Infiltration and Soil Water Distribution in Irrigation Furrows Treated with Polyacrylamide

R. D. Lentz, E. Bautista, A. C. Koehn, R. E. Sojka

Highlights

- Control furrows with 1× inflow rates were compared with 3× advance inflows treated with 10 mg L^{-1} polymer (WSPAM).
- WSPAM reduced sediment loads in furrow streams by 89%, despite its 3× greater advance inflows.
- WSPAM furrow advance times and infiltrated volumes were greater than predicted from increased inflows alone.
- WSPAM enabled reduced upper-section infiltration and increased lower-section infiltration relative to control furrows.

Abstract. *Few if any studies have measured the effects of water-soluble anionic polyacrylamide (WSPAM) on infiltration and soil water distribution in different segments of irrigation furrows. We conducted a four-year study on a silt loam soil with 1.5% slopes. Control furrows received no WSPAM and inflows were 15.1 L min^{-1}, whereas WSPAM was applied using 10 mg L^{-1} a.i. to 45 L min^{-1} inflows during furrow advance. Despite its greater advance phase inflow rates, WSPAM application reduced sediment concentrations in furrow streams by an average of 89% relative to the control. A surface irrigation model, WinSRFR 5.1, was used to separate furrow inflow rate effects on infiltration from that of WSPAM. Relative to results predicted by simulation for the entire furrow, the polymer treatment: (1) increased advance time an average 1.4-fold, (2) increased advance-phase infiltrated volume 1.5-fold, and (3) increased infiltration volume at the common opportunity time 1.2-fold. Hence, these effects resulted from WSPAM and not from differences in treatment inflow rates. Treatment infiltration amounts varied markedly among irrigations and years, as did the intensity of WSPAM effects. These were attributed mainly to differences in infiltration opportunity time, but temporal differences in soil water content during furrow formation, irrigation water electrical conductivity, initial soil surface water content and water temperature, and the irrigation-long, furrow-stream mean sediment content also appear to have influenced infiltration rates. Although inconsistent, WSPAM increased net furrow infiltration in the lower section and reduced infiltration in the upper section relative to control furrows. This effect could not be explained by the greater inflow rate and shorter advance time of the WSPAM treatments and was attributed to spatially variable WSPAM effects on infiltration opportunity time and possibly irrigation water viscosity. The WSPAM management approach, while protecting against furrow erosion, may potentially provide a means of improving irrigation uniformity and reducing associated percolation water and nutrient losses.*

Keywords. *Furrow advance, Irrigation, Irrigation uniformity, Polymers.*

Approximately 74% of the 324 Mha of worldwide irrigated area is furrow or flood irrigated (FAO, 2016). Irrigated farmland has an important impact in the U.S. economy as it produces a large share of the total crop value. In the U.S., about one-third of irrigated cropland, 8.7 Mha, is furrow irrigated (USDA-NASS, 2014). Treating irrigation furrows with water-soluble anionic polyacrylamide (WSPAM) can increase infiltration, increase advance time, reduce furrow erosion, and reduce sediment, total P, dissolved P, and total N in furrow runoff water (Sojka et al., 2007; Chao-Yin et al., 2012; McNeal et al., 2017; Li et al., 2019).

Mitchell's (1986) early research reported increases in furrow infiltration rates induced by the application of WSPAM. Subsequent studies confirmed this effect to be a surface phenomenon associated with WSPAM's capacity to stabilize surface structure and porosity and alter the formation of a soil surface seal (Sojka et al., 2007). In contrast, where soil structure is absent or has been destroyed, or in massive coarse-textured soils, infiltration may be reduced by WSPAM due to the increased viscosity of treated water (Malik and Letey, 1992; Ajwa and Trout, 2006; Li et at, 2019). The interplay between WSPAM's soil stabilizing versus viscosity effects on furrow infiltration is more apparent when WSPAM is applied to the irrigation water continuously than when WSPAM is applied

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The authors are **Rick D. Lentz,** Research Soil Scientist, USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho; **Eduardo Bautista,** Agricultural Engineer, USDA-ARS U.S. Arid Land Agricultural Research Center, Maricopa, Arizona; **Anita C. Koehn,** Soil Scientist, and **Robert E. Sojka,** Research Soil Scientist (retired), USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. **Corresponding author:** Rick D. Lentz, 3793 N. 3600 E., Kimberly, ID 83341-5076; phone: 208-423-6531; e-mail: rick.lentz@usda.gov.

only during the advance phase. For example, when the concentration of WSPAM continuously applied to the furrow inflows increases from 0 to ~1.5 mg L^{-1}, total furrow erosion losses decline to a minimum, while total furrow infiltration simultaneously increases to a maximum. However, increasing the inflow WSPAM concentration above 2 mg L^{-1} produces declining total infiltration amounts while continuing to minimize furrow erosion (Lentz, 2008).

Variations in infiltration rate and infiltration opportunity time (the time that water is in contact with the soil) cause non-uniformities in the net water application along the length of a furrow (Trout, 1990). WSPAM treatment can help reduce this non-uniformity relative to untreated furrows by stabilizing the soil structure, allowing the use of larger inflow rates on erosion-prone soils, and thus reduce differences in opportunity time along the field. Applying WSPAM only during the advance phase at ≤10 mg L^{-1} efficiently uses the polymer, ensuring adequate stability of the soil structure and porosity, yet minimizing WSPAM viscosity effects over much of the irrigation set (Sojka et al., 2007; Lentz, 2008). While research has examined WSPAM's effect on infiltration over the furrow as a whole, few if any studies have examined how WSPAM treatment may affect infiltration and soil water distribution in different reaches of the furrow. We hypothesize that applying WSPAM during the advance phase will permit tripling of the initial furrow inflow rate, which will (1) speed stream advance, (2) reduce disparities in opportunity time between upper and lower furrow locations, and (3) improve water application uniformity.

In this four-year field study, we examined the influence of control and WSPAM treatments on furrow infiltration and soil water content at upper versus lower positions in the furrows (i.e., inflow end versus outflow end). A modeling approach was used to evaluate the contribution of furrow inflow rates to infiltration separately from the contribution of WSPAM.

Materials and Methods

The field study was established on Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) near Kimberly, Idaho (42° 31′ N, 114° 22′ W, 1198 m elev.). This deep soil is formed in silt loam and very fine sandy loam sediments. The surface soil is a silt loam, with 630 g kg^{-1} silt, 150 g kg^{-1} clay, 220 g kg^{-1} sand, 10 to 13 g kg^{-1} organic carbon, 5% calcium carbonate equivalent, and a pH of 7.7 (saturated paste). The free-draining test furrows were between 175 and 180 m long, with an average 2.0% slope in the upper third of the field and 1.5% slope in the bottom two-thirds.

Water-Soluble Polyacrylamide

Two linear anionic WSPAM formulations were employed, both with molecular weights of 15 to 20 Mg mol^{-1}. The granular WSPAM (Pg) was an acrylamide/sodium acrylate copolymer with 18% charge density. The liquid emulsion WSPAM (Pe) was an acrylamide/acrylic acid-ammonium salt copolymer with 30% charge density (Lentz and Sojka, 2009). The WSPAM emulsion product included additional additives, oil, and small amounts of surfactants and emulsifiers. Two separate stock solutions were prepared from the Pg (2400 mg L^{-1}) and Pe (1200 mg L^{-1}) by dissolving or mixing in tap water (electrical conductivity [EC] = 0.09 S m^{-1}, sodium adsorption ratio [SAR] = 1.5). These solutions were injected into the furrow inflows at rates needed to meet target concentrations. The stock solutions were made up the day before an irrigation to ensure that the polymers were fully hydrated and dispersed.

