on seal properties of a loess soil, Agassi et al. (1985a) found that the impact energy of raindrops was essential for seal formation and when rain without energy was applied, high IR's were maintained. In the leeward side of the dominant wind, both the amount of rain and the impact energy of raindrops were low, thus a seal with high permeability was formed, and the percent of runoff was low.

5) On the eastern aspect, the relative efficiency of PG in preventing runoff was high at the gentle slope and diminished as the slope increased. The beneficial effect of PG was most pronounced in dispersed soils exposed to the beating action of raindrops. As the impact of raindrops decreased, the formation of the seal decreased and the beneficial effect of PG was less pronounced.

6) Finally it should be noted that no runoff data are available for the control treatment of 100% slope on the western aspect. Total collapse of the surface layer with localized landslides took place in the three replicates of this treatment (Plate 3). Conversely, no landslides occurred in the PG treatments in spite of the fact that more rain penetrated this treatment than the nontreated plots. It seems that the low concentration

of electroltyes in the rain and the dispersivity of the soil (high ESP) lead to soil slide. When PG was spread on the soil, the relatively high concentration of electrolytes in the soil solution prevented clay dispersion and soil slide in spite of the greater rain water percolation.

Soil Erosion

The effect of slopes on soil losses for the two sites is shown in Tables 1 and 2. The effect of slopes on the season soil losses (240-249 mm rain) is presented in Fig. 3. The following should be noted:

1) On the western aspect (Table 2A), increases in slope had a dramatic effect on soil losses. The effect of the topographic factor (length x slope) was quite similar to that calculated by Wischmeier and Smith (1978). There was no significant difference in soil loss between the disturbed and consolidated plots.

2) Treatment with PG reduced soil loss dramatically (Fig. 3). The effect of PG in reducing erosion increased with slope steepness. At the gentle slope, PG treatment reduced soil losses to 6-10% of that in the control, whereas at the 60% slope, PG treatments reduced erosion to 1-3% of that in the control. At 100% slope, landslide occurred in the control and comparison between PG treatment and the control was impossible. The effect of PG on erosion should be compared with that on runoff. Treatment with PG reduced runoff from about 60% in the control to about ±15% in the treated soil, and the effect of PG on runoff depended only slightly on the slope (Fig. 2). These observations suggest that the beneficial effect of PG in decreasing erosion is not only by decreasing runoff but also by diminishing

soil erosion directly. Similar observations were obtained in laboratory studies using rain simulators (Warrington et al., 1989).

3) In Plates 3 and 4, the effect of PG on the shape of the soil surface at the steep and gentle slopes, respectively, is shown. Following 140 mm rain, the surface of the untreated soil at the 8.7% slope was smooth and the aggregates were completely destroyed. Naked white sand grains from which the clay particles were removed by clay dispersion, give the white color to the surface (Plate 4). Soil treated with PG maintained part of its original structure, the surface was not as smooth, and no naked sand grains were observed on the surface. The well developed crust at the soil surface of the control caused the high runoff and erosion. Increasing the slope angle increased the velocity of the water flowing over the soil surface and intensive rill and interrill erosion took place (Plate 3). PG- treated soils did not develop intensive erosion or rills even at the 100% slope (Plate 3). It is hypothesized that the presence of electrolytes in the runoff of the PG treated soils decreased rill formation and rill erosion. This process which supplements the decrease in runoff may account for the dramatic effect of PG in reducing erosion.

4) On the eastern aspect, soil losses decreased with increase in slope. The decrease in rain intensity (Fig. 1) which was followed by a decrease in runoff (Fig. 2), brought about a decrease in soil losses. It should be noted that as the slope increased from 8.7 to 100%, the amount of effective rain dropped to 125 mm (52% of the horizontal rain), the runoff dropped to 26.3 mm (15% of the amount of runoff at 8.7% slope), and the soil losses dropped to 210g (9% of soil loss at 8.7% slope). A similar relationship was obtained at the intermediate slope. The similarity in the effect of slope

with eastern aspect on runoff and soil loss suggests that these two processes are related. We can assume that the impact energy of raindrops on soil surface in the leeward side of the wind diminished even more than the rain intensity. With the decrease in impact energy, both seal formation and soil detachment were also diminished.

## Summary and Conclusions

There is a considerable difference in the amount of rain falling on leeward or windward aspects of steep slopes. This factor must be considered in soil conservation plans. The effect of PG on soil loss reduction operates by several mechanisms (Warrington et al., 1989). (1) PG spread at the soil surface dissolved and released electrolytes into the percolating and runoff waters. The high concentration of electrolytes in the percolating water slowed down and prevented the formation of the seal and increased the fraction of rain that penetrated into the soil, thus decreasing the depth of runoff water. (2) Increasing the electrolyte concentration at the soil surface also prevents the breakdown and dispersion of the aggregates at the soil surface. Stable aggregates are less transportable by raindrop detachment and overland flow. (3) Rill formation and rill erosion are slowed down by presence of electrolytes. Finally in the presence of electrolytes in the runoff water, deposition of clay particles from runoff water is enhanced (Rose, 1985). The dramatic effect of PG in reducing runoff and erosion from steep slopes shows the important effect of water quality and soil properties on erosion and may be used in stabilizing soil structures with high slopes. This study has to be extended to include other unstable soils from semi-arid regions.

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## Figure Legends

Fig. 1: Rainfall amount as affected by soil slope, aspect and location.

Fig. 2: Percent of runoff from effective rainfall as affected by soil slope, aspect, location and surface treatments.

Fig. 3: Soil loss amount as affected by soil slope, aspect, location and surface treatments.

## Plate Legends

Plate 1: Runoff plots on natural Wadi wall.

Plate 2: Runoff plots on the roadcut (only the 57.7% and 100% slopes are seen).

Plate 3: Effect of phosphogypsum on the soil surface at the steep slopes. Note the soil collapse in the control (100% slope), compared with the phosphogypsum treatment.

Plate 4: Effect of phosphogypsum on the soil surface at 8.7% slope. (note the white PG aggregates).

Table 1. Rain, runoff, and soil loss from $1.5m^2$ field plots on consolidated grumusol (windward slopes).*

| Date | | 12% slope | | | 31.5% slope | | | 65% slope | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Rain | Runoff | Soil loss | Rain | Runoff | Soil loss | Rain | Runoff | Soil loss |
| | | mm | mm | $g.m^{-2}$ | mm | mm | $g.m^{-2}$ | mm | mm | $g.m^{-2}$ |
| 5/1 | Control | 28 | 14.1 | 42.6 | 28 | 13.5 | 97.8 | 27 | 8.4 | 297 |
| | PG | | 3.3 | 5.4 | | 3.0 | 6.8 | | 3.1 | 8.4 |
| 17/1 | Control | 47 | 25.2 | 78.2 | 45 | 22.3 | 346 | 40 | 26.2 | 2640 |
| | PG | | 6.9 | 9.7 | | 7.5 | 36.2 | | 4.5 | 47.4 |
| 3/2 | Control | 41 | 20.2 | 50.0 | 42 | 22.7 | 235.4 | 43 | 27.3 | 597 |
| | PG | | 6.7 | 7.4 | | 9.5 | 50.0 | | 4.6 | 14 |
| 18/2 | Control | 58 | 30.8 | 110.3 | 58 | 35.5 | 375.6 | 49 | 34.8 | 3607 |
| | PG | | 7.7 | 5.1 | | 10.8 | 28.5 | | 5.3 | 57.5 |
| 24/2 | Control | 52 | 23.8 | 44.9 | 54 | 30.8 | 32.3 | 44 | 30.0 | 988.2 |
| | PG | | 6.1 | 2.9 | | 11.8 | 47.2 | | 9.3 | 55.5 |
| 7/3 | Control | 23 | 11.2 | 19.6 | 23 | 7.9 | 58.6 | 20 | 10.5 | 2928 |
| | PG | | 1.9 | 0.9 | | 1.0 | 2.8 | | 1.4 | 5.0 |
| Total | Control | 249 | 125.3 | 345.6 | 250 | 132.7 | 1437.2 | 223 | 131.6 | 8429 |
| | PG | | 32.6 | 31.4 | | 43.6 | 171.5 | | 28.2 | 183.8 |

* The results presented in the table are means of 3 replicates. The standard deviations of the means were always below 10%.

