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SEASON AND EROSION PAVEMENT INFLUENCE ON SATURATED SOIL HYDRAULIC CONDUCTIVITY

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Soil infiltration controls the partitioning of rainfall into surface runoff, groundwater recharge, and soil moisture. Understanding seasonal variability and the influence of soil erosion pavement on infiltration is critical to increasing our ability to predict runoff. Our objective was to evaluate seasonal variability in infiltration and the importance of erosion pavement. A tension disc permeameter was used to measure infiltration seasonally for 3 years with soil erosion pavement in place and for up to 1 year after the pavement was removed. Seasonal and erosion pavement effects were evaluated using saturated hydraulic conductivity, flow-weighted characteristic pore size, and macropore capillary length data. There was a significant season-by-year interaction for conductivity with the erosion pavement in place. Conductivity was substantially lower in the fall season, whereas the rates were similar for the other seasons. Differences in years within seasons were also observed. The calculated soil pore structural components of size and length could not account for the seasonal changes in conductivity. The pore size and length remained comparatively constant for the seasons and years. To account for the low fall hydraulic conductivity, it was concluded that raindrop impact from the high intensity summer thunderstorms closed some pores or interconnections. Freeze-thaw cycles from late fall through spring apparently opened the pores, resulting in increases in conductivity. Soil erosion pavement removal caused an immediate significant decrease in hydraulic conductivity and pore size and an increase in pore length that lasted longer than a year. Results indicate that soil erosion pavement is important in maintaining soil surface structural integrity to maintain the higher conductivity. Disc permeameter measurements were clearly able to show seasonal and erosion pavement influences on soil conductivity and that soil erosion pavement must be incorporated into hydraulic runoff models to improve predictions. (Soil Science 2003;Volume 168:637–645)

Key words: Disc permeameter, temporal variability, pore size.

INFILTRATION is the process of water moving into the soil through the soil surface. In the hydrological cycle, infiltration capacity determines the amount of rainfall partitioned into surface runoff, subsurface drainage, groundwater recharge, and soil moisture. Spatial and temporal variability in infiltration makes the process difficult to understand and measure. Determining the factors that cause the variability is essential to infiltration evaluation.

Evaluations of spatial and temporal changes in infiltration have been directed primarily toward agricultural soils because they receive soil surface manipulation, which changes surface structure. Manipulations from tillage and wheel traffic produce significant spatial and temporal changes in infiltration (Ankeny et al., 1990; Logsdon and Jaynes, 1996; Angulo-Jaramillo et al., 1997). In rangeland environments, there is minimal soil surface manipulation except from grazing animals. Grazing generally decreases infiltration through changes in soil surface structure and density (Achouri and Gifford, 1984). Other fac-

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tors on rangelands that can cause spatial and temporal changes in infiltration are vegetation, freeze-thaw cycles, biological soil crusts, and soil surface rock distribution (Richardson, 1976; Dadkhah and Gifford, 1980; Lavee and Poesen, 1991; Blackburn et al., 1992; Lehrsch, 1998; Kuske, et al., 2002).

Vegetation has significant influence on the spatial distribution of infiltration. It creates a microtopography that has an infiltration gradient with distance from the plants (Lyford and Qashu, 1969; Dunne et al., 1991). The interspace area between plants has a lower infiltration rate; hence, it is the area that initiates surface runoff. Soil microorganisms that form biological soil crusts have been found to be more dominant in the interspace areas of an arid grassland and, therefore, could contribute to an increase in runoff from interspace areas (Kuske, et al., 2002). In some soils, freeze-thaw cycles have been shown to have little effect (Bisal and Nielsen, 1964) on increasing soil aggregate stability after only one or two cycles (Richardson, 1976; Lehrsch, 1998). These and other factors have produced measurable seasonal and spatial differences in infiltration (Emmerich and Cox, 1992; Asare et al., 1993; Cerdà, 1997, 1999), but information regarding the changes that cause the variability in infiltration is limited.