Experimental Design and Plots

The experimental design was a randomized complete block with three replicates (fig. 1). The three furrow irrigation treatments included WSPAM prepared from a granular product (Pg), WSPAM prepared from an emulsion product (Pe), and an untreated control (C). Five to seven irrigations were applied each year. These consisted of two irrigation types: (1) fresh, where irrigations were applied to newly formed furrows (two irrigations per year: the first irrigation and the irrigation after a mid-season cultivation); and (2) repeat, where irrigations were applied to previously irrigated but otherwise undisturbed furrows (table 1). Polymer

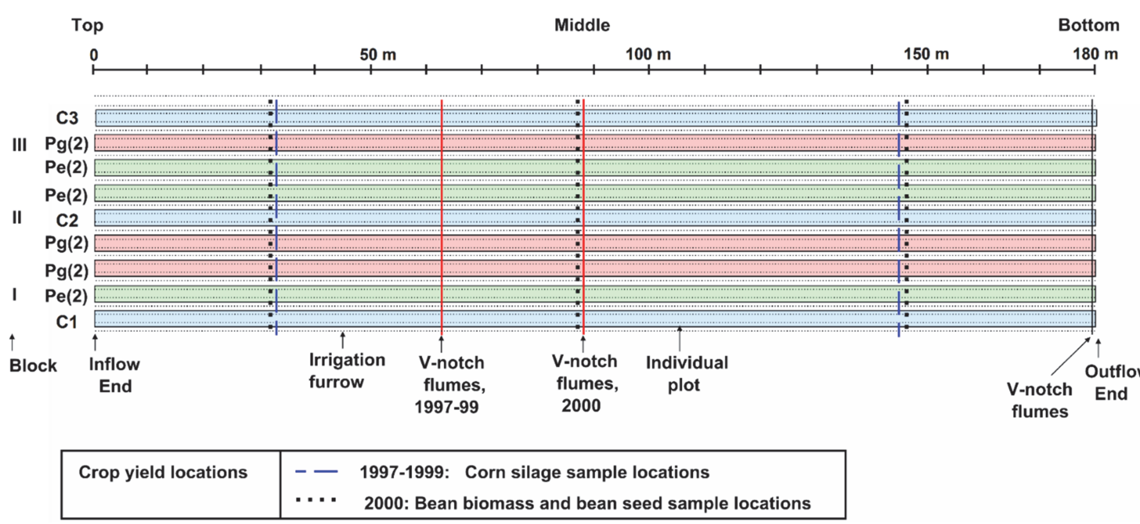

Figure 1. Experimental plot layout including locations of V-notch flumes and crop yield measurement locations in each year. Treatment plots are identified as C = control, Pe(2) = WSPAM-e (emulsion), and Pg(2) = WSPAM-g (granular), and the plot number is the replicate.

Table 1. Irrigation dates and furrow status. Fresh furrows were newly cultivated and not irrigated previously, while "1st repeat" to "5th repeat" indicate the number of repeated irrigations applied to previously irrigated but uncultivated furrows (DOY = day of year).

	Experiment 1									Experiment 2		
	1997			1998			1999			2000		
Irrigation	Date	DOY	Status	Date	DOY	Status	Date	DOY	Status	Date	DOY	Status
1	16 July	197	Fresh	8 July	189	Fresh	23 June	174	Fresh	22 June	174	Fresh
2	29 July	210	Repeat	22 July	203	Fresh	8 July	189	Fresh	11 July	193	1st repeat
3	13 Aug.	225	Fresh	5 Aug.	217	1st repeat	14 July	195	1st repeat	25 July	207	Fresh
4	27 Aug.	239	1st repeat	18 Aug.	230	2nd repeat	28 July	209	2nd repeat	8 Aug.	221	1st repeat
5	10 Sept.	253	2nd repeat	2 Sept.	245	3rd repeat	11 Aug.	223	3rd repeat	17 Aug.	230	Fresh
6	-	-	-	-	-	-	25 Aug.	237	4th repeat	-	-	-
7	-	-	-	-	-	-	8 Sept.	251	5th repeat	-	-	-

treatments were applied on an active ingredient (a.i.) basis to the furrow inflows only during the advance phase of the irrigation. The polymers were applied in each irrigation.

EXPERIMENT 1

In 1997 to 1999, the treatments consisted of an untreated control and two WSPAM treatments, the first using Pg (10 mg L^{-1} a.i.) and the second using Pe (10 mg L^{-1} a.i. emulsion PAM). Considering the potential for soil erosion, the control was irrigated with a relatively low inflow rate, nominally 15.0 L min^{-1} (mean = 15.8 L min^{-1}, SD = 1.4). This inflow rate was used throughout the irrigation (i.e., during both the advance and post-advance phases). Considering WSPAM's potential for increasing infiltration rates and producing larger differences in opportunity time along the field, and the polymer's erosion-reduction benefits (Sojka et al., 1998a), WSPAM-treated furrows were irrigated during the advance phase using a mean 45 L min^{-1} inflow rate (SD = 2.4) followed by an untreated, post-advance phase irrigation at 15 L min^{-1} (table 2). Previous research showed that, in this highly erodible soil, the 3× WSPAM inflow rate slightly decreased the WSPAM advance time relative to the untreated control (Sojka et al., 1998a).

EXPERIMENT 2

In 2000, treatments included an untreated control that used a 1× inflow rate during both the advance and post-advance phases, Pg2 (125 mg L^{-1} a.i.) applied during the advance phase at a 1× inflow rate, and Pe2 (10 mg L^{-1} a.i.) applied during the advance phase at a 30 L min^{-1} (2×) inflow rate. All three treatments were subjected to 1× inflow rates during the untreated, post-advance phase. (table 2). The advance-phase inflow rates for Pg2 were not increased because the 125 mg L^{-1} WSPAM concentration increases water viscosity and decreases infiltration, potentially decreasing advance times (Lentz, 2008).

EXPERIMENTS 1 AND 2

The nominal 1× inflow rates of 15 L min^{-1} were increased by up to 40% in some irrigations where high infiltration greatly slowed stream advance; in these cases, the high WSPAM inflow rates were not changed. The irrigation duration for each treatment was adjusted in the field to ensure that the average infiltration over the entire furrow was the same for the control treatment as for the WSPAM treatments. This allowed treatment comparisons relative to furrow sections and was also done so that measured treatment yields were not affected by differences in net water inputs. Each experimental unit consisted of a 3 m wide × 180 m long plot separated from adjacent plots by a 1.5 m wide buffer strip. Irrigation water was applied to wheel-trafficked furrows spaced 1.52 m (1.12 m in 2000) apart and parallel to the long axis of the plots.

Table 2. Furrow sections, irrigations, and treatments monitored each year. "Entire" indicates that irrigation was monitored at the bottom of the field only. For select irrigations and treatments, a V-notch flume also measured furrow flow rates at 1/3 or 1/2 of the distance from the top.

Experiment and Year	Monitored Units			
	Furrow Section[a]		Irrigations	Treatments[b]
Experiment 1				Control (0 mg L^{-1}, 15 and 15 L min^{-1})
1997	Entire furrow		All	Pg (10 mg L^{-1}, 45 and 15 L min^{-1})
	Upper 1/3	Lower 2/3	3 and 4	Pe (10 mg L^{-1}, 45 and 15 L min^{-1})
1998	Entire furrow		All	Control, Pg, Pe
	Upper 1/3	Lower 2/3	1, 2, and 3	Control, Pg, Pe
1999	Entire furrow		All	Control, Pg, Pe
	Upper 1/3	Lower 2/3	All	Control, Pg
Experiment 2				Control (0 mg L^{-1}, 15 and 15 L min^{-1})
2000	Entire furrow		All	Pg2 (125 mg L^{-1}, 15 and 15 L min^{-1})
				Pe2 (10 mg L^{-1}, 30 and 15 L min^{-1})
	Upper 1/2	Lower 1/2	All	Control, Pg2

[a] Upper = upper portion of furrow; Lower = lower portion of furrow (i.e., inflow end versus outflow end).
[b] Treatment values are WSPAM concentration (mg L^{-1}) and advance phase and post-advance phase inflows (L min^{-1}).
Pg indicates that the WSPAM source was granular form; Pe indicates that the WSPAM source was emulsion form.

FIELD OPERATIONS

Each year, plots were moldboard plowed to 0.2 m depth to prepare for planting, except in 1997 when they were disk plowed to 0.1 m depth (because no crop was grown in 1996). Field work was delayed in 1997 to troubleshoot and repair buried percolation samplers that were co-located in the field. Plots were planted to a short-season corn variety (*Zea mays* L.) on 8 July 1997, to silage corn on 1 June 1998, and to silage corn on 18 May 1999. Edible bean (*Phaseolus vulgaris* L.) was planted on 2 June 2000. Snake River water with an average EC of 0.4 dS m^{-1}, pH of 7.6, and SAR of 0.06 was used for irrigation. The first irrigation typically occurred in the first or second week of June but was delayed until 16 July in 1997 because of the late planting and until 8 July in 1998 due to cool, wet spring conditions.

DATA COLLECTION

Data were collected in 1997, 1998, 1999, and 2000. We monitored one of the two furrows in each plot, measuring furrow inflow and runoff rates and runoff sediment concentrations for all irrigations, except irrigation 5 in 1997. Prior to each irrigation, soil samples were collected at 0 to 5 cm depth at three locations in each monitored furrow. Soil water content in the samples was determined gravimetrically.

