0038-075X/07/17210-770–789
Soil Science

October 2007
Vol. 172, No. 10
Printed in U.S.A.

SEDIMENT AND POLYACRYLAMIDE EFFECTS ON SEEPAGE FROM CHANNELED FLOWS

Rodrick D. Lentz and Larry L. Freeborn

Seepage from water streams into unlined channels determines the proportion of water distributed to adjacent soil for plant use or soil or groundwater recharge or conveyed to downstream reaches. We conducted a laboratory study to determine how sediment type (none, clay, and silt), sediment concentration (0, 0.5, and 2 g L^{-1}), and water-soluble anionic polyacrylamide (PAM) concentration (0, 0.4, and 2 mg L^{-1}) influences seepage loss of irrigation water (electrical conductivity = 0.04 S m^{-1}; sodium adsorption ratio = 2.2) from unlined channels in silt loam soil. In a miniflume, a preformed channel with 7% slope was supplied with 40 mL min^{-1} simulated irrigation water inflows containing the different treatment combinations. Runoff and seepage rates and runoff sediment were monitored for 24 h. Average 23-h cumulative seepage loss was 11.8 L for silt-loaded inflows, 2.8 L for clay-loaded inflows, and 6.4 L for flows without sediment. Increasing inflow clay concentrations, 0, 0.5, and 2 g L^{-1} clay, decreased cumulative seepage volume (23 h) for the no-PAM treatment from 12.4 L to 6.7 and 0.2 L, respectively. Increasing inflow silt concentrations in no-PAM treatments resulted in a curvilinear response with a seepage volume maximum occurring for the 0.5-g L^{-1} treatment (12.4, 47.1, and 9.8 L, respectively). Increasing inflow PAM concentrations increased seepage volumes for 2-g L^{-1} silt and 2-g L^{-1} clay treatments but decreased seepage for the 0.5-g L^{-1} silt treatment. Seepage losses from these unlined channels can be significantly altered relative to untreated controls by manipulating the sediment particle size and concentration and PAM concentration of irrigation water inflows. Their effects on induced seepage changes are complex, strongly controlled by factor interactions, and appear to involve a number of mechanisms. (Soil Science 2007;172:770–789)

Key words: Silt loam, PAM, infiltration, drainage water, sedimentation, surface seal.

INFILTRATION processes in channeled water flows are important because they determine the amount of water that seeps into adjacent soil or, conversely, the amount that is conveyed downstream. Increasing infiltration or seepage from channels is often desirable when one is supplying crops from furrows or recharging the groundwater aquifer. On the other hand, if the goal is simply to convey water between locations, it is advantageous to decrease seepage loss from unlined channels.

Northwest Irrigation and Soils Research Laboratory, 3793 N. 3600 E., Kimberly, ID 83341-5076. Dr. Lentz is corresponding author. E-mail: lentz@nwisrl.ars.usda.gov

Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA-ARS.

Received Dec. 21, 2006; accepted May 7, 2007.
DOI: 10.1097/ss.0b013e3180de4a33

The presence of sediment alone in ponded and flowing water can reduce infiltration and seepage losses (Trout et al., 1995; Sirjacobs et al., 2000; Bouwer et al., 2001). Three types of sediment sealing mechanisms that inhibit infiltration have been identified, here referred to as thick-layer, thin-layer, and wash-in seals.

Thick-Layer Deposit

Gravitational settling of suspended and bed-load sediment produces a horizontally extensive depositional layer several centimeters to tens of centimeters thick above the original soil surface. This layer is subject to compressive forces from the soil layer's own mass and that of overlying water (Behnke, 1969; Bouwer and Rice, 1989; Bouwer et al., 2001). The sediment particles in these deposits can vary widely in size. In ponds, incoming sediments composed of varying particle sizes produce a graded depositional layer that was less permeable than that formed by uniform sediment (Bouwer et al., 2001).

Thin-Layer Seal

Whereas the thick-layer mechanism requires the accumulation of thick sediment layers to inhibit infiltration, sealing produced by very thin sediment deposits has also been reported. Suspended sediment carried to the wetted perimeter in flowing water and, to a limited extent, by gravitational settling can form a thin (0.1- to 2-mm), continuous, low-conductivity depositional seal on the original soil surface (Eisenhauer, 1984; Shainberg and Singer, 1985; Brown et al., 1988; Segeren and Trout, 1991). In contrast to thick-layer seals, where substantial sediment accumulates and adheres to the stream bottom under force of its mass, the particles comprising this thin seal are held in place and consolidated, along with adjacent subsoil, by negative water pressure below the soil surface (Brown et al., 1988; Segeren and Trout, 1991). The consolidation induces further conductivity reductions (Trout, 1990). Thus, thin-layer seals can form from fine soil particles that would otherwise remain suspended in the water stream. Settling of dispersed fines in ponded water produces dense surficial deposits with oriented clay layers, whereas flocculated particles form a more porous seal with random orientation (Southard et al., 1988; Shainberg and Singer, 1985). Thin-layer seals can form within minutes after flow initiation (Brown et al., 1988; Segeren and Trout, 1991).

Wash-In Seal

The third mechanism is unlike the previous two in that a continuous layer does not form atop the soil surface. Instead, suspended particles enter surface soil pores with infiltrating water and are deposited on the upper surfaces and ledges of soil particles within the matrix, filling in crevices and concavities on the particles, apparently in response to gravitational forces (Ives, 1989). Southard et al. (1988) reported that dispersed clays suspended in infiltrating water moved as much as 5 mm into loamy soils, forming oriented clay deposits that plugged finer pores. This mechanism, referred to as "wash in" or "interstitial straining" (Behnke, 1969) has been identified in sands (Hall, 1957) and soils subject to raindrop impact (McIntyre, 1958) and ponding of turbid water (Shainberg and Singer, 1985; Houston et al., 1999).

Several of these sealing processes may occur simultaneously in some flow regimes, whereas certain mechanisms may predominate in others. For example, a thin-layer seal may be relatively more important in irrigation furrows or during initial irrigation canal filling, when soils are drier and soil water potential gradients are steep. Some of the major factors that influence the complex sediment sealing process are the size distribution of solids present in the water and soil, the concentration of the sediment in the water, and the velocity of water moving vertically toward the soil surface (Behnke, 1969; Trout et al., 1995).

High-molecular-weight, anionic, polyacrylamide (PAM) polymers are used in agriculture to prevent erosion and sediment entrainment in runoff water (Lentz and Sojka, 1994) and increase water infiltration into soils whose intake is ordinarily limited by the formation of surface seals (Sojka et al., 1998a). The PAM is commonly dissolved in flowing water at concentrations 1 to 10 mg L^{-1} using brief or continuous applications (Lentz and Sojka, 2000).

The effect of PAM on water infiltration into soil has been studied in laboratory columns and miniflumes and in field irrigation furrows. In most of these studies, input water either contained no sediment or contained relatively small unmeasured concentrations. Polyacrylamide treatment of irrigation furrow inflows may influence infiltration in several ways: (i) Polyacrylamide stabilizes soil structure and porosity (Mitchell, 1986; Terry and Nelson, 1986; Sojka et al., 1998b); wet aggregate stability percentages of amended soil increase with increasing treatment PAM concentration from 0 to 50 mg L^{-1} (Helalia and Letey, 1989; Nadler et al., 1996). This channel stabilization helps maintain soil pore integrity and inhibits soil entrainment, breakdown, and dispersion and delays or prevents depositional seal formation over the wetted perimeter, resulting in higher infiltration rates than that in untreated channels (Lentz et al., 1992; Lentz and Sojka, 1994; Trout et al., 1995). However, the infiltration benefit was not realized (a) if soil structure was degraded before PAM application by wheel traffic or repeated irrigations (Sojka et al., 1998b; Lentz et al., 2000) or (b) for inherently stable soils with large pores and not susceptible to depositional seal formation (Sirjacobs et al., 2000; Trout and Ajwa, 2001; Ajwa and Trout, 2006). (ii) Polyacrylamide flocculates sediment suspended in the water stream, increasing the mean diameter of soil particles entrained and deposited in downstream reaches (Ben-Hur and Keren, 1997; Lentz et al., 2002). Thin-layer depositional seals formed by flocculated sediments are more permeable than those formed by nonflocculated particles (Southard et al., 1988; Sojka et al., 1998a; Lentz et al., 2000), which suggests that PAM treatment of sediment-bearing flows in unlined channels should result in greater infiltration and seepage losses than for untreated flows. Conversely, increased sediment deposition induced by PAM application would encourage the formation of thick-layer deposits, which may reduce seepage losses. (iii) When dissolved in irrigation water at dilute concentrations, PAM increases the solution's viscosity slightly and reduces infiltration and conductivity of the treated water through soils (Mitchell, 1986; Malik and Letey, 1992; Falatah et al., 1999; Sirjacobs et al., 2000; Lentz, 2003; Ajwa and Trout, 2006).

The magnitude of the PAM effect on soil stabilization, flocculation, or water viscosity generally increases with increasing size of the hydrated PAM molecule in solution, which increases with its molecular weight and charge density (Kulicke et al., 1982; Herrington et al., 1993; Nadler et al., 1996; Falatah et al., 1999) and decreases with increasing salt concentration in the water (Tam and Tiu, 1993). However, the hydrated PAM radius at which maximum flocculation occurs can differ depending on sediment characteristics and sediment and polymer concentration (LaMer and Healy, 1963; Hocking et al., 1999).

Thus, PAM's ultimate effect on furrow infiltration results from its combined influence on pore integrity, seal formation, and water viscosity (Sojka et al., 1998a; Sirjacobs et al., 2000; Ajwa and Trout, 2006). For example, when Lentz and Sojka (2000) applied PAM continuously to furrow stream inflows, a 2-mg L^{-1} PAM application effectively stabilized soil and reduced seal formation (99% reduction in sediment loss relative to controls), whereas the 0.5-mg L^{-1} PAM less successfully stabilized furrow soils (75% sediment loss reduction), yet produced an infiltration gain equal to that of the 2-mg L^{-1} treatment (12% infiltration increase relative to controls). The difference in soil stabilizing power of the two treatments apparently was offset by viscosity effects. Little research has examined the combined effects of PAM and stream sediment concentration on infiltration or seepage from channeled flows. However, demonstration studies have shown that the addition of PAM and sediment to unlined irrigation canals in loamy soils can substantially decrease seepage losses (J. Valiant, Colorado State Univ. Coop Ext., personal communication, 1998; D. Crabtree, U.S. Bureau of Reclamation, personal communication, 1999).