Rock fragments in soils have received some attention as a result of their importance in surface runoff and erosion (Roy and Jarrett, 1991; Poesen and Ingelmo-Sanchez, 1992). Their presence can change soil hydraulic conductivity, depending on their amount and location in the soil profile (Mehuys et al., 1975; Brakensiek et al., 1986). Rock fragments cause erosion pavement to form at the soil surface as erosion removes the smaller soil particles. The placement of the erosion pavement on the soil surface can either increase or decrease runoff and sediment yield (Poesen, 1986; Poesen and Ingelmo-Sanchez, 1992). Erosion pavement sitting on the soil surface decreases runoff and sediment production, implying increased soil hydraulic conductivity, whereas pavement embedded in the soil increases runoff and sediment. Erosion pavement likely acts in the same way as vegetation to protect the soil surface physically from raindrop impact. Vegetation removal in a semiarid environment has increased runoff, soil loss, and bulk density and decreased organic carbon at the soil surface with the possibility of irreversible soil degradation (Castillo et al., 1997). With soils containing rock fragments, erosion pavement could be as important as vegetation in maintaining soil surface structural integrity. Information about the role erosion pavement plays in sustaining soil hydraulic conductivity is essential for hydraulic modeling and maintaining ecosystem stability.

It is important that we understand how infiltration partitions rainfall on rangelands throughout the year to incorporate this information into flood and runoff model predictions. The factors that cause temporal variability in infiltration and the role erosion pavement plays in the soil surface structural integrity for infiltration are largely unknown. A disc permeameter can measure hydraulic conductivity in the critical interspace areas between vegetation that initiates surface runoff, and the interspace areas should have the least spatial variability on the landscape. By selecting interspace areas to minimize spatial variability in the measurements, temporal variability can be better evaluated. The inevitable spatial variability in the measurements will have to be overcome in the data to show any temporal variability. Soil surface structural components of capillary length and flow-weighted characteristic pore size can be estimated from disc permeameter measurements (Perroux and White, 1988). By making multiple season-year disc permeameter measurements with and without erosion pavement, temporal variability in infiltration and the importance of the erosion pavement can be assessed. The objective of this study was to evaluate temporal variability in soil hydraulic conductivity and to assess the importance of erosion pavement on soil hydraulic conductivity.

MATERIALS AND METHODS

The study was conducted on the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone in Southeastern Arizona. Western Regional Climate Center long-term (i.e., 1893–2001) temperature data indicates that Tombstone, Arizona, has had a temperature of less than −1 °C on days from Nov. 1 through April 30 and an all time low of −15 °C (http://www.wrcc.dri.edu). The soil is a Stronghold (course-loamy, mixed, thermic Ustollic Calciorthid) with 68% sand, 15% silt, 17% clay, and 50% gravel in the surface horizon. The study site slope was 1%. Dominant vegetation consists of creosote bush (*Larrea tridentata* (Sesse & Mocino ex DC.)), whitethorn (*Acacia constricta*), tarbush (*Flourensia Cernua* DC.), and bear grass (*Xerophyllum tenax*). The elevation is 1475 m, and mean annual rainfall is 275 mm, with 65% coming as high intensity summer thunderstorms (Renard et al., 1993).

Two hundred sixteen infiltration measurement plots (0.5 m × 0.5 m) were designated in the interspace area of the vegetation within a plot of 100 m × 50 m. The measurement plots were chosen to have minimal slope, uniform erosion pavement on the surface, and equal distance from vegetation. Hydraulic conductivity measurements for controls and treatments were made each season, starting in the summer season, on six randomly selected measurement plots. Because of the small number of measurements (six) and expected large variability in the measurements, any statistically significant differences found would be truly significant. An outline of when infiltration measurements were made is given in Table 1. The treatments were: (i) with the erosion pavement in place (control); (ii) with erosion pavement removed, present season; (iii) with erosion pavement removed, previous season, and (iv) with erosion pavement removed, previous year. The erosion pavement was removed from the measurement plot by gently picking up and removing rock fragments >5 mm in size from the soil surface. The hydraulic conductivity measurements and erosion pavement removal treatments were repeated for a second year on new measurement plots. Each time hydraulic conductivity measurements were made, control treatment measurements were included. At the end of the measurements, there were 3 years of seasonal measurements for the control treatment and 2 years of seasonal measurements for the sequence of erosion pavement removal treatments. The summer season measurements were made before the summer thunderstorms, which occur mid-July through September.