Furrow inflow and outflow (i.e., runoff) rates and runoff sediment concentrations were measured during each monitored irrigation. Inflows were metered into furrows under constant hydrostatic pressure, and flows were checked by measuring the time to fill a known volume. Runoff rates were measured with long-throated V-notch flumes installed at the ends of the furrows. For selected irrigations and treatments, an extra flume was installed and monitored at 1/3 the distance down the furrow in 1997 to 1999 or at the halfway point in 2000. Flow measurements were used to calculate, during the irrigation, the infiltration depth (volume per unit area) in the upper and lower portions of the monitored furrows (fig. 1 and table 2). During each irrigation, furrow inflow and outflow data were input into a modified version of the WASHOUT program, named WASH-FLD, which computed real-time cumulative net infiltration amounts and forecast the irrigation shutoff times needed for the furrow treatment groups to attain similar infiltration targets (Lentz and Sojka, 1995; Lentz, 1998). Each time runoff rates were measured, we collected 1 L of runoff and measured the volume of sediment that settled in an Imhoff cone after 0.5 h (10 to 21 times per furrow and irrigation as defined by Lentz and Sojka, 2009). Subsets of 1 L runoff samples collected from each furrow for each irrigation were filtered to obtain their soil masses, which were used with settled sediment volumes to calculate calibration functions (Sojka et al., 1992). WASHOUT (Lentz and Sojka, 1995) used the volume-mass data to fit individual calibrations as a function of irrigation, furrow type (fresh vs. repeat), and treatment, and calculate furrow sediment losses.

Crop yields were measured every year. Corn silage yields were measured at the upper-half and lower-half field locations (fig. 1). At each location, two 3 m lengths of the planted corn row were collected, one from either side of a treated irrigation furrow. Bean yields were determined from upper, middle, and lower locations (fig. 1). At each location, a 3 m length of bean row was collected.

INFILTRATION CALCULATIONS

Infiltration measurements are comparable when those measurements are obtained for the same opportunity time, i.e., for the same time of contact between the soil surface and the water, and for the same boundary conditions (infiltrating surface and water pressure). Comparing infiltration among furrows is challenging because the opportunity time naturally varies along the length of the field depending on the stream advance. In this study, opportunity time also varied because of the systematic difference in inflow rate between control and WSPAM furrows, with the latter receiving three times the inflow rate of the former during the advance phase. (A larger inflow rate increases the average opportunity time by decreasing advance time for a given application time and infiltrating surface.) Thus, the data set reported herein varied substantially in opportunity from one event to the next every year. To compare infiltration parameters across furrow events and years, we calculated them based on an equivalent opportunity time, termed the common average opportunity time, that was common to all furrows.

The common average opportunity time was defined considering only the time between the final advance (t_L) and the cutoff time (t_{co}): $t_L \le t \le t_{co}$. Within this time interval and for any furrow test (a furrow during an irrigation event), the average opportunity time (τ_{avg}) at time t is given by:

$$\tau_{avg} = \frac{1}{L}\int_0^L \left(t - t_x\right) dx \tag{1}$$

$$x = p t_x^r \tag{2}$$

where p [L/Tr] and r (dimensionless) are empirical coefficients, unique to each furrow test. The exponent r is in principle less than unity, which implies that advance rates decrease with time. Substituting equation 2 into equation 1 yields:

$$\tau_{avg} = t - \frac{a}{b+1} L^b \tag{3}$$

where $b = 1/r$ and $a = (1/p)^b$. The common average intake opportunity time (τ_{avg}^*) was defined as the value of τ_{avg} calculated for the furrow test with the shortest cutoff time and longest advance time. A value of 7.33 h was determined from irrigation 1, furrow 38 in 1997. This result was then used to determine the time (t_i) for each individual test i at which $\tau_{avg} = \tau_{avg}^*$, which is the time that was then used for computing infiltration:

$$t_i = \tau_{avg}^* + \frac{a}{b+1} L^b \tag{4}$$

For some tests, two distance versus advance time pairs were measured, and those values were used to determine p and r. For other tests, advance times were measured only at the end of the field (tests without intermediate flow rate measurements). In those cases, r was assumed equal to the average r of other tests and used to calculate p.

The time given by equation 4 was used to calculate the infiltration volume at the common opportunity time (Vinftau) for each furrow test using volume balance techniques. In volume balance analysis:

$$V_z(t_i) = V_{in}(t_i) - V_y(t_i) - V_{ro}(t_i) \tag{5}$$

where V_z, V_{in}, V_y, and V_{ro} are the infiltrated, inflow, surface storage, and runoff volumes, respectively, and t_j is a discrete time at which volume balance is calculated. V_{in} and V_{ro} were determined from the measured upstream and downstream hydrographs, respectively. Surface storage was estimated as:

$$V_y = A_0 \cdot \sigma_y \cdot L \tag{6}$$

where A_0 is an estimate of the upstream flow area, σ_y is the ratio of the average flow area to the upstream flow area, and L is as previously defined. Both A_0 and σ_y are functions of the inflow rate, the variation in furrow cross-sectional flow area with flow depth, the field bottom slope, and the roughness coefficient (the Manning n coefficient if using the Manning flow resistance equation). Procedures for their calculation are described by Bautista et al. (2012). Furrow cross-sectional measurements were used to determine the relationship between flow depth and flow area. Although the available measurements showed substantial variations in cross-section, within a furrow and among furrows, a uniform parabolic relationship was assumed and used to describe the furrow cross-section, as given by the relationship:

$$TW = 1.67 y^{0.55} \tag{7}$$

where TW is the top width [L], and y is the flow depth [L]. The exponent in this expression is dimensionless, but the constant depends on the units used for y and TW, in this case meters. The only input to equation 6 that was not measured was the Manning n coefficient, but a reasonable value for n is 0.04 (USDA-SCS, 1984) (for furrows, n can be expected to vary in the range from 0.02 to 0.08). Because the field slope is relatively steep (nearly 1.7%), surface storage can be expected to be small relative to the applied volume. Consequently, the estimated V_z values are only slightly sensitive to the furrow geometric parameters and to n. For the control furrows, which were irrigated with an inflow rate of about 15 L min^{-1}, the estimated V_y was slightly over 0.2 m^3. For the treatments, which were irrigated with a flow rate three times larger during the advance phase, V_y was approximately 0.5 m^3 during the advance phase and 0.2 m^3 during the post-advance phase.

The times t_i (eq. 4) were also used to evaluate an average near-steady infiltration rate per unit area (InfRtau [$L\ T^{-1}$]):

$$\text{InfRtau} = \frac{Q_{in}(t_i) - Q_{ro}(t_i)}{L \cdot FS} \tag{8}$$

where Q_{in} and Q_{ro} are the inflow and runoff rates, respectively, and FS is the furrow spacing. For all furrows, the infiltration rates were still declining at the calculation time, but the change was very slow. Hence, the calculated infiltration rate values provide a reasonable approximation of the long-term infiltration rates for these furrows. Finally, the advance phase infiltration rates for each furrow were calculated by dividing Vinfadv by its corresponding advance phase average opportunity time.

Irrigation Modeling

Infiltration data from experiment 1 and hydraulic simulation were used to examine if the differences in infiltrated volume between the controls and the WSPAM treatments could be attributed to the differences in inflow rate alone. The surface irrigation software WinSRFR 5.1 (Bautista and Schlegel, 2019) was used for this part of the analysis. Inputs required by the simulation are geometric parameters (length, field bottom slope, cross-sectional geometry, furrow spacing), infiltration and hydraulic resistance characteristics, the upstream inflow hydrograph, and the downstream boundary condition, i.e., whether the furrow is free-draining or blocked. All these inputs, summarized in table 3, have been described in previous paragraphs except infiltration, which is discussed next.

The simulation assumed common and spatially uniform infiltration conditions for both the control furrows and the WSPAM-treated furrows. Infiltration was modeled with an approximate solution to the two-dimensional Richards equation, identified in WinSRFR as the Warrick-Green-Ampt (WGA) equation. This equation accounts for the effects of variable wetted perimeter and water pressure on infiltration. The WGA parameters, i.e., Green-Ampt equation parameters (Green and Ampt, 1911), were determined with a combination of soil hydraulic data previously obtained at the USDA-ARS Northwest Irrigation and Soils Research Laboratory (NWISRL), pedotransfer functions, and inverse modeling. Saturated hydraulic conductivity (K_s) and an empirical factor that accounts for macropore infiltration were calibrated using inverse modeling. A single control furrow test (identified as year 1997, irrigation 1, furrow 30) was used for the calibration. WinSRFR 5.1 includes an infiltration parameter estimation procedure, known as EVALUE, that can be used in combination with the WGA infiltration equation. Details of that procedure and its use are provided by Bautista and Schlegel (2017). Table 3 summarizes the WGA param-

Table 3. Geometric parameters and Warrick-Green-Ampt equation parameters used in furrow simulations.