This study included two objectives: first, we wished to test hypotheses related to the simple effects of three individual variables on seepage losses from water flowing into unlined soil channels. Assuming that added sediment became fully dispersed in 0-PAM-treated flows and that ionic composition and concentration in water streams would not differ appreciably between treatments, we hypothesized that seepage losses would (i) decrease with decreasing inflow sediment particle size, because finer sediment should produce a less permeable surface seal than coarser sediment, (ii) decrease with increasing inflow sediment concentrations from 0 to 2 g L^{-1}, because the rate of formation, coverage, or effectiveness of the depositional seal likely will increase with sediment amounts, and (iii) increase with increasing inflow PAM concentration from 0 to 0.4 mg L^{-1}, then increase very slightly when PAM increased from 0.4 to 2 mg L^{-1}, following results observed in irrigation furrows (Lentz and Sojka, 2000). Second, we wished to test the hypothesis that inflow sediment type, sediment concentration, and PAM concentration interact with one another to influence seepage losses and for us to better understand the nature of that interaction under a selected range of conditions.

METHODS

The experiment was conducted in the laboratory using miniflumes, which allowed evaluation of treatment effects on runoff and seepage from a stream of water running in an unlined soil channel. Miniflumes were used because of the difficulty in adjusting sediment concentrations in large flows such as those of irrigation canals or even irrigated furrows and the inability to control factors such as water temperature and water chemistry in the field. In the experiment, a series of stream flows were initiated in a single soil type using inflow waters

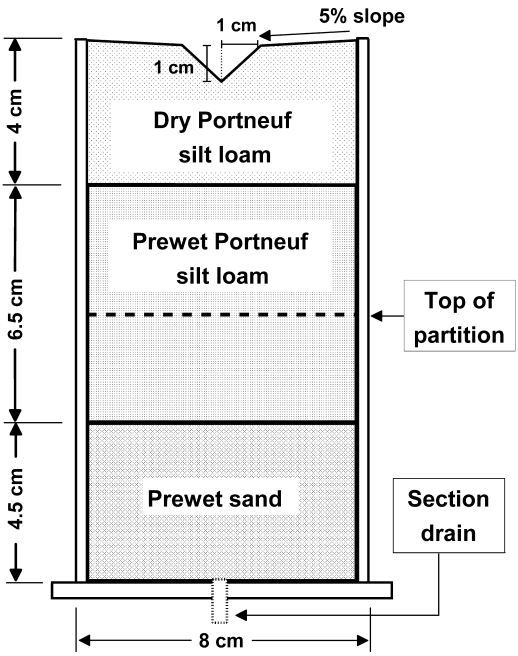

Fig. 1. Diagram showing cross-sectional view of miniflume and channel.

containing one of three concentrations of PAM and one of three concentrations of clay- or silt-sized sediment.

We constructed 100-cm-long, 8.5-cm-wide, and 15-cm-deep miniflumes from 0.6-cm-thick Plexiglas (Lentz, 2003). Three 7.5-cm-tall dividers projecting up from the base partitioned the box into four compartments, each with a drain on the downslope end. Figure 1 shows a cross-sectional view of the miniflume. A 4.5-cm layer of sand was lightly packed into the box (bulk density = 1.5 g cm^{-3}), followed by 6.5 cm of Portneuf soil (bulk density = 1.22 g cm^{-3}). A wood block was used with light hand pressure to smooth and press the soil into place. The sand and soil layers were brought to field capacity by slowly saturating with water, followed by a 24- to 48-h free drainage period. This allowed for more rapid water transit through lower soil layers during stream flow trials and reduced the lag time between initiation of water flow and measurement of seepage loss.

Just before each trial, a 4-cm layer of nonpacked dry Portneuf soil was placed over the moist soil base. The soil surface sloped (5%) toward the miniflume centerline so that if the channel filled with sediment, the flow would remain centered in the flume. A 1-cm-deep, 2.2-cm-wide, V-shaped channel was formed in the soil along the length of the miniflume by pulling a V-shaped form across the soil surface. This simulated the surface physical condition of field soils found in an irrigation furrow after being disturbed through tillage or in an irrigation canal after an off-season ditch cleaning operation, except that a larger range of soil aggregate sizes would be present in the field instances. The channel slope was set at 7% to maximize stream velocity.

The soil used in the miniflume was Portneuf silt loam, coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcids and was collected (0–15 cm) at an ARS research farm near Kimberly, Idaho. The soil is similar to many of the irrigated soils in the Pacific Northwest United States. Soil characteristics are presented in Table 1. The soil was air-dried and passed through a 2-mm sieve before use in the miniflume. Sediment added to inflows was either a montmorillonite standard clay (Osage Wyoming bentonite; Wards Natural Science,

TABLE 1

Characteristics Portneuf silt loam

Texture	Sand†	Silt†	Clay†	pH‡	EC§‡	OC¶	Soluble cations# Na	Mg	K	Ca	SAR††	ESP‡‡
	- - - - - (g kg^{-1}) - - - -				(S m^{-1})	(g kg^{-1})	- - - - (mmol$_c$ kg^{-1}) - - - -				([mmol$_c$ L^{-1}]$^{0.5}$)	(%)
Silt loam	240	560	200	7.3	0.4	8.8	3.6	14.7	1.3	20.1	0.9	2

†Particle size analysis: hydrometer method applied after removal of organic matter.
‡Determined on saturated extract
§EC = electrical conductivity.
¶OC = organic carbon, determined using dry combustion after pretreatment to remove inorganic carbon (Shimadzu Total Carbon Analyzer).
#Analyzed saturated soil extract using an atomic adsorption spectrophotometer.
††Sodium adsorption ratio.
‡‡Exchangeable sodium percentage.

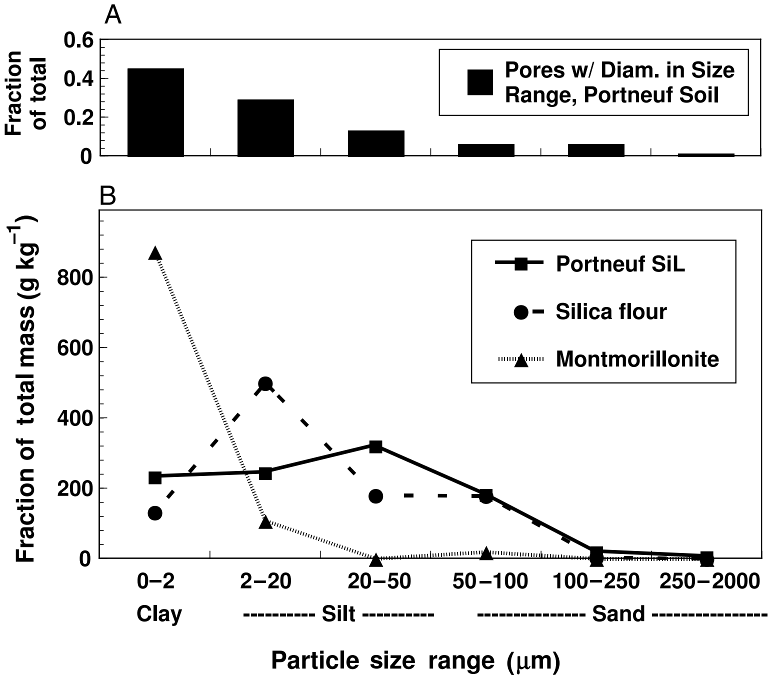

Fig. 2. (A) Fraction of soil pores in Portneuf silt loam with diameters in the given size ranges (computed from Portneuf's soil moisture curve using the capillary rise equation). (B) Particle size distributions for Portneuf silt loam soil and the silt (silica) and clay (bentonite) materials used to amend channel inflows.

Rochester, NY) or silica silt, 200 mesh screen (SIL-CO-SIL 90, U.S. Silica Co., Berkeley, WV). Particle size distributions of the soil and inflow sediments are described in Fig. 2. Portneuf soil includes roughly equal amounts of very fine sand (50–100 μm), coarse silt, fine silt, and clay. The particle size range of Portneuf and the silt additive were similar, except the latter was dominated by fine silt. The clay was comprised almost entirely of 0- to 2-μm particles with a small fraction of fine silt.

The PAM treatments used an anionic PAM copolymer (polymerized from acrylamide and sodium acrylate) with 18% charge density and 12 to 15 Mg mol^{-1} molecular weight (AN-923-PWG; Chemtall, Riceboro, GA). Solutions were prepared by dissolving the granular PAM solid (86% active ingredient, 14% water) in simulated irrigation water. The simulated irrigation water had the following characteristics: EC = 0.04 S m^{-1}; SAR = 1.7; pH = 6.9; soluble cation concentrations: Na^+ = 2.0 mmol$_c$ L^{-1}, Ca^{2+} = 1.4 mmol$_c$ L^{-1}, and Mg^{2+} = 1.4 mmol$_c$ L^{-1}.

Input waters were applied to the flume at a rate 40 mL min^{-1}. The inflow was divided into two 20-mL min^{-1} inputs, one supplied the sediment in suspension and the other the PAM solution. A multichannel peristaltic pump transferred the fluids via tube to the upstream end of the miniflume channel and dispensed them onto a 14 × 14-mm piece of porous plastic fabric, which prevented erosion caused by the impinging inflows.