Infiltration measurements were made using a 200-mm-diameter negative pressure (i.e., tension) disc permeameter (Perroux and White, 1988). Measurements were made at multiple negative pressures (−100, −70, −50, −30, and −10 mm) at the same location, in sequence, starting at −100 mm tension until steady state was observed at each tension (Ankeny et al., 1991). A 10-mm-thick sand cap was used for all measurements to ensure good contact between the soil and disc. Steady state was considered achieved when the time for a specific volume of water to enter the soil remained constant for four time periods. Antecedent soil moisture, especially when the soil was very dry, can have an impact on the measurements reaching steady state. Close attention was paid to reaching steady state, especially for dry conditions, with time to steady state taking up to 5 h. From the steady state measurements, hydraulic conductivity was calculated using a method of multiple tensions (Hussen and Warrick, 1993). For steady state infiltration from a circular pond, the Wooding (1968) equation is

$$Q = \pi r^2 K \,[1 + 4\lambda_c/\pi r], \qquad (1)$$

where Q is steady state flow rate, r is radius of the disc permeameter, K is hydraulic conductivity at supply water potential, and λ_c is macropore capillary length. The relationship (Gardner, 1958)

$$K = K_s \exp\,(\alpha h) \qquad (2)$$

TABLE 1

Outline of the season and year infiltration measurements were made for control and erosion pavement removed treatments

Season	Control	Season and year pavement removed		
			1994	
Summer	Control	Summer-94		
Fall	Control	Fall-94	Summer-94	
			1995	
Winter	Control	Winter-95	Fall-94	
Spring	Control	Spring-95	Winter-95	
Summer	Control	Summer-95	Spring-95	Summer-94
Fall	Control	Fall-95	Summer-95	Fall-94
			1996	
Winter	Control	Winter-96	Fall-95	Winter-95
Spring	Control	Spring-96	Winter-96	Spring-95
Summer	Control	Spring-96	Summer-95	
Fall	Control	Fall-95		
			1997	
Winter	Control	Winter-96		
Spring	Control	Spring-96		

is assumed with the matric potential h expressed as a length. K_s is the saturated hydraulic conductivity and α is a constant equivalent to λ_c^{-1}. Equations 1 and 2 can be combined, where

$$Q/\pi r^2 = K_s \exp(\alpha h)\,[1 + 4/\pi\alpha r]. \quad (3)$$

Steady state measurements for n tensions at the same location yield n equations, each with two unknowns of K_s and α. The best fit for K_s and α was found for Eq. (3) using steady state flow measurements at different tensions (Hussen and Warrick, 1993). A nonlinear optimization fitting program was used to minimize the mean square error between measured data and data modeled with Eq. (3). K_s was corrected to a temperature of 20 °C to account for changes in viscosity and density of water during the seasons. Temperature of the water was an average of the start and end of each infiltration measurement. Hydraulic conductivity K_s was considered to have two components, intrinsic permeability of the soil, k, and fluidity of the fluid, f, where

$$K_s = kf. \quad (4)$$

Fluidity is inversely proportional to viscosity

$$f = \rho g/\nu \quad (5)$$

where ν is the viscosity, ρ is the fluid density, and g is the gravitational acceleration. Intrinsic permeability was calculated from Eq. (4) using the K_s measured from Eq. (3) and the f from Eq. (5) for the temperature at which the measurements were made. K_s at 20 °C was calculated from Eq. (4) using f at 20 °C and the calculated k value inasmuch as k was considered temperature independent.