Parameter	Value
Geometric parameters	
Furrow length (L, m)	180
Furrow spacing (FS, m)	1.52
Furrow cross-sectional parameters	
Constant C (m mM^{-1})	1.6
Exponent M	0.55
Bottom slope (S_0, m m^{-1})	
0 to 67 m	0.02
67 to 180 m	0.015
Parameters of Warrick-Green-Ampt (WGA) equation	
Saturated water content (θ_S, V/V)	0.501
Initial water content (θ_0, V/V)	0.213
Wetting front pressure head (h_f, m)	0.341
Hydraulic conductivity (K_s, m h^{-1})	0.00275
Macropore infiltration constant (c, m)	0.002
Calibration parameter (γ)	1

eters used for simulation, as well as other hydraulic parameters. In table 3, the Green-Ampt wetting front pressure head is the value suggested by Kozak and Ahuja (2005) for a silt loam soil, which was derived from soil bubbling pressure values reported by Rawls et al. (1983). It is close to the pressure head values measured at NWISRL. The saturated hydraulic conductivity is a calibrated value and was less than half the value suggested by Rawls et al. (1983) and only a tenth of the NWISRL reported values. Infiltration appears to be dominated by porous media flow in this soil, as suggested by the calibrated value (0.002 m) for the macropore infiltration constant.

Simulations were conducted with a 180 m furrow length, first assuming an inflow rate of 15 L min^{-1}, as applied to the control furrows, and secondly by using 45 L min^{-1} during the advance phase and 15 L min^{-1} for the post-advance phase, as was done with the WSPAM-treated furrows. The cutoff time was set at 8 h, which is nearly the average of the application time t_i values described in the previous section. As with the volume balance analyses, the simulations assumed a Manning n of 0.04.

Furrow Section Net Infiltration

Net infiltration amounts for the upper and lower furrow sections were calculated for irrigations that included an additional furrow flume (table 2). These data allowed us to determine how treatments influenced the distribution of net infiltration in furrows during the full irrigation because the average net infiltration over the entire furrow was equivalent among treatments. Net infiltration was calculated for the upper section by subtracting the section's total outflow from the total furrow inflow; net infiltration was calculated for the lower section by subtracting the lower section's total outflow from the total outflow from the upper section. Total inflow and outflow values were computed with WASHOUT (Lentz and Sojka, 1995).

Calculations and Statistical Analyses

The statistical analyses were conducted using SAS (2012) and a significance probability (p-value) of 0.10. Arithmetic mean values and standard errors of the means were calculated with PROC MEANS and reported in figures. The influence of treatment and field location on crop yields each year were analyzed using PROC MIXED. Entire-furrow infiltration responses (Vinfadv, Vinftau, and InfRtau in experiments 1 and 2) were transformed using common logs as indicated by residual diagnostics. The effect of treatment, irrigation, and their interaction were analyzed using PROC MIXED ANOVA with replicate and treatment × replicate as the random effects. There was no evidence that the analysis needed to account for a covariance structure across irrigations; thus, a repeated statement was not included. Separation of irrigation × treatment mean values was determined by constructing confidence limits, and means were back-transformed to original units for reporting. Spearman rank correlations (PROC CORR option: spearman) analyzed the relationships between the infiltration estimates (Vinfadv, Vinftau, and InfRtau) and other factors that were quantified as part of the experiment, namely the advance-phase average opportunity time (Advtau), electrical conductivity (EC) of the water, initial water content, and water temperature.

The effect of treatment, irrigation, and their interaction on furrow section infiltration was analyzed as for the entire-furrow responses except that transformation of the data was not needed. Where section measurements were made for both WSPAM treatments (1997-1998), the overall differences between the two were not significant ($p > 0.3$). Therefore, the infiltration values measured in the Pg and Pe treatments were averaged within each block prior to analysis.

Results

Surface soil water content at the start of the irrigations varied from 2.3% to 17.4%, averaged 7.5% across all years and treatments, and generally did not differ among treatments for a given irrigation (fig. 2). Overall, the WSPAM applications reduced sediment concentrations in furrow streams by an average of 89% relative to the control. Thus, WSPAM successfully controlled erosion even though advance inflow rates were 3× greater than those used in control furrows.

Infiltration across Entire Furrow

Figure 3 shows the seasonal infiltration variation for each year. The first row of plots (A to D) represents the infiltration depth (volume per unit area) at the final advance time (Vinfadv), the second row (E to H) represents the infiltration depth at the common τ_{avg} (Vinftau), and the third row (I to L) represents the infiltration rate at τ_{avg} (InfRtau). Even though water infiltrates this soil very slowly (i.e., about 2.3 cm on average over nearly 8 h of average opportunity time for all furrows, irrigations, and years), the data exhibit substantial seasonal variability. The coefficient of variation was 39% for the Vinfadv data and 21% for the Vinftau data.

Experiment 1: Variability of Infiltration

While the infiltration seasonal variability pattern varied markedly from year to year, all treatments and furrows generally exhibited a similar pattern each year. During 1997, the infiltrated depth during advance (Vinfadv) decreased as the season progressed. In 1998, it increased, and in 1999 it first decreased, increased during irrigation 4, and then decreased again (figs. 3A to 3C). The same patterns can be observed in the Vinftau data. This is contrasted with previous studies that reported substantial differences in advance phase and post-advance infiltration variability resulting from macropore infiltration (Guzmán-Rojo et al., 2019). This confirms that infiltration in this soil is largely explained by porous media flow. The 1997 infiltration responses were distinguished from those of 1998 and 1999 in that the treatment differences appeared more pronounced in 1997, particularly for Vinftau (figs. 3E to 3G) and InfRtau (figs. 3I to 3K). This suggests that irrigation conditions in 1997 may have been unique relative to 1998 and 1999. Potential contributing factors are discussed later.

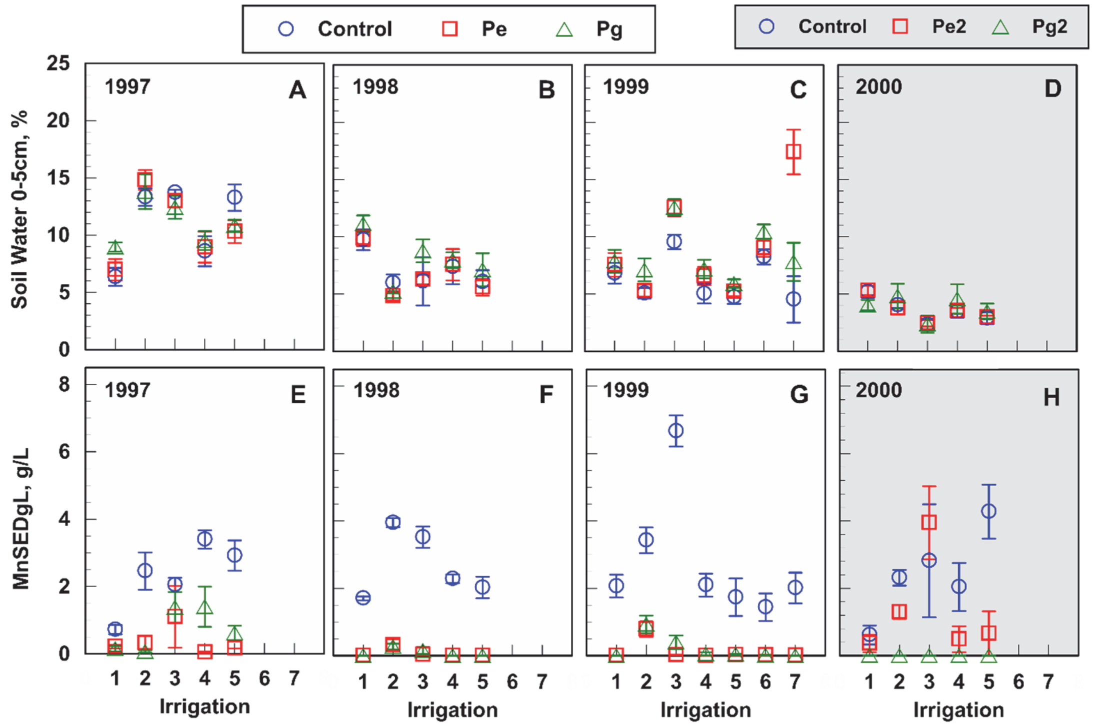

Figure 2. Mean initial furrow soil water content and mean furrow stream sediment concentrations for each irrigation in experiment 1 (1997-1999) and experiment 2 (2000). Each leg of the error bars indicates one standard error of the mean (*n* = 3).