Table 2. Rain, runoff, and soil loss from 1.5 $m^2$ field plots on disturbed ,rumusol.*

| Date 1988 | Treat-ment | 8.7% slope Rain mm | Runoff mm | Soil loss $g.m^{-2}$ | 57.5% slope Rain mm | Runoff mm | Soil loss $g.m^{-2}$ | 100% slope Rain mm | Runoff mm | Soil loss $g.m^{-2}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Western Aspect | | | | | | |
| 5.1 | Control | 26.7 | 15.8 | 110 | 28.5 | 11.0 | 200 | 23.7 | 3.9 | 40 |
| | PG | | 2.5 | 0 | | 2.1 | 0 | | 2.0 | 0 |
| 17.1 | Control | 73 | 44.2 | 410 | 82.0 | 35.0 | 1130 | 78.0 | (a) | (a) |
| | PG | | 9.5 | 10 | | 9.3 | 30 | | 5.0 | 0 |
| 3.2 | Control | 39.7 | 26.6 | 200 | 44.5 | 35.8 | 1600 | 41.2 | (a) | (a) |
| | PG | | 10.1 | 10 | | 9.8 | 20 | | 6.7 | 80 |
| 18.2 | Control | 55.5 | 46.7 | 310 | 60.0 | 44.5 | 2000 | 51.5 | (a) | (a) |
| | PG | | 13.3 | 30 | | 10.1 | 10 | | 10.1 | 0 |
| 24.2 | Control | 46.5 | 37.2 | 400 | 53.0 | 42.3 | 1000 | 51.3 | (a) | (a) |
| | PG | | 12.2 | 20 | | 14.5 | 0 | | 12.2 | 10 |
| Total | Control | 241. | 170.0 | 1430 | 268.0 | 168.0 | 5930 | 245.0 | - | - |
| | PG | | 47.6 | 90 | | 45.8 | 70 | | 36.0 | 90 |
| | | | | Eastern Aspect | | | | | | |
| 5.1 | Control | 27.0 | 12.8 | 170 | 23.2 | 6.6 | 30 | 18.0 | 1.2 | 0 |
| | PG | | 1.8 | 0 | | 1.4 | 0 | | 1.6 | 0 |
| 17.1 | Control | 70.0 | 45.7 | 1000 | 50.0 | 14.7 | 160 | 27.0 | 4.5 | 10 |
| | PG | | 12.4 | 50 | | 5.5 | 10 | | 2.2 | 0 |
| 3.2 | Control | 40.7 | 29.9 | 380 | 33.5 | 17.1 | 160 | 20.7 | 3.6 | 170 |
| | PG | | 7.9 | 10 | | 5.9 | 10 | | 2.9 | 0 |
| 18.2 | Control | 56.5 | 44.0 | 350 | 51.7 | 24.3 | 370 | 39.0 | 9.6 | 10 |
| | PG | | 9.4 | 10 | | 6.5 | 10 | | 5.1 | 0 |
| 24.2 | Control | 45.7 | 38.6 | 410 | 33.8 | 21.2 | 210 | 20.8 | 7.4 | 20 |
| | PG | | 9.4 | 0 | | 3.9 | 0 | | 3.9 | 0 |
| Total | Control | 239.0 | 171.0 | 2310 | 192.0 | 83.9 | 930 | 125.0 | 26.3 | 210 |
| | PG | | 40.9 | 80 | | 23.2 | 30 | | 15.7 | 10 |

(a) Landslide

* The results presented in the table are means of 3 replicates. The standard deviations of the means were always below 10%.

Appendix 3

# Water infiltration as affected by soil crust and moisture profile[1)]

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Abstract

The effect of wetting front depth on the infiltration rate (IR) of the Cacic Haploxeralf and the Typic Chromoxerert soils was studied under field conditions using a rainfall simulator. In both soils the IR decreased more sharply when the wetting front was deeper but this difference become smaller as the rainstorm continued. The infiltration rate of the soils at the end of the rainstorm ($8x10^{-2}$ m) was $8.5x10^{-3}$, $6.3x10^{-3}$, and $5.0x10^{-3}$ m $h^{-1}$ for the Calcic Haploxeralf soil prewetted with water at amount equivalent to 0, $3x10^{-2}$, and $2x10^{-1}$ m, respectively, and $1.5x10^{-3}$, and $1.0x10^{-3}$ m $h^{-1}$ for the Typic Chromoxereret soil prewetted with water at amount equivalent to 0, and $2x10^{-1}$ m, respectively. When the dry soil surface was covered with mulch, however, the steady state value of the IR was $3.5x10^{-2}$ m $h^{-1}$ for both soils. The high permeability of the soils during the rainstorm in the presence of mulch, and the similar low steady state IR values for the various prewetting treatments suggest that the moisture regime in the profile had a negligible effect on the IR in the presence of soil crust.

## Introduction

The significance of the infiltration process in the hydrological cycle is well known. It has long been recognized that the driving force for the water entering the soil is the gradient of the water potential between the wetting front and the soil surface, and therefore the decrease in infiltration rate is an inevitable consequence of the decreasing water potential gradient during the infiltration process (Baver et al., 1972).

Horton (1939) suggested that the reduction in infiltration rate with time, during the infiltration process, is controlled largely by factors operating at the soil surface. A gradual deterioration of the soil structure and the consequent partial sealing of the profile by the formation of a surface crust may occur in some soils under certain conditions.

Crust formation is due to the combined effect of the raindrop impact energy and the dispersion of clay particles at the soil surface (Agassi et al., 1985). The formation and permeability of a soil crust depends on the exchangeable sodium percentage (ESP) of the soil and on the electrolytes concentration of the percolating solution, tending to decrease with increasing ESP and decreasing electrolytes concentration (Agassi et al., 1981, 1985).

The infiltration rate therefore depends on the following factors: (i) hydraulic conductivity of the rain affected surface layer and of the bulk of the soil, (ii) initial water content, and (iii) water potential gradient in the soil profile. Using a rain simulator, however, it was observed that the infiltration rate is independent of the depth of the soil profile (Morin et al., 1981). Thus, the objective of this work was to

study the relative importance of crust formation and hydraulic gradient in the soil profile on the infiltration process in soils exposed to rain.

Relevant equations

Following Darcy's law and the Green and Ampt model (1911) the vertical infiltration rate in isotropic soil is described by

$$I_t = K_L \frac{H_s + H_o + L}{L} \qquad [1]$$

where $I_t$ is the infiltration rate at time t, $K_L$ is the average hydraulic conductivity of the soil, L is the thickness of the soil layer from the soil surface down to the wetting front, $H_s$ is the average suction at the wetting front, and $H_o$ is the thickness of the water layer on the soil surface.

It was assumed that the change in water content at the wetting front took place in a layer of negligible thickness, and the water potential at the wetting front has a constant value, independent of the position of the wetting front.

The suction $H_s$ at the wetting front can be calculated using Mein and Larson's (1971) method

$$H_s = \int_0^1 h \, dK_r \qquad [2]$$

where $K_r = K_L/K_{sat}$, h is the soil suction and $k_{sat}$ is the saturated hydraulic conductivity.

An infiltration equation for bare soil exposed to rain was proposed by Morin and Benyamini (1977), which is similar to Horton's equation (Horton, 1939) it is given in Eq. [3]:

$$I_t = I_f + (I_i - I_f)\exp(-\gamma pt) \qquad [3]$$

where $I_i$ and $I_f$ are the initial and final (steady state) infiltration rate, respectively, t is the time from the beginning of the rain, $\gamma$ is the soil coefficient, related to soil stability, and P is the rain intensity.

Combining Eqs. [1] and [3] and solving for $K_L$ yields:

$$K_L = \frac{L\ I_t}{L+H_s+H_0} = \frac{L[I_f+(I_i-I_f)\exp(-\gamma pt)]}{L+H_s+H_0} \qquad [4]$$

By changing the depth of the wetting front (L) and measuring the corresponding infiltration rates it is possible to evaluate the relative importance of the matric potential gradient and the hydraulic conductivity of the crust due to changing in pore geometry.

## MATERIALS AND METHODS

### Soils

The experiments were conducted on two soil types: (i) Calcic Haploxeralfs ( a silty loam loess) from a region where the average annual precipitation is $2.6\times10^{-1}$ m $y^{-1}$, and (ii) Typic Chromoxererts (a dark brown vertisol) from a region where the average annual precipitation is $4.6\times10^{-1}$ m $y^{-1}$. Some physical and chemical properties of the two soils are presented in Table 1.

### Rain Simulator Experiments

The field experiments were conducted at the end of the summer on a soil profile that was dried by wheat during the previous winter and spring

seasons. The fields, with a slope of 5%, were cultivated by disk harrow to provide a smooth surface before the rain application. Three prewetting treatments were selected: (i) no prewetting; (ii) prewetting with $3.0 \times 10^{-2}$ m of water; and (iii) prewetting with $2.0 \times 10^{-1}$ m of water. The soil in the plots was mulched before the wetting in order to prevent crust formation during the simulated rain. The prewetting was done 24 h before the soils were subjected to a simulated rainstorm of $8.0 \times 10^{-2}$ m. The prewetting treatment provided different wetting front depths. Prior to the simulated rain application, the mulch was removed and a layer of $1 \times 10^{-2}$ m of dry soil aggregates ($<5 \times 10^{-3}$ m) was spread carefully over the wet soil surface. In order to minimize variability, the dry soil aggregates were taken from one spot in the field. Spreading this dry uniform soil over the wet soil surface of the three prewetting treatments ensured that the various wetting time length had no effect on the soil surface aggregates. There were three replications of each treatment.

A portable rainfall simulator (Morin and Cluff, 1980) was used. The main characteristics of the simulated rain are as follows: median water drop diameter is $2.3 \times 10^{-3}$ m, median water drop velocity is 6.74 m $s^{-1}$, the sum of the kinetic energy of the water drop at a depth of 1 m per square meter of the surface is 22.9 KJ, and the rain intensity is $1.11 \times 10^{-5}$ m $s^{-1}$ (40 mm $h^{-1}$).

Runoff rates from a 1.5 $m^2$ area within each 2m by 2 m plot were recorded during the application of rain on the bare soils. Soil samples were taken just before and immediately after the $8 \times 10^{-2}$ m rain on the bare soil for gravimetric soil moisture determinations.