The inflow water supply system used several reservoirs and a peristaltic pump. One reservoir, a 19-L container, supplied either simulated irrigation water or PAM solution, depending on the treatment. The PAM solution was prepared using simulated irrigation water at a concentration twice that targeted for miniflume flows. Additional containers were connected via siphons to obtain necessary overnight volumes. Another reservoir, a 64-L polyethylene barrel, contained a suspension of sediment and simulated irrigation water. The sediment concentration in the suspension was twice that targeted for miniflume flows. This barrel was placed on a stand such that the tank base was elevated slightly above and located as near as practical to the peristaltic pump, which was placed a few centimeters above and to the side of the miniflume (inflow end). The 1750-r.p.m. mixer, positioned 5 to 7 cm above the bottom center of the barrel, continually stirred the suspension and ensured that the sediment was well distributed throughout volume. The mixer blade consisted of a propeller with three 2.5 cm long × 1.9 cm oval blades. Two tubes with inside diameter of 6.3 mm conveyed the suspension from an outlet at the barrel base and irrigation water from the carboy to a multichannel peristaltic pump. The calibrated pump delivered the two fluids, each at half the targeted miniflume flow rate, to the inflow end of the miniflume. There the two supply tubes joined together at a "Y" fitting secured at the point of delivery. This arrangement simulated PAM being added directly to an irrigation furrow or irrigation stream that already was carrying a suspended sediment load. Miniflume soil, input water, and room air temperature were maintained at 23 ± 1 °C.

Before each trial, the first 15 to 20 min of flow from the delivery tube was collected in a waste container and discarded. Inflow rate was verified by collecting and measuring 2.0 min of flow. Sediment concentration was confirmed by collecting 150 to 200 mL of inflow in a tared metal container and weighing before and after drying at 100 °C.

Seepage volumes from the miniflume soil and surface runoff were monitored for 24 h. We recorded the time required for stream advance. Cumulative seepage (total from all four miniflume sections) and runoff volumes were determined every 0.5 to 1 h during the first 6 or 7 h after runoff or drainage began. Seepage and runoff rates were calculated as the ratio of efflux volume over sampling interval (0.5 or 1 h). During the remaining time, cumulative percolation and runoff waters were collected in 19-L buckets. Runoff and percolation rates were again monitored at hourly intervals in the final hours of the trial.

If sediment was present in runoff at greater than trace amounts (>0.01 g L^{-1}), we measured its concentration using the following procedure. For one or more replicates of the treatment, cumulative runoff waters collected at the above monitoring times were mixed using a magnetic stirrer while a 125-mL sample was drawn using a syringe. This was placed in a tared metal container and weighed before and after drying at 100 °C. Values were reported as time-weighted means.

We also evaluated the effect of PAM and sediment amendments on the chemistry of inflow water and flocculation state of sediments. Additional solutions identical to those used in the miniflume were prepared by combining appropriate amounts of simulated irrigation water, sediment, and PAM. The pH, EC, SAR, and Na, Mg, and Ca concentrations in the solutions were determined after mixing them in a reciprocating shaker for 0.5 h, letting stand overnight, followed by a 1-h shaking before sampling. Flocculation state was determined for a given treatment by swirling 5 mL of the input suspension and 5 mL of the PAM input solution in a container for 15 s. A drop of the liquid was immediately placed on a slide and viewed under a microscope at ×50 to ×100 magnification to determine if particles were flocculated and, if so, measure floccule size.

Hydraulic parameters were determined for channels of select treatments. Cross-sectional profile and wetted perimeter were measured at four places along the miniflume (in each quarter section) at the 2-h sampling time. Average velocity was calculated by dividing flow rate (inflow minus seepage rate at each quarter section) by channel cross-sectional area. Average flow shear was computed from the tractive force equation:

$$\tau = \gamma R S \tag{1}$$

where τ is the tractive force (N m^{-2}); γ, the unit weight of water (9782 N m^{-3} at 23 °C); S, the energy slope, essentially the channel bed slope (m m^{-1}); R, the hydraulic radius ($A \cdot P^{-1}$, where A is the flow cross-sectional area [m^2] and P is the channel-wetted perimeter [m]). Dimensionless flow parameters Froude (F) and particle Reynolds (R) numbers were computed from

$$F = \frac{V}{\sqrt{g_n \cdot D}} \tag{2}$$

$$R = \frac{V \cdot L}{\upsilon} \tag{3}$$

where V is the velocity (m s^{-1}); g_n, gravitational acceleration (m s^{-2}); D, hydraulic depth (m) = channel cross-sectional area normal to flow (m) divided by the surface free water width (m) (Chow, 1959); L, length characteristic, particle diameter (m); and υ, kinematic viscosity (m^2 s^{-1}).

The experiment used a completely randomized design with three treatment factors: inflow sediment type (no sediment, clay, and silt), inflow sediment concentration (0, 0.5, and 2.0 g L^{-1}), and inflow PAM concentration (0, 0.43, and 2.1 mg L^{-1}). Sediment concentrations were selected to simulate the more substantial loads present in irrigation furrow inflows and PAM concentrations were selected to produce low and moderate viscous effects on soil water conductivity. Continuous PAM applications ensured that PAM impacts were maintained throughout the flow test period. The sediment factor levels will be referred to as 0-sediment, 0.5-clay, 0.5-silt, 2-clay, or 2-silt treatments, and the PAM factor levels will be referred to as the 0-PAM, 0.4-PAM, and 2-PAM treatments. Thus, the design included 15 different treatments with three replications and a total of 45 experimental units. Response variables included advance time, channel seepage rates at 2, 6, and 22 h, and cumulative seepage loss (23 h).

We performed two analysis of variance (ANOVA) tests. One fit the model $y = a$, where y is the channel response (seepage rate etc.) and a is the individual factor of interest (e.g., sediment type). In this analysis, the effect of other factors and levels are ignored, hence, results are more general. We also conducted an ANOVA that fitted the full main effects model, $y = a\ b\ c\ ab\ ac\ bc\ abc$, which includes all factors (a, b, and c) and their interactions. Compared with the previous model, this analysis is more efficient and accounts for interfactor relationships, but results are sometimes more difficult to interpret. Mean separations among treatment means were performed (Duncan's multiple range test) using the SAS PROC GLM procedure (SAS Institute, 1999) at the $P = 0.05$ significance level. Transformed response values (square root of 2-, 6-, and 22-h seepage rates and natural log of advance time) were used in the analysis because they improved normality of error term distributions (Snedecor and Cochran, 1980). Means, standard error, and confidence limits were back-transformed to the original units for reporting.

The water balance equation defines seepage loss (U) measured in the miniflume as

$$U = I - \Delta S_s \tag{4}$$

where

$$I(infiltration) = W - R - \Delta S_c - E \tag{5}$$

and W is inflow; R, runoff; ΔS_c, change in channel water storage (end − start); ΔS_s, change in soil water storage (end − start); E, evaporation. We assumed that E was small or invariant between treatments. The advancement of the wetting front through the soil supported the assumption that soil water storage was filled during the initial hours of irrigation and before seepage began. After seepage had initiated in each miniflume section, ΔS_s probably did not change appreciably. Seepage initiated in all but the 2-g clay treatments within 1 to 1.5 h after flow began.

RESULTS

Tests showed that the addition of 2 mg L^{-1} PAM and/or 2 g L^{-1} clay or silt to the simulated irrigation water had relatively small influence on the water's pH, EC, and SAR. Relative to simulated irrigation water, the maximum change to these values after addition of sediment and/or PAM was ≤0.5 units for pH, ≤0.01 S m^{-1} for EC, and ≤1 units for SAR. Because of their low absolute values and the relatively small differences between treatments, we concluded that the water quality effects would not significantly influence hydraulic properties of either the depositional crust (Shainberg and Singer, 1985) or soil (McNeal and Coleman, 1966). Thus, any differences in seepage observed between treatments should be because of the test parameters only.

The ANOVA results for the full main effects model indicated that treatments and treatment interactions were significant for nearly every response parameter (Table 2). Thus, the null hypothesis that treatment means were equal was rejected in most cases, and we concluded that inflow sediment type and concentration and

TABLE 2

Summary of ANOVA for the full main effects model: testing effects of factorial treatments, inflow sediment type, sediment concentration, and PAM concentration on stream advance, miniflume seepage rates, and cumulative seepage

Source	Stream advance	Seepage rate			23-h Cumulative seepage
		2 h	6 h	22 h	
Sediment type (T)	***	***	***	***	***
Sediment concentration (S)	***	***	***	***	***
T × S	ns	**	ns	*	ns
PAM concentration (P)	***	*	ns	*	ns
T × P	***	ns	*	***	***
S × P	***	***	***	***	***
T × S × P	***	**	**	***	***

ns = nonsignificant.

Significant at the *0.05, **0.01, and ***0.001 probability level, respectively.

TABLE 3

General means for sediment type, sediment concentration, and PAM concentration treatments for responses, initial stream advance time, channel seepage rates at 2, 6, and 22 h after inflow initiation and cumulative miniflume seepage volumes at 23 h (derived by fitting a single-factor ANOVA model, $y = a$)

Overall treatment	Treatment level	Stream advance min	Seepage rate 2 h	6 h	22 h	Cumulative seepage at 23 h L
			- - - - -mL min^{-1}- - - - -			
Sediment type	No sediment	29.5 a†	6.6 a	8.8 b	6.4 b	9.75 b
	Clay	13.2 b	4.1 b	3.6 b	2.8 c	4.71 c
	Silt	61.3 a	20.0 a	15.6 a	11.8 a	18.18 a
Sediment concentration	0 g L^{-1}	29.5 a	6.6 a	8.8 a	6.4 ab	9.75 ab
	0.5 g L^{-1}	42.1 a	13.7 a	11.9 a	9.6 a	14.5 a
	2 g L^{-1}	19.1 a	7.8 a	5.7 a	4.1 b	6.9 b
PAM concentration	0 mg L^{-1}	54.3 b	12.3 a	9.9 a	7.3 a	10.9 a
	0.4 mg L^{-1}	25.4 ab	9.5 a	8.7 a	7.0 a	10.7 a
	2 mg L^{-1}	17.0 a	7.5 a	7.3 a	5.4 a	9.1 a

†Similar lowercase letters indicate nonsignificant differences between treatment means within the overall treatment (Duncan's multiple range test, $P = 0.05$).

inflow PAM concentration influenced channel advance and seepage rates. The effect of treatment factor levels on channel seepage was nonlinear in many cases and varied depending on the level of the other two treatments. The numerous significant treatment and interaction effects produced relatively complex seepage response patterns among the three treatment factors.