Experiment 1: Treatment Effects

Table 4 summarizes the ANOVA analysis for the Vinfadv, Vinftau, and InfRtau data. Irrigation number, treatment, and their interaction ($p < 0.04$, table 4) had a significant effect on infiltration in most years. With a few exceptions, the irrigation mean Vinfadv for the WSPAM treatments was equal to, or less, than that of the control treatments (figs. 3A to 3C). A substantial reduction in WSPAM's Vinfadv was expected because its greater inflows reduced infiltration opportunity times, although this effect was slightly offset by a 33% increase in wetted perimeter. However, the reduction in Vinfadv was minimized because the WSPAM treatments consistently increased advance-phase intake rates by an average of 2.9-fold ($p < 0.0001$) over the control (1.0 vs. 0.35 cm h-1). This increased intake rate persisted beyond the advance phase and produced a consistent increase in cumulative infiltration (Vinftau) per irrigation, although the magnitude of the increase varied with irrigations (figs. 3E to 3G). One or both WSPAM treatments significantly increased Vinftau relative to the control in 15 of the 17 irrigations in 1997-1999. The polymer treatments as a group increased overall Vinftau ($p < 0.01$) by 1.2-fold relative to the control (2.32 cm vs. 1.94 cm), although the Pe treatment was more effective than Pg, particularly in repeat furrows. The WSPAM infiltration rate increase observed for Vinftau often was not reflected in InfRtau, the near steady-state infiltration rate at the common average opportunity time (figs. 3I to 3K). The Pe or Pg treatments increased InfRtau values relative to controls in 5 of the 17 irrigations, all in fresh furrows, but decreased InfRtau in 4 of the 17 irrigations, all in repeat furrows. These results also show that potential WSPAM treatment effects on infiltration rates are small relative to the temporal variability in infiltration. In general, the Pe and Pg treatment responses appear to be similar.

Experiment 1: Furrow Irrigation Simulation

Simulated final advance times and infiltration in comparison with measured values are shown in figure 4. Measured values were averaged for each year and treatment, with the Pe and Pg treatments combined as a single WSPAM treatment. In each plot, the first pair of bars represents the simulated values which, as was explained before, were computed using the control and WSPAM treatment inflow rates but assuming the same infiltration conditions. Of interest is quantifying the relative magnitude of the changes in simulated advance time and infiltration induced by the inflow rate and determining if the measurements are consistent with the simulation results.

The model predicted that, under the given conditions, a three-fold increase in inflow rate reduces the advance time by about 70%, from 2.1 h to 0.61 h. However, because of the non-linearity of the infiltration process and the increased wetted perimeter with a larger inflow rate, the advance phase infiltration depth decreases by only about 33% (from 0.6 cm to 0.42 cm). Ultimately, the larger advance phase inflow rate produces only a small difference in infiltration when compared at a common τ_{avg} (2.0 cm vs. 1.9 cm) when assuming a constant inflow rate of 15 L min^{-1}.

A comparison between the predicted and measured mean yearly values indicates that the control furrow values are reasonably close to the simulation results. This implies that the estimated infiltration function is representative of the infiltration process in this soil. Therefore, if WSPAM has no effect on infiltration, then the measured values for the WSPAM-treated furrows should also be similar to their corresponding

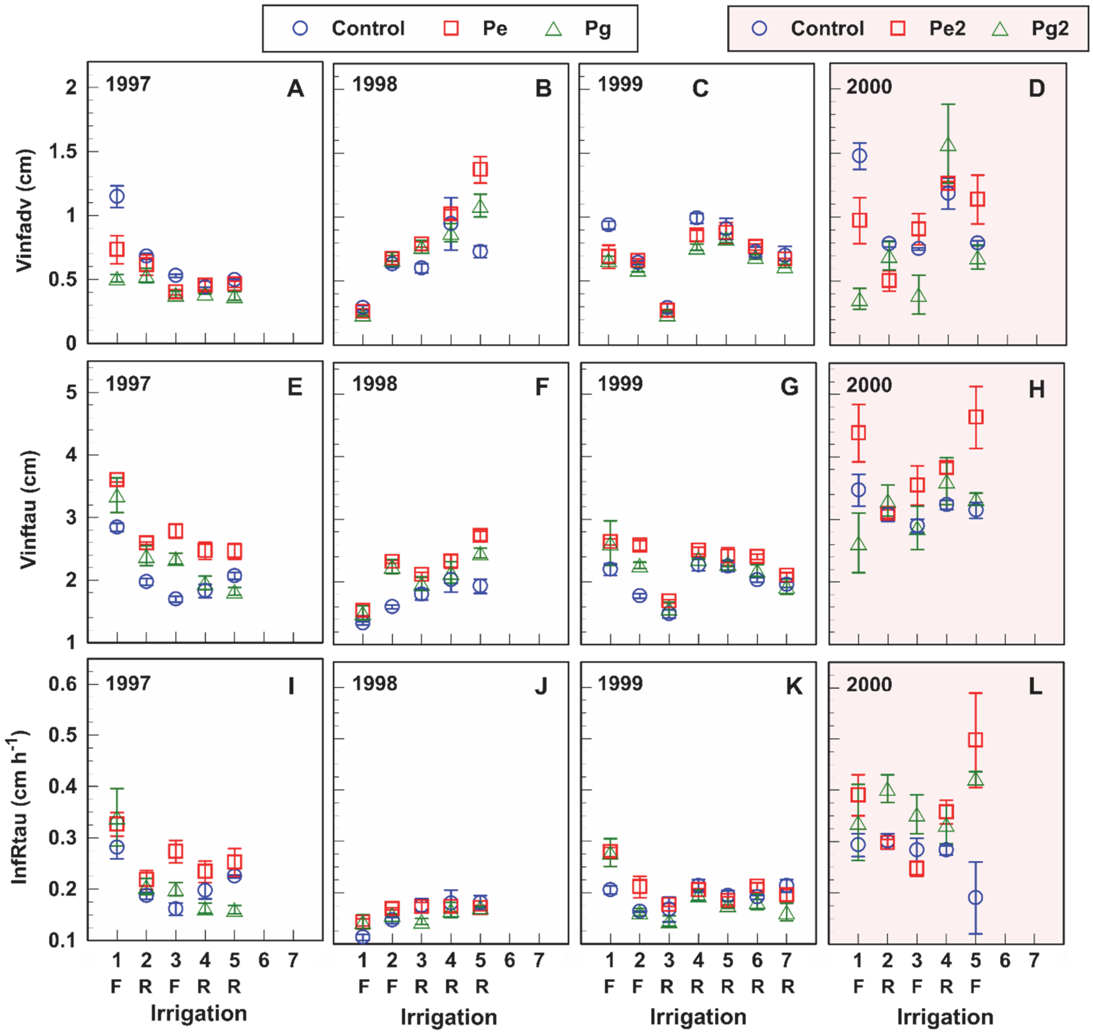

Figure 3. Infiltration components for the entire furrow for each year, irrigation, and irrigation type in experiment 1 (1997-1999) and for the entire furrow for each irrigation and irrigation type in experiment 2 (2000). Vinfadv (A, B, C, and D) is infiltrated depth at final advance, Vinftau (E, F, G, and H) is infiltrated depth at common average opportunity time (τ_{avg}), and InfRtau (I, J, K, and L) is infiltration rate at τ_{avg}. Pe = 10 mg L^{-1} and 3× inflow at advance, Pg = 10 mg L^{-1} and 3× inflow at advance, Pe2 = 10 mg L^{-1} and 2× inflow at advance, Pg2 = 125 mg L^{-1} and 1× inflow at advance, and control is untreated and 1× inflow at advance. Each leg of the error bars indicates one standard error of the mean (*n* = 3).

Table 4. Influence of irrigation, treatment, and their interaction on three irrigation infiltration parameters (Vinfadv, Vinftau, and InfRtau) in each year. Values are p-values; asterisks indicate significance (* = p ≤ 0.05, ** = p ≤ 0.01, and *** = p ≤ 0.001), and ns = non significant.

	Vinfadv			Vinftau			InfRtau		
Source of Variation	1997	1998	1999	1997	1998	1999	1997	1998	1999
Irrigation (Irr)	***	***	***	***	***	***	***	***	***
Treatment (Trt)	*	*	**	***	***	***	*	ns	ns
Trt × Irr	***	**	ns	**	*	**	*	ns	**

simulation results. This is not the case, as the measured infiltration depths for the WSPAM-treated furrows, both at the final advance time and at the common opportunity time (τ_{avg}^{*}), are always greater than the simulation results. However, there are substantial differences from year to year, which suggests interactions between the polymer effect and unidentified factors that vary from year to year. Particularly noticeable is that the WSPAM-treated furrows infiltrated more water than the controls in 1998 during the advance phase, which can only be attributed to a systematic change in the infiltration rates induced by the polymer treatment.