RESULTS AND DISCUSSION

The water content before and after prewetting and after $8x10^{-2}$ m rain for both soils is given in Fig. 1. The moisture in the upper layer was high and decreased gradually with depth, down to the wetting front. The depth of the wetting front after the prewetting treatment was 0, $2.5x10^{-1}$ and $7x10^{-1}$ for 0, $3x10^{-2}$ and $2x10^{-1}$ m of rain, respectively, for the calcic Halpoxeralf soil, and 0 and $5.x10^{-1}$ m for the Typic Chromoxerert after the prewetting by 0 and $2x10^{-1}$ m of water, respectively (Fig. 1).

The calculated water volume that penetrated the Calcic Haploxeralf soil during the rain of $8x10^{-2}$ m (the lined areas in Fig. 1) was $3.96x10^{-2}$, $3.2x10^{-2}$ and $2.49x10^{-2}$ m for the prewetting treatment of 0, $3x10^{-2}$ and $2x10^{-1}$ m, respectively. The total volume of water that penetrated the soil surface as obtained from the runoff measurements were similar ($3.93x10^{-2}$, $3.32x10^{-2}$ and $2.6x10^{-2}$ m, respectively). It is evident that the total volume of water that penetrated into the bare soil decreased as the wetting front depth increased. Since the crust formation rate for the soils was independent of the depth of the wetting front (a layer of $1x10^{-2}$ m of dry soil aggregates was spread over the wet soil surface after the prewetting), the difference in the total amount of water that infiltrated during the $8x10^{-2}$ m storm was probably due to the effect of the hydraulic gradient which controls the infiltration during the crust formation and before reaching its final form.

The infiltration rate (IR) of the calcic Haploxeralf and the Typic Chromoxerert bare soils as a function of accumulated rain depth for the three prewetting treatments are presented in Fig. 2. The lines in this figure represent the values calculated from Eq. [3] using a non-linear best fit correlation analysis. In both soils the IR decreased more sharply when

the wetting front was deeper but this difference became smaller as the storm continued (Fig. 2).

Close examination of the infiltration data at the rain depth range of $5.5 \times 10^{-2}$ - $8 \times 10^{-2}$ m (Fig. 3) indicates that steady state infiltration rate was obtained only at the prewetting treatment of $2 \times 10^{-1}$ m for both soils. The infiltration rate of the soils at the prewetting treatments of 0 and $3 \times 10^{-2}$ m of water was above the steady state values, and were approaching this value with the increase of cumulative rain. The steady state IR of the Haploxeralf and chromoxerert were $5 \times 10^{-3}$ and $1 \times 10^{-3}$ m $h^{-1}$, respectively (Fig. 3). The lower final infiltration rate value of the Typic chromoxerert soil is probably due to the higher ESP of this soil compared with the Haploxeralf (Agassi et al, 1985 and Table 1). When the dry soils were covered with mulch, the steady state infiltration rate was $3.5 \times 10^{-2}$ m $h^{-1}$ for both soils at the end of $2 \times 10^{-1}$ m application of water. This value is in agreement with the IR values obtained for the same soil, using a double ring infiltrometer (Ben-Hur et al., 1987). The high permeability of the soils in the presence of mulch on the surface, and the low steady state IR values for the various prewetting treatments suggest that the reduction in the hydraulic conductivity of the crust on the soil surface controls the IR, and the wetting front depth has only a slight effect on it.

Hydraulic parameters changes during water penetration in crusted soils

Assuming that a trapezium shape of the moisture profile represents the moisture profile during the rainstorm (Fig. 1), an equation that relates the depth of the wetting front to the applied rain can be derived, based on the Green and Ampt model.

A schematic drawing of the trapeze profile situation is presented in Figure 4, where the symbols are defined as follows: $L_a$ is the wetting front distance immediately after the rainstorm; $a=(\theta_{uA} - \theta_{uB})$ is the volumetric soil moisture difference in the upper layer, where $\theta_{uB}$ and $\theta_{uA}$ are the volumetric soil moisture before and after the rainstorm, respectively; $b=(\theta_{DA} - \theta_{DB})$ is the volumetric soil moisture difference in the wetting front layer, where $\theta_{DB}$ and $\theta_{DA}$ are the volumetric soil moisture before and after the rainstorm, respectively, and $\alpha$ is the angle in the arbitrary right-angle trapezium (dotted line) which has the same area as the moisture trapezium.

The depth of water which the profile gains from the rainstorm ($F_a$) can be calculated by the following equation:

$$F_a = \frac{(a+b)L_a}{2} \qquad [5]$$

Since

$$b = a - (L_a/\tan\alpha) \qquad [6]$$

Rearranging Eq. [5] and introducing Eq. [6] yield

$$La = 2\,F_a\,[2a - (L_a/\tan\alpha)]^{-1} \qquad [7]$$

Thus, for any depth L

$$(L^2/\tan\alpha) - 2aL + 2F = 0 \qquad [8]$$

where F is the depth of rain which penetrated the soil (the integral of Eq. 3).

$$F = \int_0^{t_i} I_t \, dt = pt_s + [(-\gamma p^{-1}(I_i - I_f) \exp(-\gamma pt) - \exp(-\gamma pt_s)] + I_f(t - t_s) \quad [9]$$

p is the rain intensity and $t_s$ is the time from the beginning of the rainfall when $I_t > p$, until the stage that $p = I_t$ assuming that p is constant; the other terms were defined above.

Solving Eq. [9] for any time (t) during the storm, one can calculate the water depth L, using Eq. [10].

$$L = (2a - [(2a)^2 - (8F/\tan \alpha)]^{1/2}\}(2 \tan \alpha\}^{-1} \quad [10]$$

Equation 10 can be used to calculate the change in the wetting front depth during the water infiltration process and crust formation. The calculated depth of the wetting front as a function of the accumulated rainstorm depth for the various prewetting treatments for both soils is presented in Figures 5a and 5b. The relation of the hydraulic conductivity to the accumulated rainstorm depth (calculated from Eq. [4]) for both soils is also presented in these Figures. The saturated hydraulic conductivity, $K_s$, of the two uncrusted soils (with the presence of mulch) after applying $2 \times 10^{-1}$ m of rain was $3.5 \times 10^{-2}$ m $h^{-1}$, whereas for the cases where the crust was formed (bare soil), the final $K_L$ values for the Calcic Haploxeralf and Typic Chromoxerert soils are in the range of $4 \times 10^{-3}$ - $5 \times 10^{-3}$ m $h^{-1}$ and $4 \times 10^{-5}$ - $6 \times 10^{-5}$ m $h^{-1}$, respectively (Fig. 5). It is evident that the wetting front depth has an insignificant effect on the average hydraulic conductivity in the presence of crust on soil surface. Since smaller flux rates dictates lower moisture content in the profile (Bresler et al., 1969, and Rubin et al., 1964), the hydraulic conductivity of the crust dictates the water front movement rate, forming a trapeze shape of moisture profile.

and Rubin et al., 1964), the hydraulic conductivity of the crust dictates the water front movement rate, forming a trapeze shape of moisture profile. Green and Ampt's piston model, however, is only an approximation of the reality. It is likely that L as a function of F advances slower than in the trapezium model calculation. In this case, the conversion of the $K_L$ values will be even faster.

## Conclusions

The results from field experiments presented herein indicate that the hydraulic conductivity of the soil surface was reduced sharply during the rainstorm, controling the infiltration rate of the soil. The wetting front depth has only a slight effect on the infiltration rate in crusted soils.

## ACKNOWLEDGMENT

The experimental work of this study was carried out by Miss. Laurence Pochard, a graduate student at ISTOM College (Le Havre, France). We thank her for her contribution.

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Figure Legends

Figure 1: Moisture profile of the soils before and after a rainstorm.

Figure 2: Infiltration rate of the loess (a) and vertisol (b) soils at various prewetting conditions.

Figure 3: Infiltration rate of the loess (a) and vertisol (b) soils at various prewetting conditions for the rain application range of $5x10^{-2}$ - $8x10^{-2}$ m.

Figure 4: Schematic presentation of the moisture profile situation.

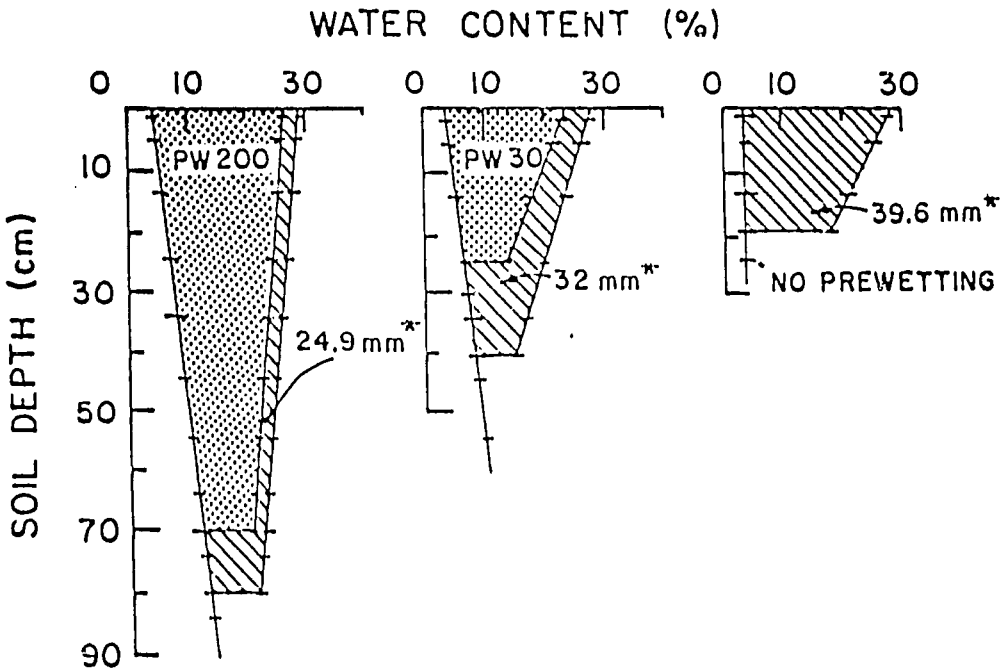
Figure 5: Depth of the wetting front and hydraulic conductivity of Calcic Haploxeralfs and Typic chromoxererts soils as a function of the cumulative rainfall.