We first examined results from the simple-model ($y = a$) ANOVA to determine the general effect of individual main factors, sediment type, sediment concentration, and PAM concentration on various seepage parameters. Relative to 0-sediment treatments, adding inflow silt generally increased the 22-h seepage rate and 23-h cumulative seepage volume 2-fold, whereas

TABLE 4

Treatment means for initial stream advance time, miniflume seepage rates at 2, 6, and 22 h after inflow initiation, and cumulative miniflume seepage volumes at 23 h (derived by fitting a full main effects ANOVA model)

Inflow sediment type	Inflow sediment concentration (g L^{-1})	Inflow PAM concentration (mg L^{-1})	Stream advance (min) Time	Sep.†	Seepage rate 2 h Rate	Sep.†	6 h Rate	Sep.†	22 h Rate	Sep.†	Cumulative seepage at 23 h (L) Vol.	Sep.†
					---------- (mL min^{-1}) ----------							
No sediment	0	0	39	c‡	12.4	def	11.8	bcd	8.7	bcd	12.42	bcd
		0.4	23.8	de	6.4	efg	6.8	de	5.0	def	7.68	de
		2.0	27.6	cde	2.7	ghi	8.3	cde	5.8	de	9.44	cde
Clay	0.5	0	35.3	cd	19.2	bcd	7.7	cde	2.4	f	6.72	ef
		0.4	15.7	fg	9.2	ef	9.3	bcd	8.3	bcd	10.98	cde
		2.0	10.6	gh	1.6	hi	3.4	ef	3.3	ef	5.98	ef
	2.0	0	8.6	h	0.3	i	0.2	g	0.1	g	0.17	g
		0.4	12.4	gh	0.4	i	2.1	fg	2.6	f	3.48	f
		2.0	8.4	h	5.3	fgh	3.1	ef	3.7	ef	5.72	ef
Silt	0.5	0	1439	a	37.7	a	39.3	a	38.9	a	47.14	a
		0.4	33.1	cd	14.8	cde	12.7	bcd	9.9	bc	15.85	bc
		2.0	20.0	ef	12.6	edf	10.2	bcd	8.6	bcd	13.25	bcd
	2.0	0	27.9	cde	8.7	ef	7.8	cde	6.2	cde	9.84	cde
		0.4	68.5	b	29.2	ab	16.5	b	11.1	b	19.35	b
		2.0	29.1	cde	24.6	abc	14.7	bc	6.2	cde	12.67	bcd

†Mean separation treatment response.

‡Similar lowercase letters indicate nonsignificant differences between treatment means within columns (Duncan's multiple range test, $P = 0.05$).

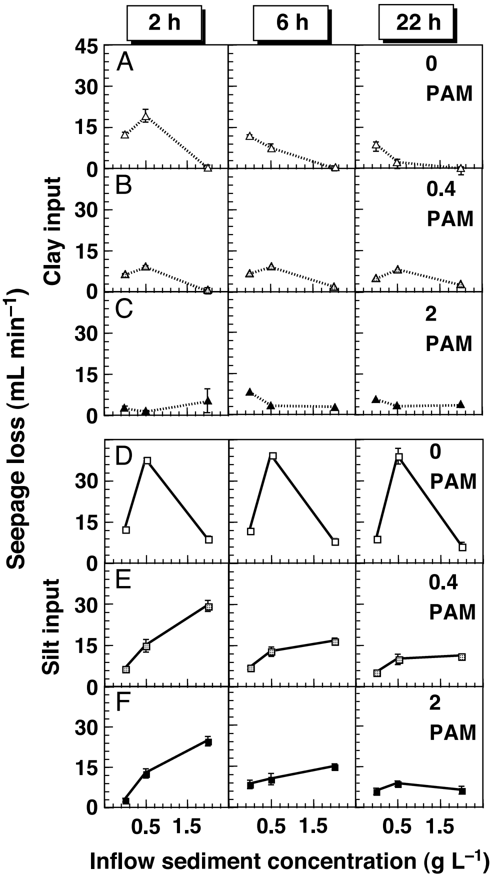

Fig. 3. The effect of inflow clay (A–C) or silt (D–F) concentrations on channel seepage loss rates for inflow PAM concentrations of 0, 0.4, and 2 mg L^{-1} at 2, 6, and 22 h. Error bars represent the standard error of the mean at each sampling time (if not visible, bar is shorter than symbol size).

adding inflow clay decreased the 22-h seepage rate and 23-h cumulative seepage volume by half (Table 3). The same trends were exhibited for advance time and 2- and 6-h seepage rates, although differences were not always significant. In general, increasing inflow sediment concentration from 0.5 to 2 g L^{-1} decreased mean stream advance, seepage rate (2-, 6-, and 22-h), and 23-h cumulative seepage volume by half, although the effect was significant only for the 22-h seepage rate and 23-h cumulative seepage volume (Table 3). In general, increasing inflow PAM concentrations decreased stream advance times and, thus, initial seepage rates of treated flows (Table 3). As time passed, the effect of inflow PAM concentration on seepage rates decreased and became statistically insignificant. Overall, the 0.5-silt/0-PAM treatment produced the greatest 23-h cumulative seepage loss, a 3.8-fold increase over the control (0-sediment/0-PAM); the 2-clay/0-PAM treatment produced the least seepage loss, resulting in a 99% reduction in seepage relative to controls (Table 4).

Seepage Loss Rates

Sediment Type by Sediment Concentration Interaction

Seepage rates tended to decrease with increasing inflow clay (Fig. 3A–C) but increased with increasing inflow silt concentrations (Fig. 3D–F). The 0-PAM/silt treatment was the exception; it produced a seepage rate maximum at midlevel silt inputs (Fig. 3D).

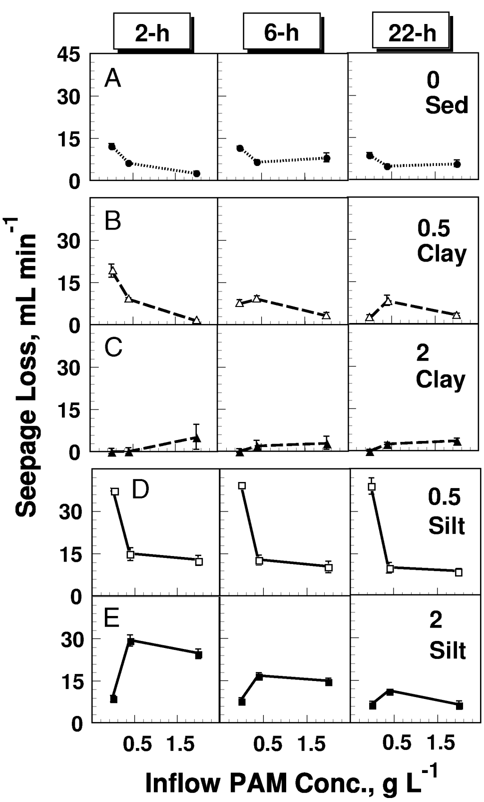

Fig. 4. The effect of inflow PAM concentrations on channel seepage loss rates for 0-sediment (A), 0.5-clay (B), 2-clay (C), 0.5-silt (D), and 2-silt (E) treatments at 2-, 6-, and 22-h sampling times. Error bars represent the standard error of the mean at each sampling time (if not visible, bar is shorter than symbol size).

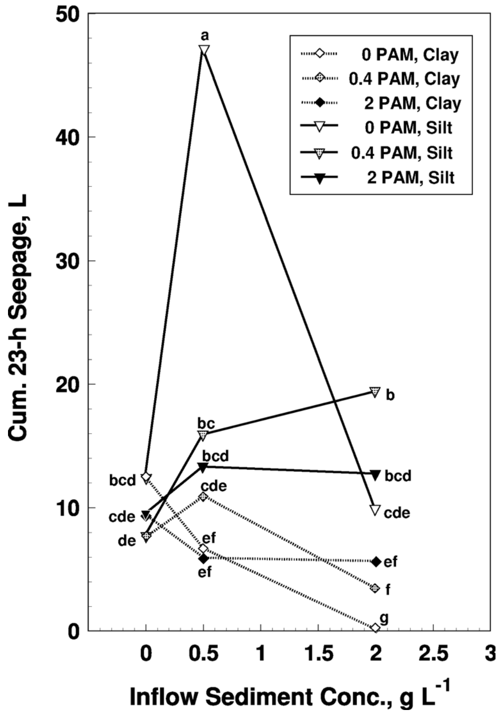

Fig. 5. The effect of inflow sediment concentrations on 23-h cumulative seepage losses for PAM concentration/sediment type treatments. Similar lowercase letters indicate nonsignificant differences between treatment means (Duncan's multiple range test, $P = 0.05$).

Sediment Concentration by PAM Concentration Interaction

Increasing inflow PAM concentrations tended to decrease seepage rates when sediment concentrations were low, 0.5 g L^{-1} (Fig. 4B, D), but increase seepage rates when sediment concentrations were high, 2 g L^{-1} (Fig. 4C, E).

Sediment Type by Sediment Concentration by PAM Concentration Interaction

Polyacrylamide additions suppressed the effect of increasing clay or silt concentrations on seepage rates, especially late in the irrigations (Fig. 3).

Cumulative Seepage Losses

Interactions described above for seepage rate data were duplicated in the 23-h cumulative seepage volume data (Table 4, Fig. 5). Similarly, the addition of PAM inhibited the impact that increasing sediment (silt or clay) concentration had on cumulative seepage volume (Fig. 5).

As also observed in the seepage rate data, when inflow sediments were low, PAM amendments either had no effect or reduced seepage volumes; however, when inflow sediment was high (>0.5 g L^{-1}), PAM amendments tended to increase seepage volumes (Fig. 6).