Overall, the results suggest that infiltration increased due to WSPAM treatment, separate from the effect of inflow rate. This is manifested by an average 1.4-fold greater advance time, 1.5-fold greater InfVadv, and 1.2-fold greater Vinftau than the simulated values.

In 1997, the measured advance time and infiltration responses for WSPAM consistently diverged from the corresponding values in 1998 and 1999. The 1997 WSPAM advance time and Vinfadv means were smaller than the corresponding values in 1998 and 1999, and the 1997 WSPAM Vinftau response was larger than the corresponding values in the other years (fig. 4). This further suggests that the irrigation conditions in 1997 differed from the conditions in later years.

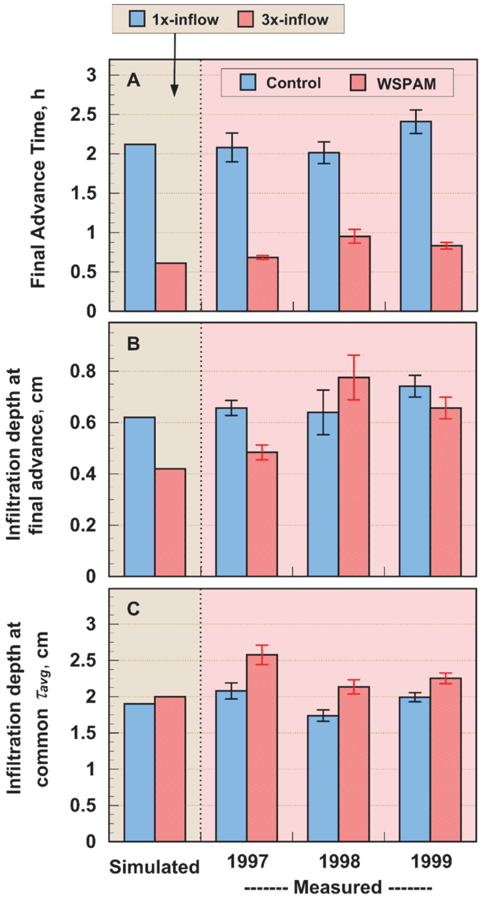

Figure 4. Simulated versus measured hydrologic components averaged across irrigations: 1× (15 L m^{-1} advance inflow) and 3× (45 L m^{-1} advance inflow) were simulated, and untreated 1× (control) and 3× (WSPAM, mean of Pe and Pg) were measured (experiment 1). Parameters include (A) final advance time, (B) infiltration depth at final advance, and (C) infiltration depth at common average opportunity time (τ_{avg}). Error bars indicate one standard error of the mean (*n* = 12, 15, and 21 for 1997, 1998, and 1999, respectively).

A secondary effect of a larger inflow rate is to increase the wetted perimeter and therefore the infiltrating surface. It also has the effect of increasing the water pressure acting on that surface. These two factors should contribute to increase infiltration for a given opportunity time. That combined effect was examined via simulation. Considering the cross-sectional geometry of the tested furrows and the field slope, the wetted perimeter calculated at the upstream end of the field is about 16 cm when the inflow rate is 15 L min^{-1} and 22 cm when the inflow rate is 45 L min^{-1}, while the corresponding flow depths are 1.5 and 2.5 cm. This translates into an increase in infiltration depth from 2.15 to 2.22 cm (3% increase) for 8 h of opportunity time, when accounting for the inflow rate reduction with the 45 L min^{-1} scenario. This effect is small relative to the 1.2-fold Vinftau increase measured in the WSPAM furrows, providing further support for the idea that the differences in measured versus simulated values for the WSPAM furrows are due to treatment effects and not to hydraulic factors.

Experiment 2: Infiltration across Entire Furrow

Unlike the results from experiment 1, the Vinfadv, Vinftau, and InfRtau measurements revealed no clear pattern of seasonal variation in 2000 (figs. 3D, 3H, and 3L). In addition, the values, treatment differences, and data scatter tended to be larger on average than in the previous three years. However, 1997 and 2000 were similar in that, for the first irrigation, the mean Vinfadv values for the Pg (1997) and Pg2 (2000) treatments were less than half that of the control value (figs. 3A and 3D). The Pg treatments substantially decreased the advance-phase infiltration compared to the controls in these two irrigations.

Correlation Analysis

The correlation analysis revealed three important relationships between the infiltration indicators and irrigation parameters for the two treatments (table 5). First, for both the control and WSPAM furrows, the infiltration indicators (Vinfadv, Vinftau, and InfRtau) universally increased with advance opportunity time and universally decreased with furrow soil water content (0 to 5 cm depth). Second, for the controls, the three infiltration indicators were universally related to inflow rate at advance, inflow rate at average opportunity time, average furrow sediment load, and inflow water EC; for WSPAM, the same parameters were correlated either with the advance-phase indicator (Vinfadv) or with both

Table 5. Spearman rank correlations and significance for three irrigation infiltration indicators (Vinfadv, Vinftau, and InfRtau) versus selected irrigation parameters for 1997 through 2000. Correlations for control and WSPAM treatments were computed separately (*n* = 117). Asterisks indicate significance: $^{+}$ = p ≤ 0.10, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, and ns = non significant.

	Spearman Rank Correlation and Significance[a]					
Irrigation	Infiltration Indicators for Control Treatment			Infiltration Indicators for WSPAM Treatments		
Parameters[b]	Vinfadv	Vinftau	InfRtau	Vinfadv	Vinftau	InfRtau
Advtau	0.74***	0.38**	0.25*	0.99***	0.49***	0.23*
Q0adv	0.33**	0.60***	0.52***	-0.02	-0.32***	-0.40***
Q0tau	0.33**	0.58***	0.73***	0.01	0.57***	0.64***
MnSedgL	-0.43***	-0.35**	-0.26*	-0.29**	0.13	0.09
H2O_EC	0.44***	0.53***	0.31**	0.59***	0.16^{+}	0.07
SoilWtr	-0.53***	-0.56***	-0.43***	-0.60***	-0.46***	-0.19**
H2OTemp	0.04	-0.03	-0.11	0.35***	0.00	-0.29**
IrrT	0.01	-0.03	0.01	0.32**	-0.23**	-0.21*

[a] Control = No WSPAM, 1× advance inflow, and 1× post-advance inflow; WSPAM = Pg and Pe [Pe2] = 10 mg L^{-1} WSPAM and 3× [2×] inflow during advance phase with post-advance inflows equal to controls; VinfAdv = infiltration volume at end of advance phase; Vinftau = infiltration volume at common opportunity time; and InfRtau = average near-steady infiltration rate.

[b] Advtau = advance phase average opportunity time, Q0adv = mean inflow rate for advance phase, Q0tau = inflow rate at the average opportunity time, MnSedgL = mean runoff sediment concentration during irrigation, H2O_EC = electrical conductivity of inflow water, SoilWtr = soil water content in furrow (0 to 5 cm depth), H2OTemp = initial inflow water temperature, and IrrT = irrigation type.

post-advance indicators (Vinftau and InfRtau) but not universally to both the advance and post-advance indicators. Third, only for WSPAM were the infiltration indicators correlated with inflow water temperature and irrigation type; for both parameters, the correlation was positive for the advance phase but negative for post-advance infiltration. These results suggest that: (1) irrigation parameters, including advance opportunity time and furrow soil water content, had a primary influence on furrow infiltration, which was not altered by WSPAM application; (2) the effects of WSPAM on infiltration differed in the advance and post-advance phases; and (3) WSPAM's influence on furrow infiltration was sensitive to inflow water temperature and irrigation type.

Furrow Section Infiltration

Experiment 1

In lower furrow sections, the mean total infiltration values for WSPAM-treated furrows consistently trended higher than for the control, but the effect was significant only in 1998 (table 6). In 1998, WSPAM increased total infiltration in the lower furrow sections by 1.2-fold compared to the control. Likewise, in the upper furrow sections, the mean total infiltration for WSPAM tended to be smaller than for the control, but the difference was significant only in 1997. Thus, in 1997, WSPAM decreased the mean total infiltration by 39% relative to the control.