Table 1: Some physical and chemical properties of the loess and vertisol soils used in the experiments.

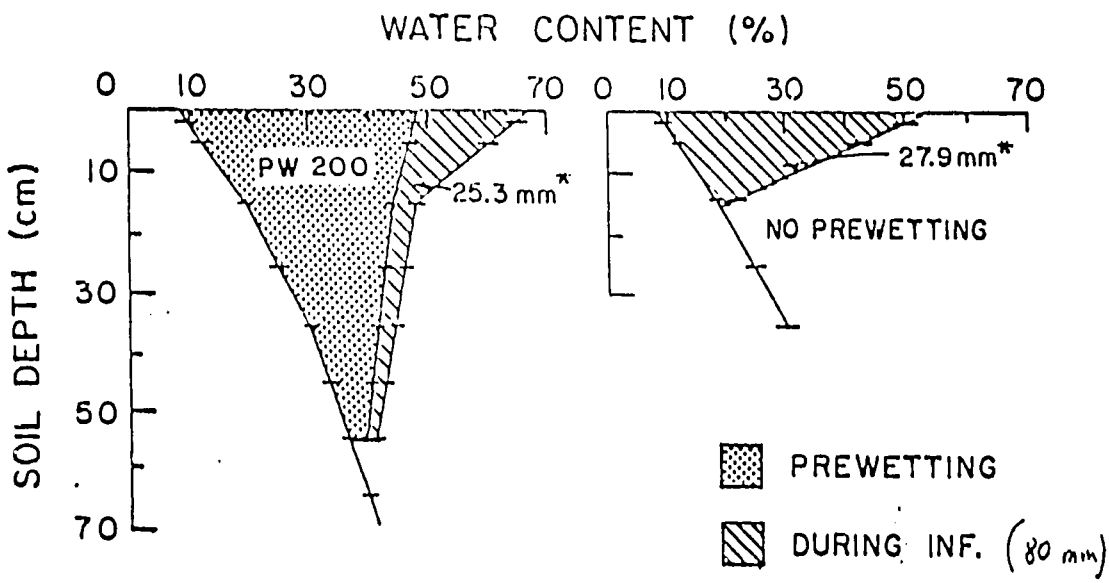
| Soil type | Particle Size sand | silt | clay | $CaCO_3$ | Sat. paste EC | pH | SAR | ESP | CEC | Water content at sat. | $H_s$* average suct. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ----------%---------- | | | | dS/m | | | % | cmole (+)/kg | % | m |
| Loess | 34.0 | 40.0 | 26.0 | 18.0 | 0.4 | 7.5 | 1.0 | 1.6 | 17.7 | 60 | 0.13 |
| Vertisol | 23.8 | 28.4 | 47.8 | 17.4 | 0.6 | 7.8 | 2.0 | 3.7 | 35.2 | 68 | 0.10 |

* From Russo and Bresler, 1977.