In addition, the macropore capillary length (λ_c) was calculated by

$$\lambda_c = \alpha^{-1}. \quad (6)$$

Philip (1987) has shown that λ_c is related to flow-weighted characteristic pore size (λ_m) by

$$\lambda_m = 7.4/\lambda_c, \quad (7)$$

where λ_c and λ_m are shown in millimeters.

Analysis of variance procedures were used to test the main effects of season and year (SAS Institute, 1998). Levene's test was used to test for homogeneity of variance. Variance heterogeneity was handled with log and square root transformations of the data before analysis and converted back for presentation. The 3 years of control data were used to test the effects of season and year. Control minus the erosion pavement-removed treatment data were used to remove any naturally occurring variability in main effects when evaluating erosion pavement removal treatments. These difference data were also used to test the control against the treatments by determining if the difference was greater than zero. A 0.05 probability level was considered significant for main effects, and separation of main and treatment effects was determined using an exceedingly conservative method of non-overlap of the 95% confidence intervals (Jones, 1984).

RESULTS AND DISCUSSION

Control Analysis

Analysis of variance of the control data indicated a significant interaction between season and year for saturated hydraulic conductivity (Table 2). The capillary length and pore size were not significantly influenced by season and/or year. The hydraulic conductivity data were separated by season and year for analysis because of the interaction. Season and year were found to be significant influences on soil hydraulic conductivity (Table 3). The fall season consistently had lower hydraulic conductivity than the other seasons, with the other seasons generally similar in conductivity values (Fig. 1). The significant year effects within season was not the same for each season (Table 3). Observed seasonal and yearly changes in conductivity in the literature have been related to impacts at the soil surface (Achouri and Gifford, 1984; Starr, 1990; Thurow et al., 1993; Logsdon and Jaynes, 1996). Impacts include grazing, plant growth, tillage, and vehicle traffic. These impacts cause physical changes to the soil structure primarily as alterations to soil bulk density. In this study, soil structure was not

TABLE 2

Control data analysis of variance significance values for macropore capillary length, flow weighted characteristic pore size, and saturated hydraulic conductivity

Source	Capillary length	Pore size	Hydraulic conductivity
Replication	0.55	0.51	0.88
Season	0.35	0.38	<0.001
Year	0.18	0.17	0.19
Season:Year	0.08	0.13	0.01

TABLE 3

Average control saturated hydraulic conductivity by season for each year (mm/hr) (n=6)

Year	Summer	Fall	Winter	Spring
1994–95	177a[†*‡]	74b*	159a	103ab
	(70)[§]	(17)	(66)	(50)
1995–96	112a	39b*	141a	107a*
	(39)	(14)	(59)	(15)
1996–97	74ac*	69a	143bc	155b*
	(26)	(18)	(53)	(18)

[†] Values followed by the same letter within year are not significantly different by overlap of 95% confidence interval.

[‡] Values followed by * within season are significantly different by non-overlap of 95% confidence interval.

[§] 95% confidence interval.

TABLE 4

Average control data flow weighted characteristic pore size by season for each year (mm) (n=6)

Year	Summer	Fall	Winter	Spring
1994–95	0.389	0.328*[†]	0.318	0.234
	(0.097)[‡]	(0.076)	(0.075)	(0.102)
1995–96	0.270	0.196*	0.285	0.285
	(0.078)	(0.037)	(0.080)	(0.083)
1996–97	0.263	0.238	0.324	0.349
	(0.098)	(0.089)	(0.157)	(0.066)

[†] Values followed by * within season are significantly different by non-overlap of 95% confidence interval.

[‡] 95% confidence interval.

manipulated by similar external forces, and plant growth would have minimal effect on soil structure in the interspace areas where measurements were made.