Four specific response patterns are evident in Fig. 6, in which cumulative 23-h seepage volumes are plotted as a function of inflow PAM concentration for sediment type by sediment concentration treatments. (i) Polyacrylamide had no significant influence on cumulative seepage for 0-sediment and 0.5-clay treatments. (ii) Increasing inflow PAM concentrations caused seepage volume to increase for the 2-clay treatment. (iii) Increasing inflow PAM from 0 to

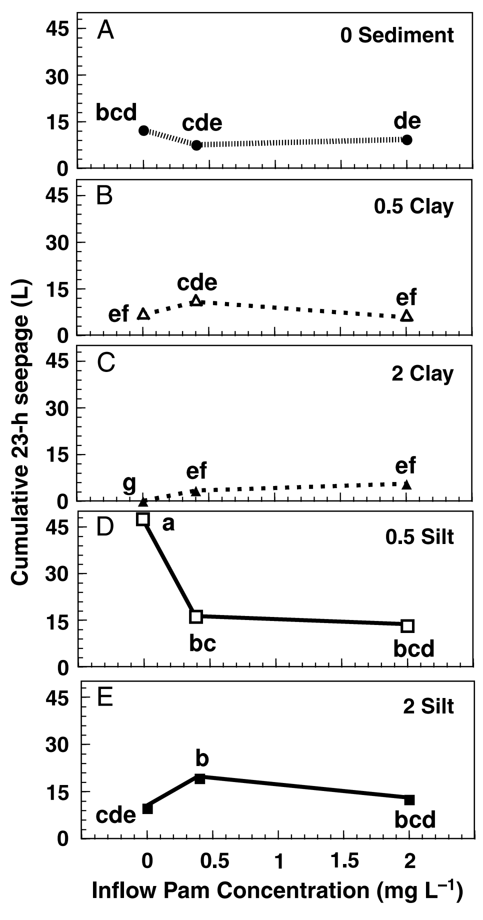

Fig. 6. The effect of inflow PAM concentrations on 23-h cumulative seepage losses for 0-sediment (A), 0.5-clay (B), 2-clay (C), 0.5-silt (D), and 2-silt (E) treatments. Similar lowercase letters indicate nonsignificant differences between treatment means (Duncan's multiple range test).

TABLE 5

Description of treatment effects on miniflume channels, wetting and flocculation conditions, and runoff sediment concentrations

Inflow sediment		PAM	Flow effects on channel		Wetting condition at soil surface			Sediment flocculation		Runoff sediment concentration (g L^{-1})
Type	Concentration (g L^{-1})	Concentration (mg L^{-1})	Shape	Sediment deposition	Type†	Distance‡ cm	Extent %§	Percent flocculated	Floccule size (μm)	
No	0	0	Degraded	Moderate	–	–	–	0	–	2.5
Sed.		0.4	Stable	Slight	–	–	–	0	–	0.25
		2.0	Stable	None	–	–	–	0	–	<0.1
Clay	0.5	0	Aggraded	Heavy, gellike	T	0.5–4	30	<5	<2	0.49
		0.4	Aggraded	Heavy, gellike	T, S	1–7	78	95	90	0.48
		2.0	Aggraded	Heavy, gellike	T, S	1–5	25	95	55	0.47
	2.0	0	Aggraded	Slight	T	0.5–1	15	<5	<2	2.0
		0.4	Aggraded	Moderate	T, S	1–5	20	95	150	<0.1
		2.0	Aggraded	Heavy, gellike	T, S	2–7	90	95	400	1.14
Silt	0.5	0	Mixed	Slight	T, S	0–3	17	0	–	<0.1
		0.4	Stable	Slight	T	0.5–1	8	<5	10	0.5
		2.0	Aggraded	Moderate	T	0.5–1.5	8	<5	10	0.4
	2.0	0	Degraded	Moderate	T	1–2	15	0	–	2.4
		0.4	Aggraded	Heavy, gellike	T	1–2	17	5–10	20–30	1.9
		2.0	Aggraded	Heavy, gellike	T	1–3	13	5–10	20–30	1.8

†T = tension, narrow tongues of water and sediment that moved laterally up channel sides and onto soil surface, apparently because of surface tension effects, no downstream flow was associated with these; S = sheet, because of channel filling, the flow spreads across the soil surface, becoming wider and shallower, and it included a downstream flow component and typically developed during the last few hours of the test period.

‡Distance surface water phenomenon extended from channel center.

§Percentage of the miniflume soil surface effected by the wetting phenomenon on an area basis.

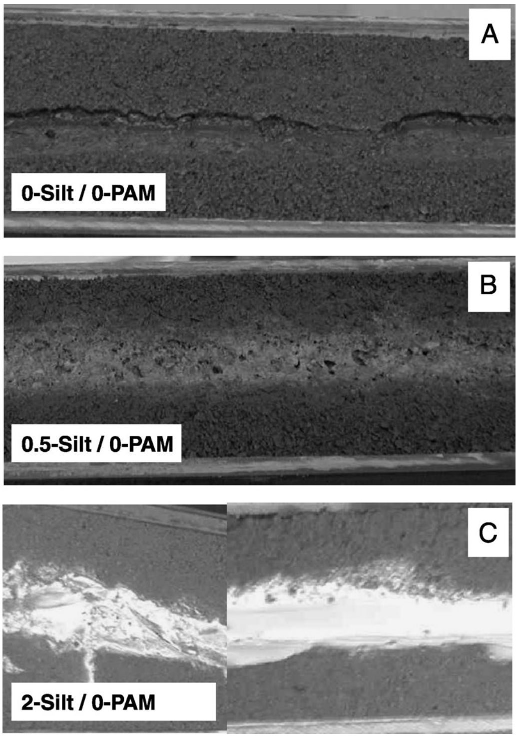

Fig. 7. Channel morphology resulting from 0-silt/0-PAM (A), 0.5-silt/0-PAM (B), and 2-silt/0-PAM (C) treatments.

0.4 mg L^{-1} moderately increased seepage volume for the 2-silt treatment but no significant further enhancement occurred when PAM concentration increased to 2 mg L^{-1}. (iv) Increasing PAM concentration from 0 to 0.4 mg L^{-1} caused a dramatic seepage reduction for the 0.5-silt treatment, but no further change occurred when PAM concentration increased to 2 mg L^{-1}.

Stream Advance Time, Sediment flocculation, and Channel Characteristics

Stream advance time values were correlated with treatment seepage rates (R^2 = 0.74), with longer advance times occurring for treatments with greater seepage rates and cumulative seepage volumes. Observations of flocculation states in treatment mixtures confirmed that clay and silt particles in 0-PAM waters were fully dispersed (Table 5). When clay amended waters were treated with PAM, clay particles were 95% flocculated. Flocculated masses had mean maximum diameters ranging from 55 to 400 μm, and size increased with clay concentration. However, in silt- and PAM-amended waters, silt particles were only 5% to 10% flocculated, and the mean maximum floccule size was no greater than that of individual silt grains, <30 μm.

Inflow sediment and PAM treatments influenced channel erosion and deposition processes (Table 5). Most treatments resulted in aggrading channels in which deposited sediment progressively filled the channel cross-section. All clay and two silt treatments resulted in aggraded channels. However, three treatments stabilized the channels, causing little erosion or deposition (0-sediment/0.4-PAM, 0-sediment/2-PAM, and 0.5-silt/0.4-PAM; Fig. 8A); and two treatments produced degraded channels, that is, downcut and widened cross-sections (0-sediment/0-PAM and 2-silt/0-PAM (Table 5, Fig. 7A,C). In PAM treatments, sediment deposition often began with the formation of moss-like filaments of soil particles and floccules along the wetted perimeter of the channel. Clay channel deposits were hydrated and gel-like in appearance (Fig. 8D), whereas silt deposits were more dense and compact (Fig. 8A).

The clay treatments produced the greatest channel filling, which caused flows to spread over the soil surface adjacent to the channel, especially in the upper parts of the miniflume (Fig. 8F). All sediment-applying treatments produced what appeared to be a surface-tension-induced lateral transport of water and sediment up the channel sides and onto the soil surface (Fig. 8C). This phenomenon tended to increase with inflow PAM concentration.

The 0.5-silt/0-PAM application produced a channel response that was unique among all treatments (Fig 8B). When this treatment was applied, the channel walls sloughed toward the center, forming a channel with a broader, shallower cross-section. Silt deposition was appreciable in the upper third of the channel. From a third to a half of the distance down the miniflume, silt deposition declined, the flow slowed considerably, and air appeared in the water, forming stationary bubbles that persisted over time. Flows did not advance much beyond this region because of the high percolation rate there. In general, channels of silt-treated flows were characterized by the presence of 0.5- to 2-mm soil macropores that formed along the wetted perimeter (Fig. 7B). These were not observed in clay-treated channels. The macropores were most common in channels treated with the 0.5-silt/0-PAM application, and the phenomenon was consistent in this treatment across all three replicates.