## a - CALCIC HAPLOXERALFS

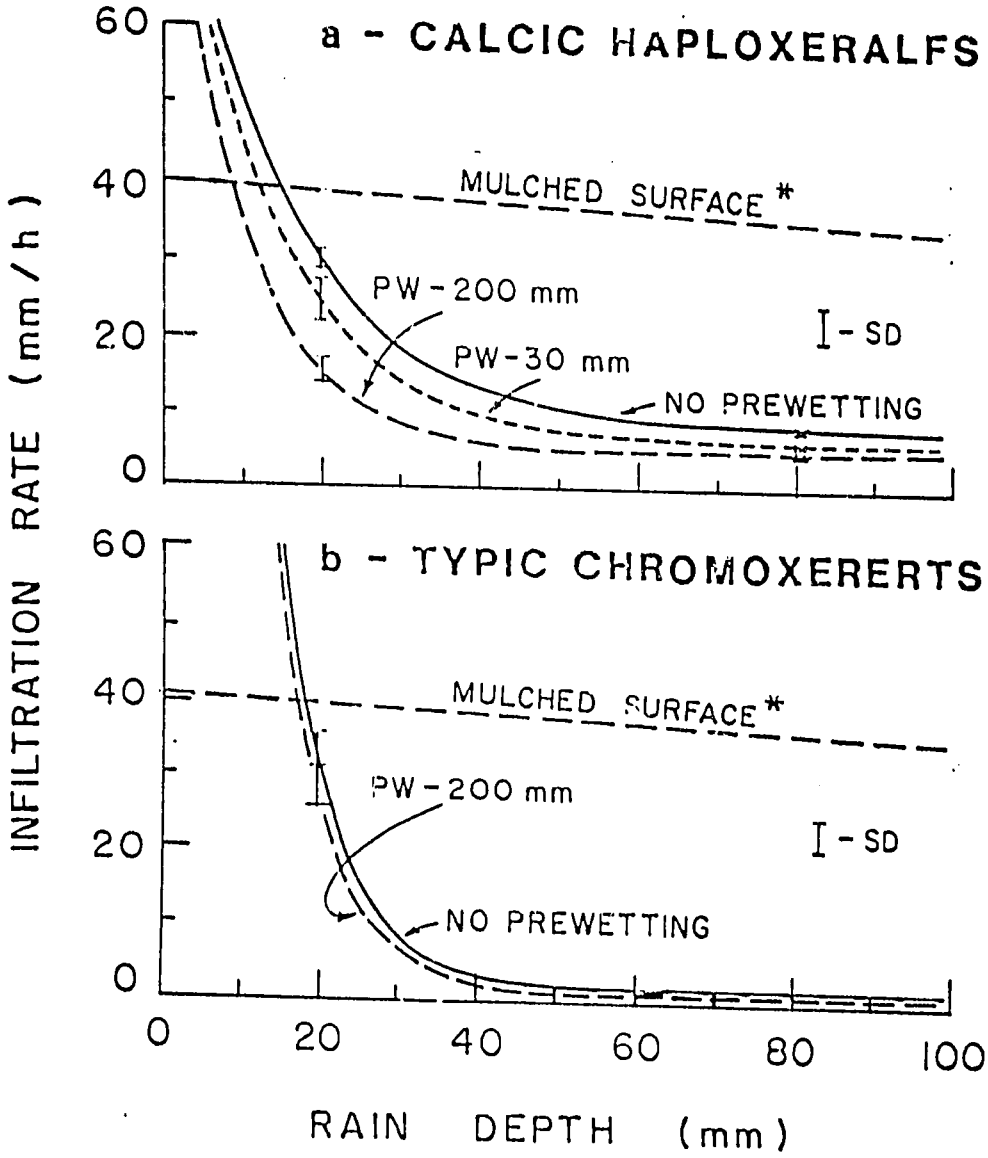



## b - TYPIC CHROMOXERERTS




* Fa Values

Fig. 1




* The 200mm prewetting infiltration rates

Fig.2

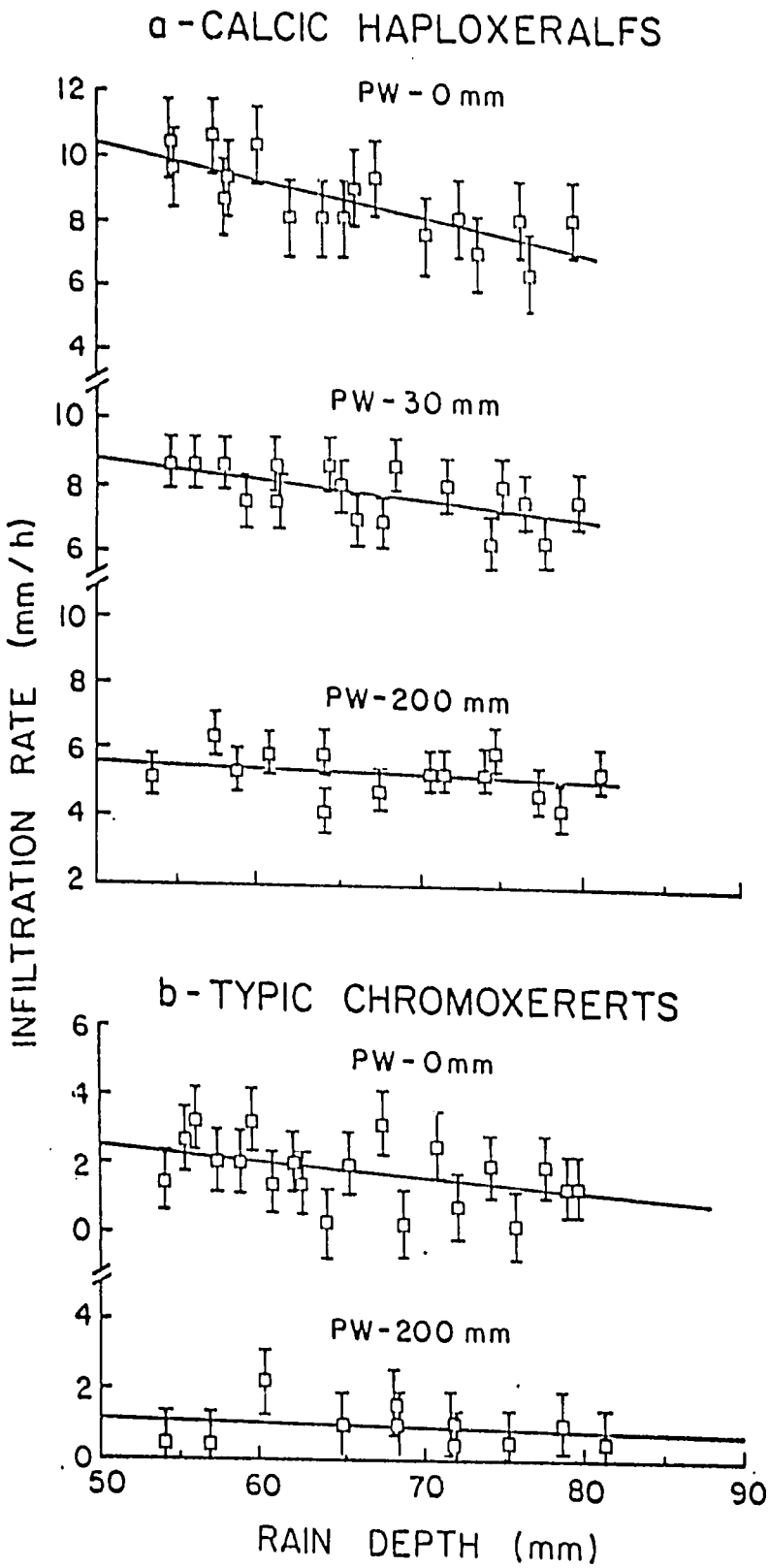

a - CALCIC HAPLOXERALFS
PW - 0 mm
PW - 30 mm
PW - 200 mm
b - TYPIC CHROMOXERERTS
PW - 0mm
PW - 200 mm
INFILTRATION RATE (mm/h)
RAIN DEPTH (mm)
12
10
8
6
4
2
0
50
60
70
80
90

Fig. 3

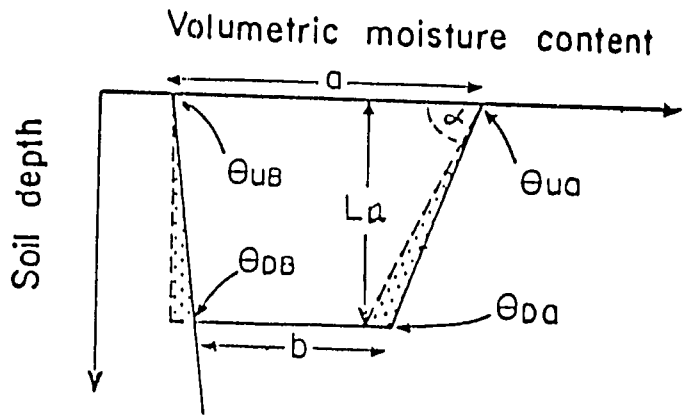

Volumetric moisture content
a
Soil depth
θuB
θuA
La
α
θDB
θDA
b

Fig. 4

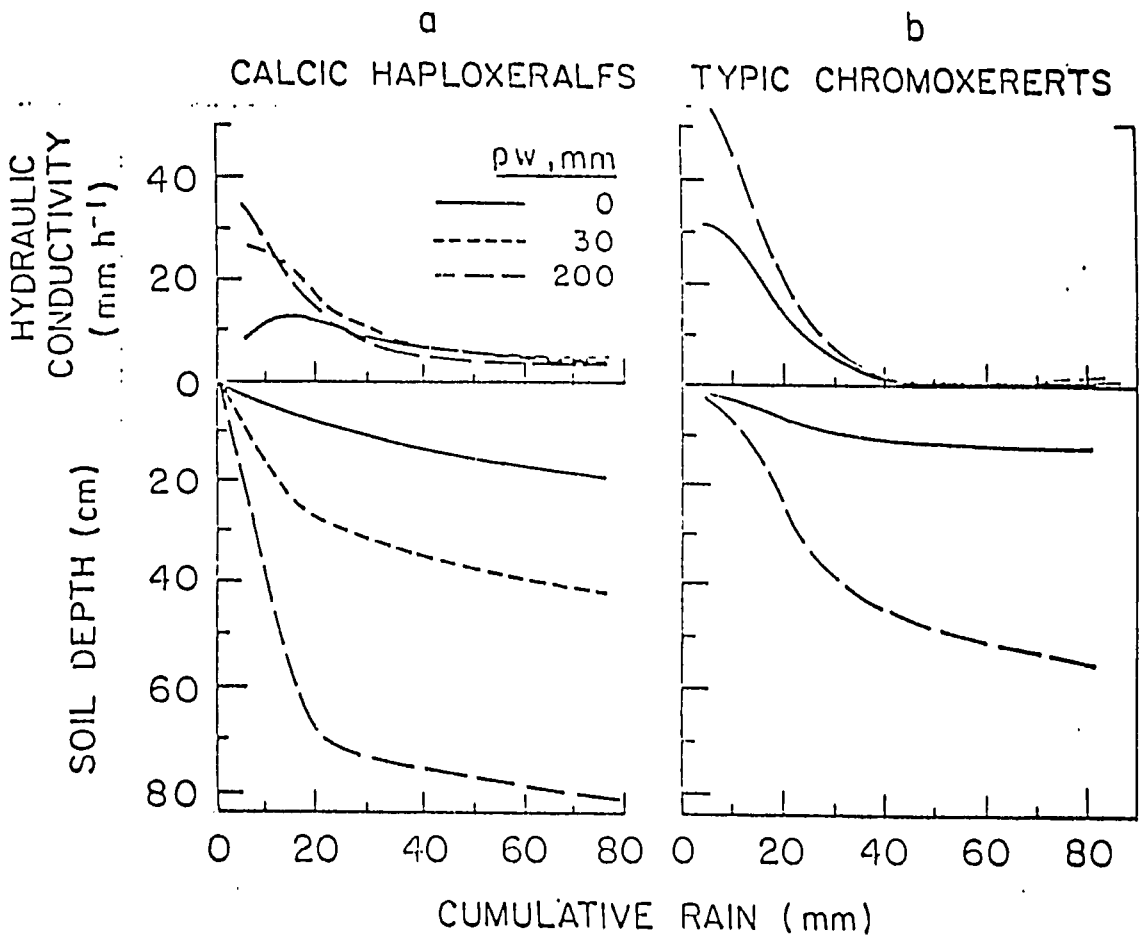

a
b
CALCIC HAPLOXERALFS
TYPIC CHROMOXERERTS
HYDRAULIC CONDUCTIVITY (mm h⁻¹)
pw, mm
0
30
200
40
20
0
SOIL DEPTH (cm)
20
40
60
80
0
20
40
60
80
0
20
40
60
80
CUMULATIVE RAIN (mm)

Fig. 5

Appendix 4

# EFFECT OF PAM AND GYPSUM APPLICATION ON RAIN INFILTRATION AND RUNOFF

I. Shainberg*, D. Warrington and P. Rengasamy

Author/paper documentation

I. Shainberg and D. Warrington, Institute of Soils and Water, ARO, The Volcani Center, POB 6, Bet Dagan, Israel and P. Rengasamy, Institute for Irrigation and Salinity Research, Tatura, Victoria 3616, Australia.

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## SUMMARY

Seals, formed at the soil surface during rainstorms, reduce rain penetration resulting in runoff and erosion. The effect of surface application of anionic polyacrylamide (PAM) at rates of 10, 20 and 40 $kg.ha^{-1}$ on the infiltration rate (IR) of two soils, a loess (Calcic Haploxeralf) and a grumusol (Typic Chroloxerert), during simulated rainstorms, was studied. The interaction between PAM and electrolyte concentration at the soil surface was determined under a simulated rainfall of distilled water or tap water, and by spreading gypsum. Electrolytes in the soil solutions, which flocculate the soil clay prior to cementation by the polymer, enhanced aggregate stability and greatly reduced water losses. Complete drying of the polymer-soil surfaces improved the binding action of the polymer.

Treatments with PAM under the optimal conditions increased the final IR of the loess from 2.0 to 23.3 $mm.h^{-1}$ and increased rain intake of an 80mm rainstorm from 12.3 to 65.0 mm. PAM treatment of the grumusol increased the final IR from 3.0 in the control to 29.1 $mm.h^{-1}$ and the rain intake from 22.8 to 60.8 mm. As soils from semi-arid regions are unstable, form crusts and produce much runoff (50%) during rainstorms, the use of PAM to reduce runoff should be considered.

The formation of a seal at the soil surface, especially due to the action of raindrops but also as a result of sprinkler irrigation (Aarstad and Miller, 1973), is a common feature of many soils, particularly in the arid and semi-arid regions. Surface seals are thin (<2-3 mm) and are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soils. Soil seals have an important effect on many soil phenomena, e.g. the reduction of infiltration and increase in runoff and erosion, and interference with seed germination.

Seal formation in soils exposed to rain is due to two complementary mechanisms: i) physical disintegration of soil aggregates and their compaction caused by the impact of the raindrops at the soil surface, and ii) chemical dispersion and movement of clay particles into a region of <1.0 mm depth below the soil surface, where they lodge and clog the conducting pores forming the "washed in" layer (Agassi *et al.*, 1981; McIntyre, 1958). The chemical mechanism supplements the physical one under dispersive conditions (i.e. in sodic soils with low electrolyte concentrations in the soil solution).