Physical forces on the soil during the course of this study were primarily rain drop impact and freeze-thaw cycles. Rainfall simulation studies have shown that as the rainfall intensity increases, the time to ponding decreases with surface sealing (Ragab, 1983). The high intensity summer thunderstorms beat the soil surface and apparently closed or sealed some of the soil pores producing the observed decrease in fall season hydraulic conductivity (Fig. 1). Evidence for soil pore closure or loss of pore interconnection from the thunderstorms, rather than filling of soil pores, was found in the flow weighted characteristic pore size and macropore capillary length data (Tables 4 and 5). The pore sizes and lengths remained relatively constant for the seasons and years. A partial filling of the soil pores by raindrop impact on the surface would have caused a decrease in size and an increase in length. To account for the decrease in hydraulic conductivity with constant pore sizes and lengths, there must have been a change in the number of pores and/or the interconnection of the pores. The energy from the high intensity summer thunderstorms resulting in particle dislocation closed soil pores or formed a crust, reducing the number of pores available for infiltration (Ragab, 1983; Smith et al., 1990), or blocked pore interconnections (Angulo-Jaramillo et al., 1997).

The higher hydraulic conductivities for the winter season, and continuing through to the summer measurements, were attributed to freeze-thaw cycles occurring after the fall measurements and continuing to the spring (Table 3). Water content of the soil at the time of freezing dictates the amount of soil particle movement (Bullock et al., 1988). Freeze-thaw cycles can disrupt soil crusts and aggregate stability or increase aggregate stability (Bullock, et al., 1988; Lehrsch, 1998). Lehrsch (1998) showed significant increases in aggregate stability with two to three

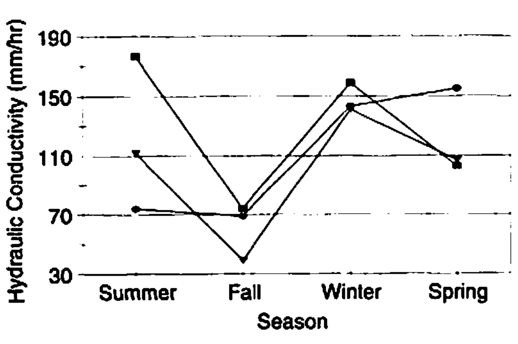

Fig. 1. Average seasonal hydraulic conductivity for 3 years with erosion pavement in place (■ 1994–1995, ▼ 1995–1996, ● 1996–1997) (*n* = 6).

TABLE 5

Average control data macropore capillary length by season for each year (mm) (n=6)

Year	Summer	Fall	Winter	Spring
1994–95	20.3	24.2*[†]	24.8	37.6
	(4.9)[‡]	(5.7)	(5.7)	(14.7)
1995–96	30.5	39.2*	28.4	28.4
	(8.8)	(7.1)	(7.9)	(7.8)
1996–97	32.7	37.2	27.4	22.1
	(11.5)	(13.7)	(10.0)	(4.0)

[†] Values followed by * within season are significantly different by non-overlap of 95% confidence interval.

[‡] 95% confidence interval.

freeze-thaw cycles in three soils. During most winter and spring measurement times, evidence of frost heaving was observed in the top centimeters of soil. The freeze-thaw cycles probably opened some of the pores or connections to produce the observed increase in hydraulic conductivity in the winter (Fig. 1).

Angulo-Jaramillo et al. (1997) studied a similar coarse textured soil through a growing season in France utilizing disc permeameter measurements. The soil was moldboard plowed and irrigated using a high-pressure gun. The mean soil pore size remained unchanged, as it did in this study (Table 4), from before plowing to harvest of the maize crop. They concluded that the coarse material at the soil surface formed a rigid skeleton that kept a relatively constant pore size through the growing season. The observed loss of conductivity by harvest time was attributed to the fine fraction soil particle changes in structural pattern from an interconnected porous network to a less connected one. The same situation may have occurred in this study, with the freeze-thaw cycles reconnecting the porous network to regain the higher hydraulic conductivity in the winter (Fig. 1).

Some significant differences in hydraulic conductivity were found between years for three of the seasons (Table 3). The differences are believed to be the result of yearly variations in rainfall events and freeze-thaw cycles. For example, in late spring 1996 there was a 65-mm rainfall event, typical of summer events, that occurred after the spring and before the summer measurements. It is believed that this event lowered the summer conductivity measurements, causing a year effect in the summer season between years 1994–95 and 1996–97 (Table 3). It would be unlikely in late spring for a freeze-thaw cycle to occur and open soil pores. The variability in the conductivity data and the year effects were attributed to the sequences of rainfall events and freeze-thaw cycles.