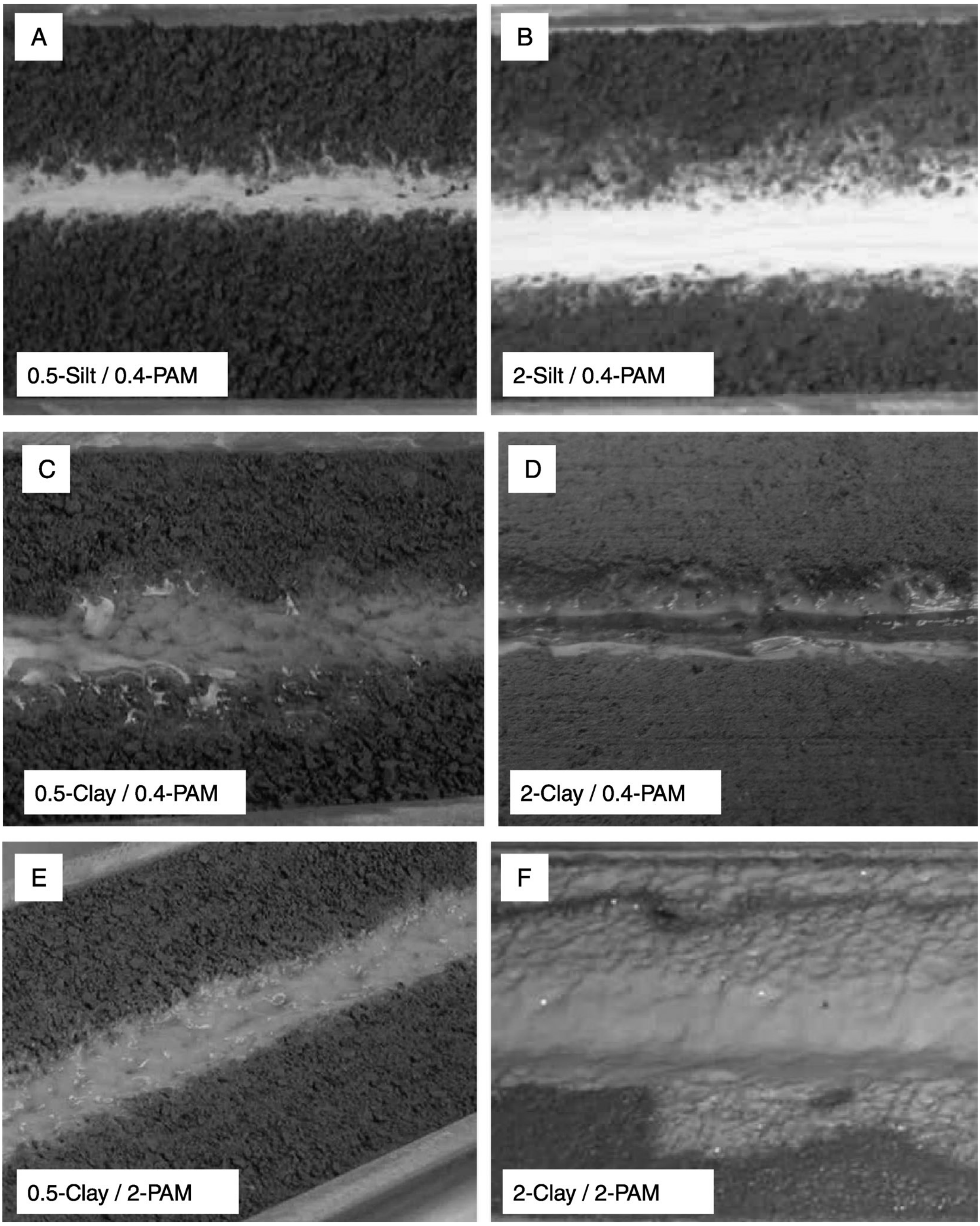

Fig. 8. Channel morphology resulting from 0.5-silt/0.4-PAM (A), 2-silt/0.4-PAM (B), and 0.5-clay/0-PAM (C), 2-clay/0-PAM (D), 0.5-clay/2-PAM (E), and 2-clay/2-PAM (F) treatments.

In general, runoff sediment concentrations mirrored those of the inflow concentrations (Table 5). Exceptions to this pattern included two of the 0-sediment treatments: the 0-sediment/0-PAM treatment produced the greatest runoff sediment concentrations among all treatments, 2.5 g L^{-1}, whereas the 0-sediment/2-PAM treatment produced runoff having the least sediment. The 2-clay/0.4-PAM and 0.5-silt/0-PAM treatments produced near-zero runoff sediment as well, whereas the 2-clay/2-PAM treatment runoff sediment was about half of that present in the inflow.

DISCUSSION

Four processes likely occur simultaneously in these flows. (i) Rapid wetting of soil aggregates early in the irrigation causes soil aggregates to slake, disaggregate, and collapse (Kemper et al., 1985; Trout, 1990). Small soil aggregates moving in the flow as bedload settle into and fill larger openings in the channel perimeter (Brown et al., 1988). These processes decrease the number of large pores in the channel perimeter and decrease the seepage rate. (ii) Erosion and abrading of stream beds disturb channel surface morphology such as depositional seals or macropores, expose new soil surfaces, and increase seepage. (iii) Sediment generated from erosion or present in inflow buries channel surface structures, promotes seal development and wash-in (if particles are small relative to soil pore sizes), and reduces seepage. (iv) The formation of surface macropores in the wetted perimeter of the channel was observed in silt treatments, particularly the 0.5-silt/0-PAM. These pores appeared to be only a few millimeters deep, sufficient to penetrate the thin depositional seal and provide a pathway for surface water to rapidly infiltrate into the soil. The surface pores may have resulted from entrapped air escaping from the soil, as evidenced by bubbles present in the surface waters. Why the bubbles were so prevalent in this particular treatment is not clear. Such persistent macropores have been observed in the sand filtration industry, where the so-called wormholes are observed to penetrate into the filter media and remain open despite a continuing flow of deposits into them (Ives, 1989); however, such media are typically subject to higher flux rates and pressures than presented here. Macropores have also been observed opening to the surface in some irrigation furrows, but these were attributed to actual worm activity (Kemper and Trout, 1987).

Poiseuille's law indicates that water flux through a simple soil pore is proportional to the fourth power of its radius, directly proportional to the pressure head, and inversely proportional to the fluid viscosity and length of the pore (Hillel, 1998). Estimates of the number and sizes of pores in Portneuf soil (based on its pore size distribution) indicate that most of the initial infiltration through Portneuf soil occurs in pores larger than 100 μm in diameter. Wetting-induced disintegration of soil aggregates in the channel-wetted perimeter early in the irrigation decreases the number of large pores and, hence, seepage rate. Eliminating the relatively few >250-μm-diameter soil pores initially present in the channel perimeter could reduce infiltration by one half. At that point, as much as 70% of the infiltration likely occurs in the remaining large (100- to 250-μm) soil pores, whose number can be two orders of magnitude greater than the original number of the now-filled >250-μm diameter pores. Therefore, flow through these 100- to 250-μm diameter soil pores must be substantially reduced if further sizeable seepage reductions are to be achieved. Increasing inflow PAM concentration to 2 mg L^{-1} will increase solution viscosity and decrease conductivity through such pores, but Letey (1996) showed that solutions containing 2.5 mg L^{-1} of PAM reduced flow through sands dominated by these pore sizes by only 10 to 20%.

Effect of Inflow Sediment Type

Results showing the effect of sediment type on seepage loss from miniflume channels support the hypothesis that efficacy of channel sealing increases with decreasing inflow-sediment particle size. Seepage loss rates (Table 4, Fig. 3) and cumulative seepage losses (Table 4, Fig. 5) were greater for silt than clay inflow applications. Adding PAM generally did not alter this relationship. However, the explanations for observed differences between silt and clay likely are different for 0-PAM and PAM-amended treatments, because PAM flocculated the clay and altered particle size distributions. As evidence that different processes are involved in 0-PAM and PAM treatments, note how seepage rates decline with time for clay/0-PAM treatments, but not for clay/0.04-PAM treatments (Fig. 3A, B), suggesting that one process is more time dependent than the other.

In 0-PAM treatments, several processes may be influencing infiltration. First, the number of <2-μm soil particles was seven times greater and particle size range was smaller for input clay in comparison to input silt (Fig. 2). Therefore, the thin depositional seal that formed on the soil surface by dispersed clay was less permeable than that produced by silt. Second, the input <2-μm particles are too small to plug larger pores (>100 μm), where they open at the channel surface. However, because particle momentum is proportional to the third power of the radius, these small particles are more likely than larger particles to move with infiltrating water into large pores. In addition, more <2-μm particles should enter the large pores than small pores because inflow rates are 10 to 10^4 times greater in large-diameter pores. Thus, the dispersed clay should wash into the large soil pores more rapidly than silt, where it can adhere to and seal interior pore walls (wash-in seal) and reduce seepage losses. Third, if all particles carried downstream in the flow attain similar velocities, the larger silt-derived particles will develop kinetic energies 10 to 10^6 times greater than 98% of all the clay-sized particles. When these large silt particles collide with the wetted perimeter, they have a greater potential than the <2-μm particles for disrupting or delaying development of the thin depositional seal layer. If a collision causes even a small breach in the depositional seal, it can reduce the local soil water tension gradient that holds the deposited fines to the channel perimeter and result in the flaking off of the nearby depositional layer (Brown et al., 1988). This can produce a chain reaction leading to an ever-widening area of unsealed surface.

In PAM-amended treatments, the PAM (i) flocculated 95% of the clay, forming aggregates up to 400 μm in diameter, (ii) flocculated <10% of the silt particles, with no increase in maximum particle size, and (iii) stabilized the channel soils and helped preserve large-diameter pores in the wetted perimeter (Table 6). Yet, clay/PAM treatments still produced lower seepage rates than silt/PAM, although not quite as low as clay/0-PAM treatments. Because dispersed <2-μm particles were nearly absent in clay- and PAM-amended waters, development of a washed-in seal was unlikely. We speculate that clay floccules effectively plugged the >100-μm-diameter pores where they opened to the channel perimeter. The clay floccules also produced a more permeable thin depositional seal than formed in clay/0-PAM treatments from dispersed <2-μm particles, which may explain why the seepage losses trended lower for clay/0-PAM compared with clay/PAM treatments.

Effect of Inflow Sediment Concentration

Our hypothesis that seepage decreases with increasing inflow sediment concentration (ostensibly because of increased effectiveness and coverage of the depositional seals) was not fully supported by results, whether or not PAM was added to inflows. The influence of sediment concentration on seepage losses was dependent on inflow sediment type and PAM concentration. For the 0-PAM treatments, we observed that increasing inflow clay concentrations in clay/0-PAM treatments decreased seepage rates and accelerated the sealing process (i.e., seepage rates declined more steeply with time as clay increased; Fig. 3A). This was the result expected under our hypothesis, but it did not hold true for the silt/0-PAM treatments: the 0.5-silt/0-PAM treatment produced sharply greater seepage volumes than the 0-silt/0-PAM and the 2-silt/0-PAM treatments, the latter two being equivalent (Fig. 5). The reason for this unanticipated result is not clear.