Naturally occurring soil polymers, especially humic substances and polysaccharides, play an important role in promoting and maintaining soil structure. Since the introduction of synthetic polymers for soil conditioning in the early 1950's, there has been considerable interest in the mechanisms by which these materials bind to the soil colloidal constituents and in the mechanics of stabilizing aggregates. In general, soil conditioners were not cost effective for general agricultural purposes where stabilization of the plough layer was required. However, polymers can

be effectively used as anti-crusting agents where it is necessary only to stabilize the aggregates at the soil surface.

In this study, the effect of application of an anionic polyacrylamide with a high molecular weight (PAM) at rates of 10, 20 and 40 $kg.ha^{-1}$ on the infiltration rate (IR) during rainstorms was studied.

Following Bradfield's (1936) statement that "granulation is flocculation plus", it was assumed that stable aggregate formation requires the cementation by the polymer of flocculated soil colloids. The assumption was tested by combining PAM application with rain which contained electrolytes and by spreading phosphogypsum (PG) on the soil surface prior to distilled water rainfall. PG is a byproduct of the phosphate fertilizer industry with a dry composition of 97% $CaSO_4$ and 0.6% $P_2O_5$. PG dissolves readily and maintains $Ca^{2+}$ and $SO_4^{2-}$ concentration above 5 $mol.m^{-3}$ (Agassi *et al.*, 1986). Since the adsorption of polyanion by clay minerals depends on dehydration of the clays (Theng, 1982), the effect of complete drying prior to the rain application was also studied.

## MATERIALS AND METHODS

The <4 mm aggregates of a typical loess (Calcic Haploxeralf) from Bet Oama and of a dark brown grumusol (Typic Chromoxerert) from Sede Yoav were used in this study. Some chemical and physical properties of the soils are given in Table 1.

[INSERT TABLE 1 HERE]



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Soil samples were packed to a depth of 2 cm in 30 x 50 cm perforated metal trays over 8 cm of coarse sand (four replications). PAM solutions with 0.5 $g.l^{-1}$ concentration were sprayed onto the soil uniformly. PAM solutions of higher concentration could be prepared but their viscosity was too high to be hand sprayed conveniently. PAM solutions were applied in 2.0 $l.m^{-2}$ portions (equivalent to 10 $kg.ha^{-1}$) with a period of drying (~1 hour) between applications. This method of application assured that the polymer was concentrated in the surface layer of the soil.

In most treatments, the soil treated with PAM solutions was allowed to dry completely by placing the trays for 24 h in the sun. The effect of complete drying was evaluated by comparing this "dry" treatment with a partially dried treatment in which the soil was left to dry for 24 h in the shade.

Following the application of PAM solution, the trays were placed in a rainfall simulator (Morin *et al.*, 1967) at a slope of 5%, and the soil in the trays was saturated slowly from below. At the end of the saturation process, the soil was subjected to a simulated rainfall with an intensity of 37 $mm.h^{-1}$. The designed "rainstorm" depth was 80 mm. In most studies distilled water (DW) was used to simulate rainwater. Typical mechanical parameters of the applied "rain" were: raindrop median diameter = 1.9 mm, median drop velocity = 6.02 $m.s^{-1}$; the kinetic energy was 19.3 $J.mm^{-1}m^{-2}$. The volume of effluent was measured during the rainstorm and the infiltration rate (IR) and final IR were calculated. The depth of water which percolated into the soil during the application of 80 mm of rainfall (cumulative infiltration), was calculated from the infiltration curves.



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Samples of runoff water were taken during the rainstorm and the electrical conductivity (EC) was measured. In order to study the effect of electrolyte concentration on the IR powdered PG at a rate of 5 ton.ha$^{-1}$ was spread over the soil prior to the distilled water rainstorm. The EC of the percolating water was estimated from the EC measurements of the runoff water (Agassi *et al.*, 1986). In another experiment, tap water (TW)(EC = 0.97 dS.m$^{-1}$, SAR = 2.5) was rained on the soil instead of DW. As will be shown, the effect of PG and TW treatments on IR was similar.

The stability of the treatment with PAM in subsequent storms was determined by exposing the treated soil samples to three consecutive storms with a drying interval of one week between rainstorms. The second and third rainstorms were of 60 mm each.

## RESULTS AND DISCUSSION

### Infiltration Studies

[INSERT FIG.1 HERE]

The effect of PAM application on the IR of the loess is presented in Fig.1 for the control and PG treated soil. From the rapid drop in the IR of the untreated soil and the low value of the final IR (2.2 mm h$^{-1}$) it is evident that the loess is susceptible to surface sealing. Soils which contain 19% clay, low organic matter and have an exchangeable sodium percentage (ESP) of 5 are known to be unstable and prone to sealing and crusting (Ben Hur *et al*, 1985). The impact of the raindrops combined with the low concentration of electrolytes in the rainwater caused the IR of the soil to fall from the initial rate of approximately 50 mm.h$^{-1}$ to a final IR of 2.0 mm.h$^{-1}$. The IR of the soil treated with PG dropped less rapidly than

that of the untreated soil and the final IR was higher (Fig.1). PG reduced surface sealing by raising the electrolyte concentration in the solution at the soil surface, thus reducing clay dispersion and the formation of the "washed in" layer (Gal *et al.*, 1984; Agassi *et al.*, 1986). Thus, in the PG treated soils the seal is slow to form and is more permeable than the seal of the untreated soils.

Application of PAM increased the infiltration of rain (Fig.1). Applying 10, 20 and 40 $kg.ha^{-1}$ PAM increased the final IR of the soil from 2.0 $mm.h^{-1}$ in the control to 5.9, 6.5 and 6.5 $mm.h^{-1}$, respectively. PAM increased the cumulative infiltration of the soil from 12.3 mm in the control to 29.3, 38.6 and 39.0 mm at PAM rates of 10, 20 and 40 $kg.ha^{-1}$, respectively. At rates above 20 $kg.ha^{-1}$, the effect of additional PAM was insignificant (the curves are not presented).

The dramatic effect of PAM in combination with PG is also presented in Figure 1. PG increased the final IR of the loess treated with 10 $kg.ha^{-1}$ PAM from 5.9 to 15.7 $mm.h^{-1}$, and that of the soil treated with 20 $kg.ha^{-1}$ PAM from 6.5 to 23.3 $mm.h^{-1}$. Similarly, runoff from an 80 mm rainstorm dropped from 84.6% in the control to 38.3% and 63.3% in the 10 $kg.ha^{-1}$ PAM treatment with and without PG, respectively. Likewise, runoff percentages in the 20 $kg.ha^{-1}$ PAM treatments dropped to 18.8% and 51.8%, respectively. It is evident that PAM is much more effective in the presence of gypsum at the soil surface. Similar phenomena were observed by Shaviv *et al.* (1985). PG spread at the soil surface dissolves and increases the electrolyte concentration in the soil solutions to values above the flocculation value of the clays (Oster *et al.*, 1980). Flocculation of the soil clay is a



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precondition for the cementing and stabilization of aggregates at the soil surface (Bradfield, 1936).

[INSERT FIG.2 HERE]

The beneficial effect of PAM on the IR depends upon the application conditions. In Fig.2(a and b), PAM at the optimal rate of 20 $kg.ha^{-1}$ was applied to the loess under the following conditions: (a) PAM was sprayed on to the soil and the trays were either completely dried or only partially dried, and (b) DW or TW rainfall was applied. The following is noted: i) complete drying increased the beneficial effect of the polymer. Whereas the final IR and the cumulative infiltration of the incomplete drying treatment were 11.2 $mm.h^{-1}$ and 27.7 mm, respectively (compared with 2.0 $mm.h^{-1}$ and 12.3 mm for the control treatment), these values for the completely dried treatment were 23.3 $mm.h^{-1}$ and 65.0 mm. It is evident that complete drying more than doubled the efficiency of the polymer in stabilizing the aggregates and preventing crust formation. The effect of drying is explainable by the bonding mechanism between the anionic polyelectrolyte and the negative clay (Tate and Theng's chapter in Theng, 1979). Tate and Theng suggested two types of cation-bridging as being responsible for the polymer adsorption and the binding of clay platelets. In the first type, an anionic group of the polymer interacts with an exchangeable cation through a water molecule to yield an "outer-sphere" complex. This mode of bonding is obtained in aqueous systems. The second type of cation bridging may occur under dehydrating conditions. In this instance, an anionic group of the polymer is directly associated with an exchangeable cation to form an "inner-sphere" complex.



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Inner-sphere complex formation involves the displacement (from the interface to the bulk solution) of numerous water molecules by a single polyanion chain. The resultant gain in entropy (0.3-0.5 $kJ.mol.^{-1}K^{-1}$) has a promoting effect on adsorption. In addition, the uncharged segments of the adsorbed chain may interact with each other and with the surface through van der Waals forces. Drying induces inner-sphere complex formation and van der Waals interactions and this would explain why air drying leads to a marked increase in the water-stability of soil aggregates.

ii) The electrolyte effect on PAM effectiveness is demonstrated by the PG treatment and by the effect of raining with TW (Fig.2). The concentration of electrolytes in TW increased the IR values of the control (no PAM) (Fig. 2b). However, PG was more effective in increasing the IR than TW. The electrolyte concentration in the effluent of PG-treated soils was 1.2 - 1.4 $dS.m^{-1}$, compared with an EC of 0.97 $dS.m^{-1}$ for the TW. The increase in electrolyte concentration in the PG treated soil compared with TW, partially explains the increase in the IR values (Agassi *et al.*, 1981). In addition to the electrolyte concentration effect, Agassi *et al.* (1986) also suggested that PG treatments interfere with the continuity of the seal and may act as a mulch, and thus increase the IR of the soil beyond the electrolyte effect.