Experiment 2

WSPAM decreased mean total infiltration in the upper section by 18% and increased total infiltration the lower section by 1.3-fold relative to the control (table 6). The Pg2 treatment (125 mg L^{-1} WSPAM) in 2000 produced similar results to those of 1997, which suggests a similar mode of action. That is, the change in section infiltration pattern caused by Pg2 in 2000 resulted from an increase in advance-phase irrigation water viscosity, which reduced infiltration in the upper section relative to that of the control. It is feasible that a similar process was responsible for the analogous section infiltration pattern produced by Pg and Pe in 1997.

Effect of Irrigation

Mean total infiltration, when averaged across treatments for a given furrow section, varied significantly in 1998 and 1999 (table 6). The differences resulted primarily because of the disparity in total water applied in individual irrigations for the given year. For example, in 1998, irrigation 1 applied less water than irrigations 2 to 5, and in 1999, irrigations 2 and 3 applied less water than irrigations 1, 3, 5, and 6.

Furrow Infiltration Uniformity

Furrow infiltration uniformity, defined as the similarity between upper and lower section net infiltration values, varied substantially among years for both the control and WSPAM treatments. The absolute difference in mean total infiltration amounts between upper and lower sections was less for WSPAM than for the control treatments in 1997 (13.3 vs. 15.8), 1998 (19.7 vs. 36.6), and 2000 (10.4 vs. 11.1). This suggests that WSPAM can potentially improve furrow infiltration uniformity, albeit slightly in some cases (table 6).

In a given year, crop yields did not always respond to treatment-induced changes in furrow section infiltration. In 1997 through 1999, neither treatment nor the treatment × location interaction significantly influenced corn silage yields ($p > 0.4$, data not shown). Thus, differences in infiltration, when differences occurred between treatments or furrow sections, did not appear to influence corn productivity. In contrast, bean yields showed significant effects of both treatment and location factors and their interaction (fig. 5). Bean seed yields for all treatments were similar in the upper (top) section, but the control and Pe2 yields decreased from the upper (top) to lower (bottom) sections, whereas Pg2 yields remained the same from top to bottom (fig. 5).

Table 6. Effects of treatment, irrigation, and their interaction on total section infiltration in the top 1/3 and bottom 2/3 furrow sections in experiment 1 (1997-1999) and in the top 1/2 and bottom 1/2 furrow sections in experiment 2 (2000). In experiment 1, the control was compared with WSPAM where the two 10 mg L^{-1} WSPAM, 3× advance inflow rate treatments (Pg and Pe) were averaged when both were monitored. In experiment 2, the control was compared with the 125 mg L^{-1} WSPAM, 1× advance inflow rate treatment (Pg2) only.

Source of Variation	Total Section Infiltration[a]											
	Experiment 1									Experiment 2		
	1997			1998			1999			2000		
		Upper	Lower		Upper	Lower		Upper	Lower		Upper	Lower
p-Values[b]												
Irrigation		ns	ns		***	**		***	***		ns	*
Treatment		+	ns		ns	+		ns	ns		*	*
Irr × Trt		ns	ns		ns	ns		ns	ns		ns	ns
Factor (mm irrigation^{-1})[c]												
Control		44.2 a	28.4		68.0 A	31.4 bB		46.3	43.9		51.0 aA	39.9 bB
WSPAM		27.7 b	41.0		57.4 A	37.7 aB		56.0	47.0		42.0 b	52.4 a
Irrigation type[d]												
Irr 1	F	-	-	F	32.3 c	28.2 c	F	81.3 aB	47.0 aA	F	43.6	50.4 a
Irr 2	R	-	-	F	95.9 aA	26.5 cB	F	47.7 b	54.0 a	R	51.4	49.6 a
Irr 3	F	40.5 A	32.6 B	R	68.2 bA	40.9 aB	R	17.5 c	24.8 b	F	45.4	43.8 a
Irr 4	R	33.9	35.7	R	78.4 aA	33.0 bB	R	58.7 b	54.3 a	R	45.1	49.2 a
Irr 5	R	-	-	R	57.6 b	47.9 a	R	60.1 b	56.4 a	F	47.0	37.7 b
Irr 6	R	-	-	-	-	-	R	72.4 ab	52.3 a	-	-	-

[a] These data include irrigations and treatments for which upper and lower furrow section infiltration was measured, as detailed in table 2.

[b] Asterisks indicate significance: + = $p \leq 0.10$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, and ns = non significant.

[c] Treatment or irrigation means in a given column with the same lowercase letter are not significantly different ($p \leq 0.1$). Upper and lower section means in a given year with the same uppercase letter are not significantly different. Letters are not shown if the effect was not significant.

[d] Irrigation type: F = fresh, and R = repeat.

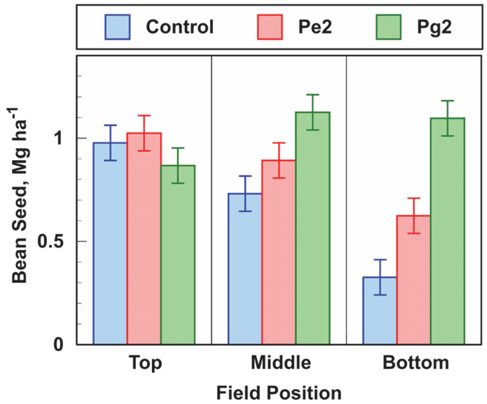

Figure 5. Treatment effects on mean bean seed yields in 2000 for top, middle, and bottom furrow sections. Pe2 =10 mg L^{-1} emulsion WSPAM and 2× advance inflow rate (30 L min^{-1}), and Pg2 = 125 mg L^{-1} granular WSPAM and 1× advance inflow rate (15 L min^{-1}). Each leg of the error bars indicates one standard error of the mean (*n* = 3).

Discussion

Determining the effect of WSPAM on infiltration is difficult due to the considerable natural variability present in furrow soils, both in space and time (Oyonarte et al., 2002). The data set reflects substantial changes in the infiltration behavior from year to year and from irrigation to irrigation for each year. Possible reasons for this variation are discussed in this section. Despite the variation, the statistical analyses for 1997-1999, in combination with the simulations, suggest that infiltration over the entire furrow increased in the WSPAM-treated furrows. This is consistent with the idea that the polymer helps preserve soil structure and perhaps helps prevent, or at least delay, the formation of a surface seal.

Because the WSPAM-treated furrows were irrigated differently from the controls, it can be argued that the differences in infiltration may be the result of the different inflow rates applied to the furrows. The simulation results provide us with a measure of how much the infiltration should have changed as a result of hydraulic factors, assuming infiltration is on average the same for both sets of furrows. The results show that the WSPAM-treated furrows infiltrated more water than predicted by the simulation, i.e., considering only the hydraulic factors, and the effect was more prominent during the advance phase. Thus, it seems that the WSPAM effect is greater during the early stages of infiltration, and that steady infiltration rates are less affected.

The results also suggest that the intensity of the WSPAM effect differed each year, e.g., 1997 showed a much weaker infiltration enhancement during advance than the other years (fig. 4B). This difference is believed to be related to the electrical conductivity of the inflow water (table 7), although other factors may be involved, as discussed next.

Surface Seal Formation

Previous studies provide additional information about the physical processes that affect infiltration in silt loam soils that could help explain some of the results reported herein. Infiltration in these soils is controlled by the properties of a depositional seal that forms in the fresh furrow during irrigation (Trout et al., 1995). At the start of irrigation, prior to seal formation, the primary driving force for infiltration is the soil water potential gradient, which is reduced as the soil wetting zone increases (Hillel, 1971). Segeren and Trout (1991) reported that depositional seals formed in furrow-irrigated Portneuf soils during the first 100 min and were fully developed after 300 min, reducing infiltration by 47%. Seal formation increases with the concentration of suspended sediment, particularly dispersed, fine particles in the furrow stream (Sojka et al., 1998a, 1998b). Thus, the presence of WSPAM, an increase in divalent cations, or a decrease in monovalent cations in the inflow water reduces sediment load, inhibits dispersion, and slows seal formation (Sojka et al., 1998a, 1998b; Kang et al., 2014; Shainberg and Singer, 1985). Depositional seals formed in WSPAM-treated furrows are more porous than in untreated furrows; Sojka et al. (1998b) reported that steady-state, unsaturated infiltration through WSPAM-treated furrow seals was nearly twice that of untreated furrows. Yet WSPAM viscosity effects can also reduce infiltration, particularly during application (Li et al., 2019). It follows that variations in water intake among treatments, irrigations, and years occur in response to changes in factors that control the soil water potential gradient, soil erosion, particle dispersion, and WSPAM activity.

Table 7. Electrical conductivity of water drawn from the Snake River's Milner Reservoir during each irrigation and year.