Both the 0-sediment/0-PAM and 2-silt/0-PAM treatments produced visible channel erosion and high runoff sediment concentrations (Table 5, Fig. 7A, C), which resulted in moderate 2-h seepage rates, 9 to 12 mL min^{-1}, that declined slowly with time (Table 5). This implies that seepage-inhibiting sealing processes were competing with seepage-enhancing erosion processes, with the former slowly gaining the upper hand. The slow decline in seepage rate suggests that the channel stabilized over time and allowed

TABLE 6

Hydraulic characteristics, including nondimensional Froude and particle Reynolds numbers, for various irrigation flows in southern Idaho, compared with that of miniflumes

Source	Slope	Channel cross-section (m^2)	Velocity ($m\ s^{-1}$)	Shear stress ($N\ m^2$)	Froude number	Particle Reynolds number†
Miniflume	0.069	0.00005–0.0012	0.04–0.11	0.5–1.3	0.02–1.46	0.01–46.0
Portneuf furrows‡	0.011–0.013	0.0002–0.003	0.09–0.36	0.25–2.1	0.29–1.57	0.08–125
Small canals§	0.0007–0.002	0.43–2.07	0.46–1.4	2.7–12.1	0.22–1.3	0.4–485

†Calculated using minimum and maximum particle diameter values of 1 and 400 ìm, respectively.

‡Computed from local furrow measurements (D. L. Bjorneberg, USDA-ARS-NWISRL, personal communication, 2007).

§Computed from local (unpublished data, 2004) and regional observations (F. J. Peterson, U.S. Bureau of Reclamation, 2007).

more extensive seal development. The explanation appears plausible because, in both treatments, channel erosion rates were high during the first hours of the irrigation (>6 g L^{-1} runoff sediment), moderate for the next 5 to 10 h, then declined to low rates (<0.5 g L^{-1} runoff sediment) at later times (data not shown).

Clearly, something very different occurred in the 0.5-silt/0-PAM treatment. Here, erosion and runoff sediment concentrations were low, and the channel was relatively stable (Table 6), yet the 22-h seepage was high, 38.9 mL min^{-1}. If lack of erosion and deposition caused the high seepage rate, then the similarly characterized 0.5-silt/0.4-PAM treatment also should have had high rates, but it did not. The moderate inflow silt concentrations may have been sufficient to stabilize channel morphology by reducing erosion (Sirjacobs et al., 2000), yet not so great as to form continuous depositional seals or interfere with the formation and persistence of macropores. If surface macropores caused the sharply increased seepage in the 0.5-silt/0-PAM treatment relative to the other 0-PAM treatments, the presence of moderate silt inflow concentrations must have contributed to their development or persistence. The presence of silt particles suspended in the flow may have actually prevented seal formation by forming a thin but continually ablating and reforming coating over the surface, which never became thick or impervious enough to inhibit seepage or establishment of the surface macropores.

At higher inflow silt concentrations (2-silt/0-PAM), erosion was significant (Table 5), but the high inflow sediment concentrations and/or heavy sediment deposition produced thicker and less permeable deposits and perhaps interfered with the formation of air bubbles and surface macropores (Fig. 7C). The mechanism responsible for eliminating macropore initiation/growth in the 2-silt/0-PAM treatment apparently acted soon after flow began. Seepage loss rates were drastically smaller than that of 0.5-silt/0-PAM beginning early in the test period (Fig. 3D).

Polyacrylamide amendments changed how increasing sediment influenced seepage losses. Adding PAM appeared to interfere with a time-dependent sealing process that was operating in the clay/0-PAM treatment. The seepage rates of 0-clay/0-PAM and 0.5-clay/0-PAM treatments declined over time, and the rate of decline was greater as clay concentration increased (Fig. 3A). In contrast, seepage rates of clay/PAM treatments did not decline with time (Fig. 3B, C). Adding PAM to silt treatments also altered the sealing process, but in this case, PAM caused the sealing to become more time dependent (Fig. 3D vs. Fig. 3E, F).

Because soil slaking and the formation of a thin depositional seal typically occur in Portneuf furrows within 1 to 2.5 h after the start of irrigation (Segeren and Trout, 1991; Lentz and Bjorneberg, 2002), we surmised that the time-dependent process occurring after 2 h in the 0-PAM treatments was the result of the progressive formation of a wash-in seal. Apparently, PAM amendments inhibited wash-in seal formation by flocculating the <2-μm soil particles in the clay/PAM treatments, leaving few available to enter moderate-sized pores. Although PAM stabilized soil structure and helped preserve the larger pores, these apparently were occluded or screened by settling clay floccules. Either the presence of pores between the floccules in the deposited layer or the inhibition of wash-in sealing resulted in higher seepage rates and volumes for clay/PAM relative to clay/0-PAM treatments.

We hypothesize that it was PAM's stabilizing influence on the wetted perimeter of the silt/PAM channels that increased the time dependence of the seal formation process. Without PAM, silt-associated erosion and deposition continually expose and cover pores in the perimeter surface, and wash-in processes could not proceed on any given pore long enough to effectively seal it. By stabilizing the perimeter from erosion, PAM may maintain pore openings in the perimeter, giving an opportunity for wash-in sealing to proceed. Because the wash-in sealing rate is a function of the <2-μm particle load and because PAM caused little flocculation of silt particles, the sealing process proceeded more rapidly with increasing inflow silt concentrations.

Effect of Inflow PAM Concentration

When no inflow sediment was added, increasing inflow PAM concentrations had no significant effect on final seepage rate or cumulative seepage volume. In irrigation furrows, PAM commonly is observed to increase infiltration, although the effect is not always consistent in Portneuf soils (Lentz et al., 1992; Trout et al., 1995). The lack of seepage effect here may result from differences between furrows and miniflumes (see later discussion).

When inflow sediment was added, small PAM concentrations (0.4 mg L^{-1}) tended to increase cumulative seepage, whereas increasing PAM from 0.4 to 2 mg L^{-1} had no significant further effect (Fig. 6). The exception to this was the 0.5-silt treatment, which was discussed previously. These trends likely resulted from counteracting PAM effects on sediment flocculation and fluid viscosity. When inflow sediment was present, PAM flocculated the individual particles, and the resulting depositional seals were more permeable. At higher inflow PAM concentrations, the effects of flocculation were counteracted by the increased fluid viscosity, which inhibited water transport through soil pores.

Cumulative seepage volume trends of the clay/PAM treatment series imply a floccule-size effect. When inflow clay was 0.5 g L^{-1}, increasing PAM concentration from 0 to 0.4 mg L^{-1} increased the particle/floccule size from 2 to 90 μm (Table 5) and increased seepage volume (Fig. 6B). But when PAM concentration was increased from 0.4 to 2 mg L^{-1}, floccule size decreased from 90 to 55 μm (Table 5) and seepage volume decreased (Fig. 6B). Another example is illustrated in Fig. 6C. When inflow clay was 2 g L^{-1}, increasing PAM concentration increased floccule size from 2 to 150 μm, then to 440 μm (Table 6), and infiltration trended steadily upward. Apparently, the viscosity effect caused by increasing PAM concentration was opposed by the attendant increase in pore size (floccule size) in the depositional layer.

Multiple Seepage Control Mechanisms

Several lines of evidence suggest that seepage rates from channels are the end result of multiple soil or hydraulic processes. Consider, for example, the 0.5-silt and 2-silt treatments. First, the seepage patterns produced by 0.5- and 2-silt treatments in response to increasing inflow PAM concentrations were diametrically opposed (Fig. 6D, E). Second, note how the presence of PAM in inflows alters the 2-h seepage rate patterns produced by silt treatments in Fig. 3D–F. Without PAM, a seepage rate maximum occurs at 0.5-silt, but with PAM, the 2-h seepage rate increases linearly with sediment concentration. Third, consider that the seepage rate patterns for silt treatments without PAM are temporally invariant, whereas those for silt treatments with PAM change with time (Fig. 3D, E).

It is difficult to explain these responses to inflow silt and PAM based only on the actions of a single mechanism. Mechanisms controlling channel seepage may act simultaneously, both to inhibit seepage (i.e., gravitational settled layers, depositional seals, and wash-in sealing) or maintain or enhance seepage (i.e., erosional stripping of depositional layers and seals, development of macropores that bypass surface seals, or the occurrence of an ablation-deposition equilibrium [silt sediments], which prevents formation of surface seals).

Relating Results to Larger-Scale Channels

Many of the small channel processes studied here are present in larger channels such as irrigation furrows or unlined irrigation canals. The formation of thin depositional seals, wash-in sealing of wetted perimeter soils, and erosional processes potentially occur at both scales. Similarly, the effect of inflow PAM concentrations on flocculation of suspended particles and any viscous effects on infiltrations should occur in small or large channels. Obviously, the formation of >1-cm-thick sediment layers by gravitationally induced settling was not possible in miniflume channels.

Interpretation and extension of miniflume results to larger-scale flows can be influenced by hydrologic imparities between the flow regimes. The miniflume advance rates, 0.02 to 0.2 m min^{-1}, were slower than typically present in irrigation furrows, approximately 1 m min^{-1}. Thus, miniflume flows wet-up the soils more slowly and were not as destabilizing and dispersive of soil aggregates or as erosive as furrow streams. However, because well dispersed sediment was already being applied in most treatment inflows, the stream advance impacts on aggregate stability, and dispersion were likely more a concern for 0-sediment treatments.

Average flow shear in miniflume channels was similar to that in irrigation furrow streams; however, furrow stream velocities (Table 6) and channel depths, 0.01 to 0.06 m, are typically greater than that in the miniflume flows (0.0017- to 0.003-m channel depths). Because stream transport capacity is considered proportional to stream velocity and channel depth (Graf, 1984), a furrow stream has a greater capacity to transport sediment than miniflume flows. Thus, sediment deposition produced in the miniflumes at given inflow sediment concentrations may be greater than that produced in furrow streams, at equivalent sediment concentrations. In furrow streams, the same change in seepage rate patterns we produced in miniflumes, at a given level of inflow sediment concentration, may require greater sediment concentrations.

A means of determining how well our miniflume flow-field models the behavior of larger irrigation flows is to examine the dynamic similarity of the small-scale model and full-size systems. Assuming that the critical forces acting on water flow fields and sediment particle settling in channeled flows are gravitational, inertial, and viscous, the dynamic similarity of the model and full-scale systems are thought to be compatible if their nondimensional particle Reynolds and Froude numbers are comparable (Vennard and Street, 1982). The range of the Reynolds and Froude number values computed for miniflume and several furrow and small canal systems were found to overlap one another (Table 6). This suggests that the miniflume results may be applicable in several furrow and small irrigation canal systems, with due consideration for limitations previously discussed.