In the PAM treatments the effect of TW was more pronounced than that in the untreated soil. Whereas in the untreated soil TW increased cumulative infiltration from 12.3 mm in DW to 16.8 in the PAM treatment, cumulative infiltration in DW was 23.0 mm and in TW 56.2 mm. As the concentration of electrolyte in TW exceeds the flocculation value of the clay, the polymer acts efficiently as a cementing agent which stabilizes



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the soil aggregates, prevents seal formation and maintains high IR values. It should be noted that in the PAM treatment, the effects of TW rain were quite similar to those of PG treatments. The small differences may be due to the fact that in the PG treatments the predominant cation in the soil solution is $Ca^{2+}$, whereas in TW $Na^{+}$ and $Ca^{2+}$ cations are present in similar concentrations.

The flocculation effect of the electrolytes in the TW suggests that only under natural rainstorms must PG be applied to soil treated with PAM to ensure stabilization of the soil aggregates. When irrigation water is applied by sprinklers, PAM alone will prevent seal formation and will be effective in maintaining high water penetration. The IR of the grumusol as a function of cumulative rain is presented in Figure 3. The following should be noted:

i) The grumusol is less dispersive than the loess. Whereas the final IR of the loess dropped to 2.0 $mm.h^{-1}$ and the cumulative infiltration was only 12.3 mm, the final IR of the grumusol was 3.0 $mm.h^{-1}$ and the IR dropped more gradually with cumulative infiltration of 21.9 mm. The higher percentage of clay, which acts as cementing material, stabilizes the aggregates at the soil surface of the grumusol and slows their breakdown and, therefore, the formation of a seal at the soil surface. Also, the ESP of the grumusol is lower than that of the loess (Table 1).

[INSERT FIG.3 HERE]

ii) The beneficial effect of PG on the IR of the grumusol is not as pronounced as in the loess. The lower ESP of the grumusol, compared with the loess, may account for the low response of this soil to PG application (Katzman *et al.*,1983).



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iii) PAM, applied at a rate of 20 $kg.ha^{-1}$ and following complete drying, was quite efficient in stabilizing the soil aggregates at the soil surface and preventing sealing. PAM increased the final IR of the grumusol to 12.7 $mm.h^{-1}$ and the cumulative infiltration to 42.1 mm. When PAM was applied with PG its beneficial effect was much more pronounced: PAM + PG increased the final IR of the soil to 24.1 $mm.h^{-1}$ and the cumulative infiltration to 63.4 mm. It is evident that treating the soil with a combination of PAM and PG produces the best results. For a soil conditioner to be effective, the soil clays must continue to be flocculated. PG dissolution supplies to the rain water the electrolytes which are needed to flocculate the clay.

Effect of consecutive storms

The amount of rain during a rainy season may exceed 80 mm but the rain is not continuous and there are dry periods between rainstorms. Thus the question arises as to the effect of more rain and of dry intervals between rainstorms on the efficiency of PAM as an amendment? The effect of drying for periods of 24 h, 6 and 11 days on the crust and IR was studied by Morin and Benyamini (1977). They found that the drying periods increased the initial IR, but had no effect on the final IR. Their explanation was that the increase in the initial IR's in the second storm was due to crack formation in the crust. A drying period of 7 days was enough to break the crust completely. Thus this interval was used in this study. The effect of the second and third consecutive storms of 60 mm each on the efficiency of PG and PAM treatments in maintaining high IR is shown in Fig.4 (a & b, respectively). The final IR and the percentage of runoff in the control treatments were similar in the three storms (84.6, 80.7 and 83.8% in the first, second and third storms, respectively).



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[INSERT FIG.4]

In the PG treatments, the final IR at the end of the first, second and third storms was 6.8, 6.4 and 5.9 $mm.h^{-1}$, respectively. Similarly the percentage of runoff in the three storms was 60.4, 67.7 and 72.6, respectively. PG, spread at a rate of 5 $ton.ha^{-1}$, continued to be effective throughout the 3 storms (200 mm rain). In a saturated solution the concentration of gypsum is 2 $g.l^{-1}$. In the rain studies only 50% saturation was obtained, thus 200 mm rain dissolved ~2 $ton.ha^{-1}$ and the PG was still present in sufficient quantities to be beneficial.

The final IR in the PAM treatments (w/o PG) stayed the same in the first, second and third storms. The runoff increased slightly in the three consecutive storms. It seems that the PAM only treatment maintained its stabilization effects throughout the three storms.

The final IR of the PAM+PG treatments dropped from 23.3 $mm.h^{-1}$ in the first storm to 14.0 and 8 $mm.h^{-1}$ in the second and third storms, respectively. Similarly the runoff was 18.8, 39.4 and 58.0% for the three storms, respectively. It is evident that PAM in the PAM+PG treatment loses its effectiveness. Nevertheless, the percentage of the rainfall that penetrated the soil in the third storm was still three times that in the control.

## CONCLUSIONS

The effect of application of dilute solutions of PAM at 20 $kg.ha^{-1}$ on the infiltration rate, runoff and erosion of non-stable soils was very beneficial. Drying of the polymer-soil surface and maintaining the electrolyte concentration in the soil solution, which flocculates the soil



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clays, enhance the binding action of the polymer and stabilize the aggregates at the surface. PAM treatments at the optimal rate increased rain intake in the two soils by three to fourfold. Since soils from semi-arid regions are unstable and form seals which lead to 50% runoff during the rainy season, the possibility of reducing runoff by PAM treatment to only 10-15% of the rain at a cost of $100 per ha should be studied further.

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Table 1: Some physical and chemical properties of the soils used.

| Soil | Classification | Particle size distribution | | | $CaCO_3$ | CEC | ESP |
|---|---|---|---|---|---|---|---|
| | | sand | silt | clay | | | |
| | | ----------%---------- | | | | $cmol_c kg^{-1}$ | % |
| Loess, Bet Qama | Calcic Haploxeralf | 50.0 | 31.0 | 19.0 | 11.0 | 14.5 | 5.0 |
| Grumusol, Sede Yoav | Typic Chromoxerert | 32.0 | 28.0 | 40.0 | 10.4 | 29.5 | 2.5 |

Figure Legend

Fig. 1: Infiltration rate of loess as a function of cumulative rainfall, the level of PAM application (10, 20 and 40 $kg.ha^{-1}$) in the control and phosphogypsum, PG (5 $ton.ha^{-1}$) treatments.

Fig. 2: Infiltration rate of loess treated with 20 $kg.ha^{-1}$ PAM as a function of cumulative rainfall, the drying treatments of PAM (a) and the electrolyte concentration in the applied water (TW = tap water and DW = distilled water); (b) PG represents treatment with phosphogypsum at 5 $ton.ha^{-1}$, PAM represents treatment with polyacrylamide polymers at 20 $kg.ha^{-1}$.

Fig. 3. Infiltration rate of grumusol as a function of cumulative rainfall, phosphogypsum treatment (PG, at 5 $ton.ha^{-1}$, and PAM application (at 20 $kg.ha^{-1}$).

Fig. 4: Infiltration rate of loess as a function of cumulative rainfall for the second (a) and third (b) consecutive storms. PAM represents treatment with PAM at 20 $kg.ha^{-1}$ and PG represents treatment with phosphogypsum at 5 $ton.ha^{-1}$.

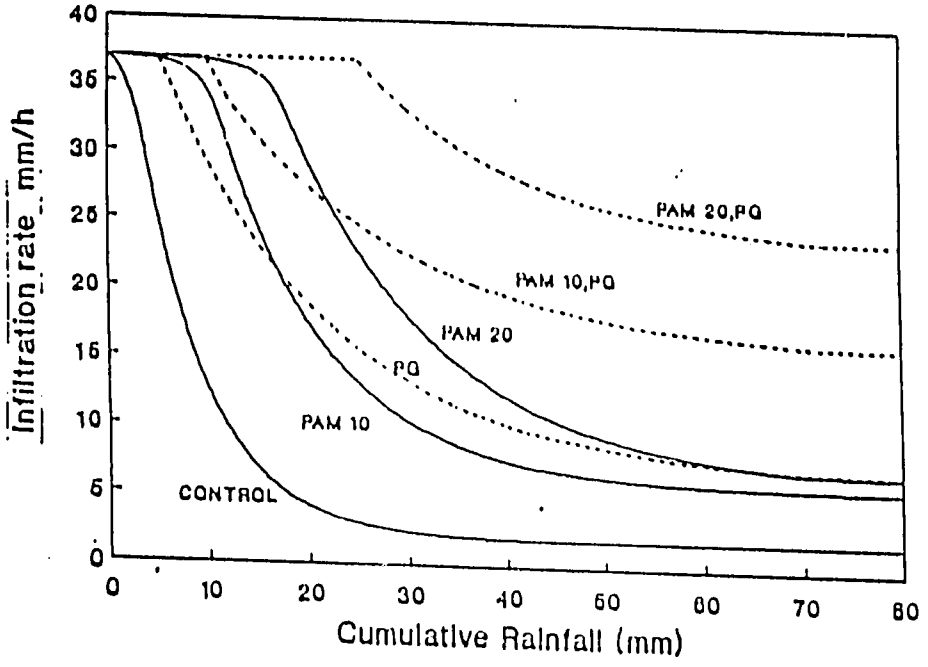
Infiltration rate mm/h
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
Cumulative Rainfall (mm)
PAM 20,PQ
PAM 10,PQ
PAM 20
PQ
PAM 10
CONTROL