Erosion Pavement Analysis

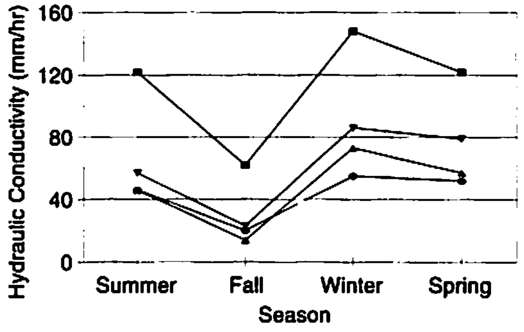

Fig. 2. Average seasonal hydraulic conductivity for erosion pavement present (■) (n = 18), pavement removed present season (▼), removed previous season (●), removed previous year (●) (others n = 12).

Removal of the erosion pavement was expected to have an effect on the hydraulic conductivity, flow-weighted characteristic pore size, and macropore capillary length. The control minus the treatment data was significantly different than zero, indicating that the control was different from all other treatments for hydraulic conductivity and pore size and length. The control hydraulic conductivity was consistently greater than that of all other treatments (Fig. 2). Analysis of the control minus the treatment data indicated there were no season, year, or treatment effects. Once the erosion pavement was removed, the soil hydraulic conductivity decreased immediately and remained lower for at least 1 year. The soil conductivity of the treatments still followed the same seasonal changes as the control, with the lowest conductivity in the fall. The erosion pavement was important in maintaining the soil hydraulic conductivity as its removal caused an immediate and continuous change in conductivity.

The control flow-weighted characteristic pore size was significantly greater than the pore size for all other treatments (Fig. 3). The control minus pavement removal treatment data for pore size had no season, year, or treatment effects. The removal of the erosion pavement caused the pore size to decrease and remain smaller for at least 1 year. The decrease in pore size would cause and

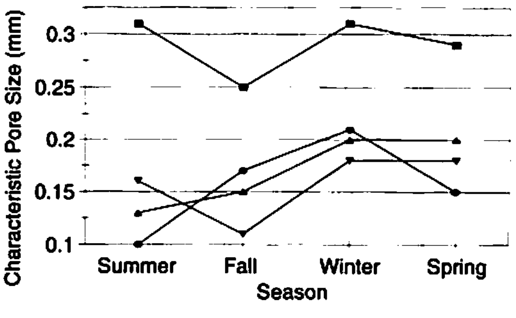

Fig. 3. Average seasonal flow weighted characteristic pore size for erosion pavement present (■) (n = 18), pavement removed present season (▼), removed previous season (●), removed previous year (▲) (others n = 12).

explain the observed decrease in hydraulic conductivity (Fig. 2). Erosion pavement was important in maintaining the larger pore size and higher hydraulic conductivity. The mean pore size tended to be larger in the winter, as was the conductivity (Figs. 2 and 3). The increase in pore size in the winter season was not as dramatic as the increase in control hydraulic conductivity (Figs. 1 and 3), but some of the winter freeze-thaw cycles could have made some of the pores larger on the erosion pavement removed treatments.

Macropore capillary length was significantly less for the control than for all other erosion pavement removal treatments (Fig. 4). The immediate and continual change in pore length indicates that the erosion pavement was important in maintaining the capillary length. The control minus erosion pavement removal data analysis had significant season-by-treatment and season-by-year interactions. The pore length data were then separated for analysis by season and treatment and by season and year. In general, capillary length tended to be smaller in winter. However, there were no consistent differences between seasons within treatments (Table 6). Within seasons, there were no differences in pore length for the treatments. For the season-by-year interaction, year 1996 had differences within seasons, with winter again having the smallest length, and there were no differences between years (Table 7). The significant differences for pore length with season, treatment, and year were most likely related to the timing of freeze-thaw cycles, as with the control hydraulic conductivity.