CONCLUSIONS

This research evaluated the influence of inflow sediment type and concentration and inflow PAM concentration on seepage loss from an unlined silt loam channel in a miniflume. These factors interacted in a complex fashion to increase or decrease seepage losses from the flowing stream relative to untreated inflows. For the conditions in this experiment, we found the following:

1) When sediment was added to channel inflows, seepage losses were greater for coarse particles (silt) than for clay treatments. We hypothesized that silt produces greater seepage because of its lower <2-μm particle content and increased ablation activity. This relationship held even when PAM was added, suggesting that several mechanisms are active in the sealing process.
2) However, the addition of sediment to inflowing water and its deposition in the channel did not always result in a reduced seepage. For example, the 0.5-silt/0-PAM treatment produced greater seepage loss than the 0-sediment/0-PAM.
3) The effect of increasing inflow sediment concentrations on seepage losses was a function of inflow sediment type and inflow PAM concentration. In general, increasing clay sediment tended to decrease seepage loss, whereas increasing silt sediment tended to increase seepage. Adding PAM to inflows mitigated the influence of inflow sediment concentration on seepage losses.
4) The influence of increasing inflow PAM concentrations on seepage losses was a function of inflow sediment type and concentration. Increasing PAM inputs increased seepage losses only at higher (2 g L^{-1}) sediment inflow rates. At 0 and 0.5 g L^{-1} inflow sediment rates, increasing PAM inputs either decreased or had no effect on seepage losses.
5) Unlike the thin depositional seal, which forms rapidly after the irrigation start, we hypothesized that the wash-in seal formation progresses more slowly and is promoted by PAM amendments, which stabilize the large soil pores that are most susceptible to wash-in plugging.
6) In addition to the effects of thin depositional seals and the plugging of soil pores by wash-in seals, which act to inhibit seepage losses, other mechanisms associated with inflow silt inputs can act to maintain or increase seepage rates. These mechanisms may be related to ablation activity, macropore formation, or stabilization of the channel-wetted perimeter and are sensitive to inflow concentrations of sediment or PAM.

REFERENCES

Ajwa, H. A., and T. J. Trout. 2006. Polyacrylamide and water quality effects on infiltration in sandy loam soils. Soil Sci. Soc. Am. J. 70:643–650.

Behnke, J. J. 1969. Clogging in surface spreading operation for artificial ground-water recharge. Water Resour. Res. 5:870–876.

Ben-Hur, M., and R. Keren. 1997. Polymer effects on water infiltration and soil aggregation. Soil Sci. Soc. Am. J. 61:565–570.

Bouwer, H., J. Ludke, and R. C. Rice. 2001. Sealing pond bottoms with muddy water. Ecol. Eng. 18:233–238.

Bouwer, H., and R. C. Rice. 1989. Effect of water depth in groundwater recharge basins on infiltration. J. Irrig. Drain. Eng. 115:556–567.

Brown, M. J., W. D. Kemper, T. J. Trout, and A. S. Humphreys. 1988. Sediment, erosion and water intake in furrows. Irrig. Sci. 9:45–55.

Chow, V. T. 1959. Open-Channel Hydraulics. McGraw-Hill, New York.

Eisenhauer, D. E. 1984. Surface sealing and infiltration with surface irrigation. PhD dissertation. Dissertation Abstract 84-17087. Colorado State University, Fort Collins, CO.

Falatah, A. M., A. M. Al-Omran, A. A. Shalaby, and M. M. Mursi. 1999. Infiltration in a calcareous sandy soil as affected by water-soluble polymers. Arid Soil Res. Rehab. 13:61–73.

Graf, W. H. 1984. Hydraulics of Sediment Transport. Water Resources Publications, Littleton, CO.

Hall, W. A. 1957. An analyses of sand filtration. J. Am. Soc. Civil Eng. Sanit. Eng. Div. 83 (SA 3). Paper 1276.

Helalia, A. M., and J. Letey. 1989. Effects of different polymers on seedling emergence, aggregate stability, and crust hardness. Soil Sci. 148:199–203.

Herrington, T. M., B. R. Midmore, and J. C. Watts. 1993. Flocculation of kaolin suspensions by polyelectrolytes. *In:* Colloid-Polymer Interactions. Vol. ACS Symp. Ser. (ACSMC8). American Chemical Society, Washington, DC, pp. 532 (161–181).

Hillel, D. 1998. Environmental Soil Physics. Academic Press, New York, NY.

Hocking, M. B., K. A. Klimchuk, and S. Lowen. 1999. Polymeric flocculants and flocculation. J. Macromol. Sci. Polym. Rev. 39:177–203.

Houston, S. L., P. D. Duryea, and R. Hong. 1999. Infiltration considerations for ground-water recharge with waste effluent. J. Irrig. Drain. Eng. 125:264–272.

Ives, K. J. 1989. Filtration studied with endoscopes. Water Res. 23:861–866.

Kemper, W. D., R. Rosenau, and S. Nelson. 1985. Gas displacement and aggregate stability of soils. Soil Sci. Soc. Am. J. 49:25–28.

Kemper, W. D., and T. J. Trout. 1987. Worms and water. J. Soil Water Conserv. 42:401–404.

Kulicke, W. M., R. Kniewske, and J. Klein. 1982. Preparation, characterization, solution properties and rheological behaviour of polyacrylamide. Prog. Polym. Sci. 8:373–468.

LaMer, V. K., and T. W. Healy. 1963. Adsorption-flocculation reactions of macromolecules at the solid-liquid interface. Rev. Pure Appl. Chem. 13:112–132.

Lentz, R. D. 2003. Inhibiting water infiltration with PAM and surfactants: Applications for irrigated agriculture. J. Soil Water Conserv. 58:290–300.

Lentz, R. D., and D. L. Bjorneberg. 2002. Influence of irrigation water properties on furrow infiltration: Temperature effects. *In:* Sustaining the Global Farm [CD-ROM computer file]. 10th ISCO Conference Proceedings, May 23–28, 1999. D. Stout, R. H. Mohtar, and G. C. Steinhardt (eds.). ISCO and USDA-ARS NSERL, West Lafayette, IN.

Lentz, R. D., I. Shainberg, R. E. Sojka, and D. L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Lentz, R. D., and R. E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158:274–282.

Lentz, R. D., and R. E. Sojka. 2000. Applying polymers to irrigation water: Evaluating strategies for furrow erosion control. Trans. ASAE 43:1561–1568.

Lentz, R. D., R. E. Sojka, and B. E. Mackey. 2002. Fate and efficacy of polyacrylamide applied in furrow irrigation: Full-advance and continuous treatments. J. Environ. Qual. 31:661–670.

Lentz, R. D., R. E. Sojka, and C. W. Ross. 2000. Polymer charge and molecular weight effects on treated irrigation furrow processes. Int. J. Sediment Res. 15:17–30.

Letey, J. 1996. Effective viscosity of PAM solutions through porous media. *In:* Managing Irrigation-Induced Erosion and Infiltration With Polyacrylamide. Proc. Workshop, Twin Falls, ID, May 6–8, 1996. R. E. Sojka and R. D. Lentz (eds.). University of Idaho Miscellaneous Publication No. 101-96. University of Idaho, Moscow, ID, pp. 94–96.

Malik, M., and J. Letey. 1992. Pore-size-dependent apparent viscosity for organic solutes in saturated porous media. Soil Sci. Soc. Am. J. 56:1032–1035.

McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci. 85:185–1889.

McNeal, B. L., and N. T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc. 30:308–312.

Mitchell, A. R. 1986. Polyacrylamide application in irrigation water to increase infiltration. Soil Sci. 141:353–358.

Nadler, A., E. Perfect, and B. D. Kay. 1996. Effect of polyacrylamide application on the stability of dry and wet aggregates. Soil Sci. Soc. Am. J. 60: 555–561.

SAS Institute. 1999. SAS/STAT User's Guide, Version 8. Vols. 1, 2, and 3. SAS Institute, Cary, NC.

Segeren, A. G., and T. J. Trout. 1991. Hydraulic resistance of soil surface seals in irrigated furrows. Soil Sci. Soc. Am. J. 55:640–646.

Shainberg I., and M. J. Singer. 1985. Effect of electrolytic concentration on the hydraulic properties of depositional crust. Soil Sci. Soc. Am. J. 49:1260–1263.

Sirjacobs, D., I. Shainberg, I. Rapp, and G. J. Levy. 2000. Polyacrylamide, sediments, and interrupted flow effects on rill erosion and intake rate. Soil Sci. Soc. Am. J. 64:1487–1495.

Snedecor, G. W., and W. G. Cochran. 1980. Statistical Methods, 7th Ed. Iowa State University Press, Ames, IA.

Sojka, R. E., R. D. Lentz, C. W. Ross, T. J. Trout, D. L. Bjorneberg, and J. K. Aase. 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. J. Soil Water Conserv. 53:325–331.

Sojka, R. E., R. D. Lentz, and D. T. Westermann. 1998b. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J. 62:1672–1680.

Southard, R. J., I. Shainberg, and M. J. Singer. 1988. Influence of electrolyte concentration on the micromorphology of artificial depositional crust. Soil Sci. 145:278–288.

Tam, K. C., and C. Tiu. 1993. Rheology of water-soluble polymers: A comparative study on the effect of monovalent salt. Polym.-Plast. Technol. Eng. 32:123–138.

Terry, R. E., and S. D. Nelson. 1986. Effects of polyacrylamide and irrigation method on soil physical-properties. Soil Sci. 141:317–320.

Trout, T. J. 1990. Surface seal influence on surge flow furrow infiltration. Trans. ASAE 35: 1583–1589.

Trout, T. J., and H. Ajwa. 2001. Polyacrylamide effects on infiltration in San Joaquin Valley sandy loam soils. 2001 ASAE Annual Meeting, Sacramento, CA. Paper 012259. ASAE American Society of Agricultural and Biologically Systems Engineers, St. Joseph, MI.

Trout, T. J., R. E. Sojka, and R. D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. Am. Soc. Agric. Eng. 38:761–765.

Vennard, J. K., and R. L. Street. 1982. Elementary fluid Mechanics. Wiley, New York, NY.