Fig.1

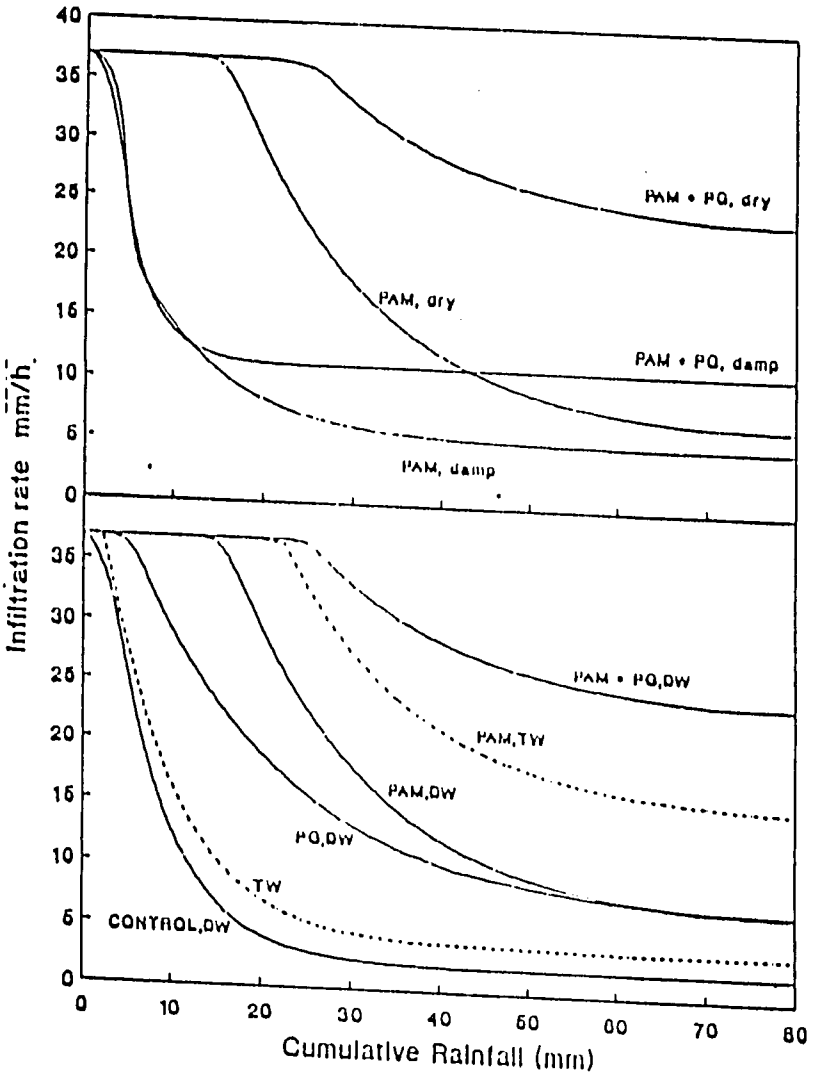
Infiltration rate mm/h
Cumulative Rainfall (mm)
PAM • PQ, dry
PAM, dry
PAM • PQ, damp
PAM, damp
PAM • PQ,DW
PAM,TW
PAM,DW
PQ,DW
TW
CONTROL,DW
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80

Fig.2

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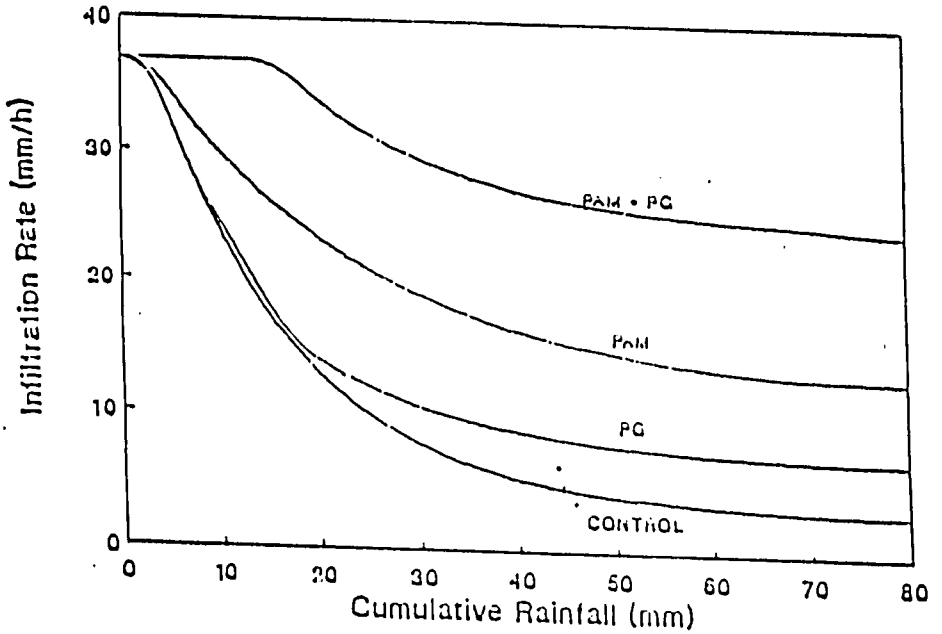
Infiltration Rate (mm/h)
40
30
20
10
0
PAM • PG
PAM
PG
CONTROL
0
10
20
30
40
50
60
70
80
Cumulative Rainfall (mm)

Fig.3

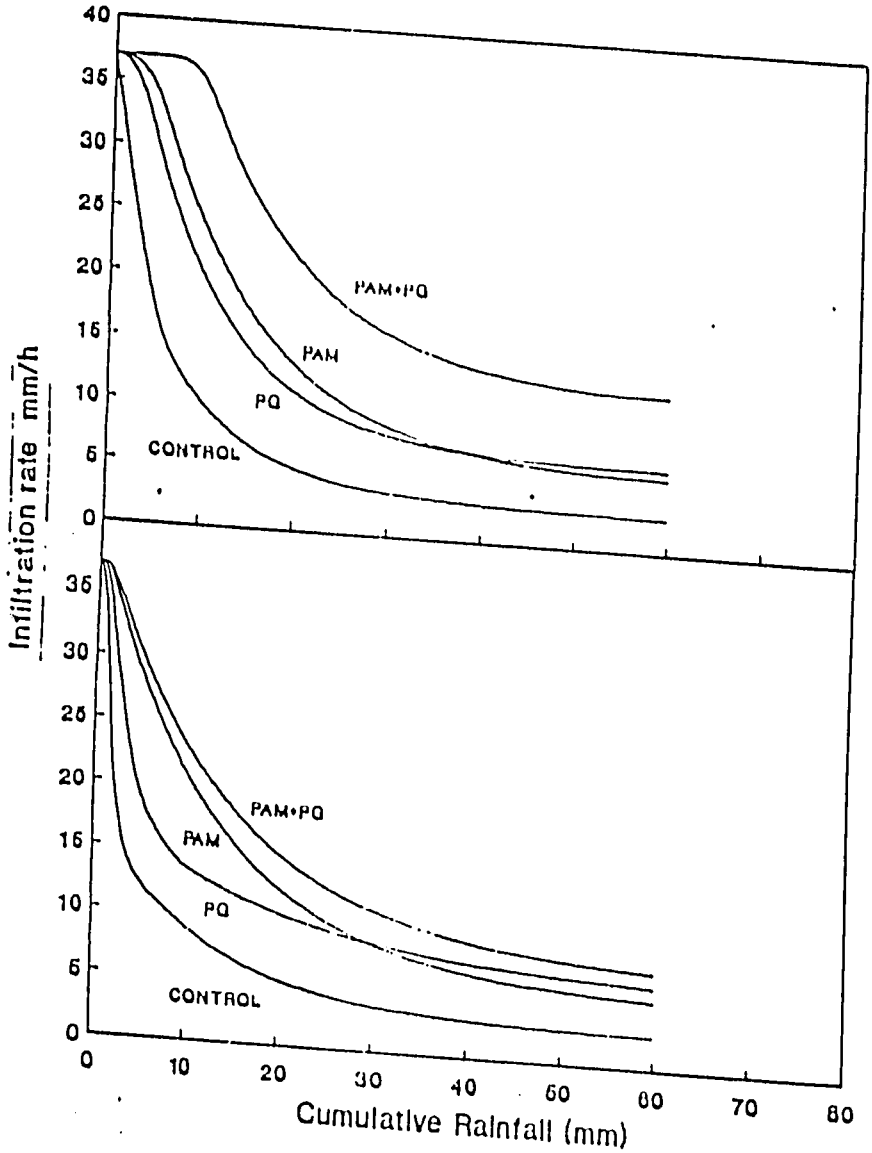
Infiltration rate mm/h
Cumulative Rainfall (mm)
PAM•PQ
PAM
PQ
CONTROL
PAM•PQ
PAM
PQ
CONTROL
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80

Fig.4