TABLE 6

Average control minus erosion pavement removed treatment data for macropore capillary length by season and treatment (mm) (n=12)

Treatment	Summer	Fall	Winter	Spring
Present Season	−28ac[†]	−38a	−19bc	−13bc
	(21)[‡]	(12)	(7)	(13)
Previous Season	−50a	−35a	−12b	−21ab
	(21)	(12)	(7)	(13)
Previous Year	−42a	−18ab	−11b	−15ab
	(21)	(12)	(7)	(13)

[†] Values followed by the same letter within treatment are not significantly different by non-overlap of 95% confidence interval.

[‡] 95% confidence interval.

The immediate change in soil hydraulic conductivity, flow-weighted characteristic pore size, and macropore capillary length by the removal of the erosion pavement indicated the importance of the pavement in maintaining soil surface structural integrity. Just the removal of the erosion pavement was enough to change the soil surface structure. The change lasted longer than 1 year, implying that the soil structural changes, as measured by the pore size and length, were significant and not easily reversible. The time to recover the original soil hydraulic conductivity could be as long as it takes to restore the soil erosion pavement. Soil erosion to expose new rock fragments for soil surface protection from raindrop impact and freeze-thaw cycles to open up the soil pores would probably be needed to return the hydraulic conductivity to previous rates.

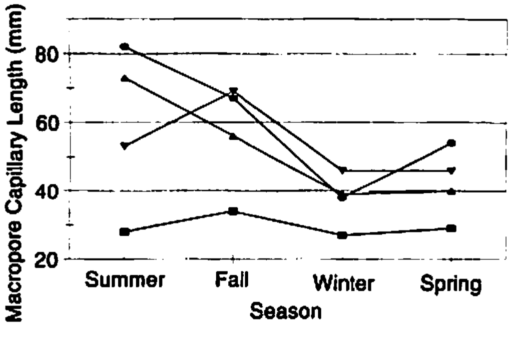

Fig. 4. Average seasonal macropore capillary length for erosion pavement present (■) (n = 18), pavement removed present season (▼), removed previous season (●), removed previous year (▲) (others n = 12).

SUMMARY AND CONCLUSIONS

Soil hydraulic conductivity was significantly lower in the fall season for the control measurements with the erosion pavement in place. The calculated flow-weighted characteristic pore size and macropore capillary length remained rela-

TABLE 7

Average control minus erosion pavement removed treatment data for macropore capillary length by season and year (mm) (n=18)

Year	Summer	Fall	Winter	Spring
1995	−25a[†]	−31a	−17a	−14a
	(19)[‡]	(10)	(6)	(13)
1996	−55a	−29ac	−10b	−18bc
	(19)	(10)	(6)	(13)

[†] Values followed by the same letter within year are not significantly different by non-overlap of 95% confidence interval.

[‡] 95% confidence interval.

tively constant for the controls during the 3 years; therefore, the seasonal changes in hydraulic conductivity could not be explained by the pore size and length. The observed reduction in hydraulic conductivity in the fall season was attributed to pore closure or decrease in interconnectivity. The removal of erosion pavement immediately changed the soil surface structure, causing a decrease in hydraulic conductivity and pore size and an increase in pore length. Results showed that the erosion pavement was instrumental in maintaining soil surface structure and its removal effects lasted longer than a year.

The disc permeameter measurements showed the influence of season and erosion pavement on soil hydraulic conductivity clearly, but they were not able to give measurements that could be incorporated directly into runoff models. The lowest calculated saturated hydraulic conductivity was greater than most rainfall intensities. With observed runoff at much lower rainfall intensities, the disc permeameter overestimated rainfall hydraulic conductivity. Cerdà (1996) found that a cylinder infiltrometer overestimated infiltration 8 times more than simulated rainfall at 55 mm h^{-1}. To fully utilize the disc permeameter measurements to improve runoff model predictions, a functional relationship will have to be developed. This is the next research challenge: to take the easily made tension infiltrometer measurements and relate them to rainfall hydraulic conductivities.

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