	Electrical Conductivity (dS m^{-1})			
Irrigation	1997	1998	1999	2000
1	0.31	0.36	0.34	0.41
2	0.31	0.36	0.33	0.41
3	0.34	0.35	0.33	0.42
4	0.33	0.37	0.38	0.41
5	-	0.38	0.39	0.42
6	-	-	0.42	-
7	-	-	0.37	-

Initial Soil Water Content

Mean yearly Vinfadv, Vinftau, and InfRtau values increased as the initial soil water decreased (figs. 2A to 2D and fig. 3). Decreasing initial furrow soil water content can increase infiltration by steepening the water potential gradient, but the importance of this driving force fades as the wetting front deepens and the depositional seal develops. To have a prolonged infiltration influence, soil water must influence depositional seal formation and conductance. In contrast to the relationship found in the current study, drier initial soil conditions in furrows were found to decrease soil aggregate stability, e.g., by promoting the collapse of soil aggregates during rapid soil wetting, and increase stream sediment loads, which should encourage seal formation (Kemper et al., 1985). However, Bjorneberg et al. (2002) reported that increasing pre-irrigation gravimetric soil water contents from 3% to 33% had no effect of furrow runoff in Portneuf soils. Because the initial soil water content in the current study was well below 33% (figs. 2A to 2D), this likely was not a factor. It is possible that in the control furrows, the negative correspondence with soil water was due to soil water's robust negative correlation with water EC (-0.59, $p < 0.0001$). In the WSPAM-treated furrows, the drier initial soils may have increased polymer absorption on soil aggregates, resulting in better soil stabilization and smaller stream WSPAM concentrations, which would reduce viscosity effects and increase infiltration.

Inflow Water Electrical Conductivity

Mean yearly infiltration parameter values increased as inflow water EC increased (fig. 3 and table 7). Inflow water EC can influence both sediment dispersion in the furrow stream and WSPAM activity. High EC and divalent cation concentrations in the inflow cause the hydrated, coil-like WSPAM molecular conformation to contract, making the solution less viscous but also reducing WSPAM's capacity to flocculate soil particles. Decreasing the inflow EC and divalent cation concentrations allows the hydrated coil to expand, which increases the solution's viscosity and WSPAM's flocculating capability (Lakatos et al., 1981; Hocking et al., 1999). However, if the divalent cation concentrations in the inflow water become too dilute, the WSPAM molecules lose their ability to bind and flocculate soil particles (Lentz and Sojka, 2009). Snake River water ECs were unusually low in 1997 due to snowmelt contributions from heavy winter snowfalls, and again during the early irrigations of 1999 (table 7). In 1997, the mean Snake River flow rate from March through June was 3.1 times the 1996-2016 average, and 2.1 times the average in 1999. These large flushes of snowmelt water diluted the groundwater contribution to the river flow and lowered the EC of the water impounded in the Milner Reservoir, which supplies water to the Twin Falls Irrigation Tract. The increased viscosity of the dissolved WSPAM in those irrigations may partly explain why the Vinfadv values for WSPAM were less than the controls in 1997 and early 1999 (figs. 3A to 3C). A similar WSPAM viscosity effect occurred for the Pg2 irrigations on fresh furrows in 2000, where 125 mg L^{-1} WSPAM concentrations contributed to high viscosities in advance flows, which decreased Vinfadv relative to the control (fig. 3D). Changes in inflow water EC may have also influenced the year-to-year variation in seasonal infiltration patterns (fig. 3).

Effects of Water Temperature and Irrigation Type on WSPAM Furrows

Inflow EC and inflow water temperature had highly significant, positive correlations with Vinfadv but not with Vinftau or InfRtau in WSPAM-treated furrows (table 5). The former indicates that polymer viscosity-induced reductions in hydraulic conductivity do not persist very long after the application ceases (Malik and Letey, 1992; Letey, 1996). Thus, any residual polymer solution remaining in the soil pores did not appear to inhibit water movement in the long term. The temperature correlation is also consistent with polymer viscosity effects because the increase in polymer solution viscosity caused by decreasing temperature is orders of magnitude greater than that for unamended water (Chin and Cho, 1993). Hence, water temperature was unrelated to Vinfadv in the control furrows.

In contrast to the control furrows, infiltration in the WSPAM-treated furrows was negatively correlated with irrigation type (table 5). In repeat-irrigated furrows, the soil structure in both untreated and treated furrows was degraded because the native aggregated soil structure in the furrows had been altered. Thus, WSPAM had a subdued effect on furrow infiltration in repeat-irrigated furrows because there were fewer large pores to preserve. This can be seen in the mean InfRtau values, particularly for the 1998, 1999, and 2000 irrigations (figs. 3J to 3L). Drying of furrow soils between irrigations produces cracks in the depositional seal, which may penetrate the crust and produce subtle changes in treatment effects (Zhang et al., 2019).

Stream Sediment Concentration

In a given year, the seasonal irrigation pattern of the three infiltration responses (Vinfadv, Vinftau, and InfRtau) generally paralleled the inverse stream sediment concentration pattern (figs. 2E to 2H and fig. 3). A pronounced separation between treatment Vinfadv responses occurred in the first irrigation of 1997 and 2000 (figs. 3A and 3D). These events were unusual in that streams in control furrows produced little erosion and mean sediment concentrations were small (<0.7 g L^{-1}) (figs. 2E and 2H). This inhibited seal formation, and produced large infiltration rates in control furrows, which greatly slowed advance and maximized Vinfadv relative to WSPAM furrows. In 1997 and 2000, the generally greater Vinftau increases produced by the Pg, Pe, and Pe2 WSPAM treatments over that of controls (figs. 3E and 3H) showed that the polymers produced conductive and stable depositional seals under both low water EC-high initial soil water (1997) and high water EC-low soil water (2000) conditions (figs. 2A and 2D and table 7).

Furrow Section Infiltration

All else being equal, the net infiltration in the upper furrow section should exceed that in the lower section due to the upper section's greater opportunity time. If the speed of advance increases, the net infiltration in the lower section approaches, but cannot exceed, that of the upper section. Thus, the greater flow rate and shorter advance time of the WSPAM treatments does not explain how infiltration in the lower section could exceed that of the upper section (table 6). Several factors may have contributed to the observed infiltration pattern. Treatments may have differentially altered the furrow channel cross-sections over several irrigations, with associated effects on infiltration (Sojka et al., 1998a).

We suggest that the influence of decreased advance time on section infiltration was altered by WSPAM viscosity effects. Furrow stream WSPAM concentrations can decline by 25% as water traverses the furrow (Lentz et al., 2002). The downstream decline in WSPAM concentration, and hence furrow stream viscosity, may have led to smaller increases in water intake in the upper section and greater increases in the lower section (Aiwa and Trout, 2006; Li et al., 2019). The WSPAM treatments' reversal of the typical upper-lower section net infiltration pattern in 1997 occurred when irrigation water ECs were low and PAM viscosity effects were greater, relative to 1998 and 1999. The other section infiltration reversal occurred in 2000 for Pg2, whose high advance phase WSPAM loads also produced strong viscosity effects. The downstream decline in WSPAM concentration may also have led to reduced polymer deposition in the lower sections, but the significance of this is less clear.

Other factors may have contributed to the infiltration patterns. Spatial variability of soil properties along furrows can produce sizeable changes in soil hydraulic conductivity. Large variability in section infiltration among blocks generated uncertainty in the data. Coefficients of variation averaged 26%, with a maximum of 49% in an individual irrigation. The deviations may partly be due to inconsistent flume installation or maintenance. Control furrows in particular can produce heavy sediment loads that accumulate near flumes and influence flow measurements unless properly cleaned.

The 1997-1999 corn yields among treatments and furrow sections were similar, giving little confirmation that WSPAM increased lower section infiltration relative to the control. However, bean yields in 2000 appeared to respond to WSPAM effects on infiltration uniformity (fig. 5). It is possible that irrigation met or exceeded crop water requirements for corn in the control plots.

CONCLUSIONS

The WSPAM treatments produced generally greater cumulative infiltration than the controls, which was not caused solely by the greater inflow rates employed during the advance phase. Compared to the controls, one or both of the 10 mg L^{-1} polymer, 2× to 3× advance inflow treatments produced increased cumulative infiltration depths at the common average opportunity time (Vinftau) in most irrigations each year. However, the magnitude of the increase varied substantially by irrigation and year. To accurately predict infiltration outcomes, better understanding is needed of the factors that influence WSPAM's action in furrow streams. This research suggests several parameters that could be further studied, which interact in a complex fashion to alter the balance between the two opposing, contributory effects of WSPAM on infiltration, i.e., between infiltration-enhancing (aggregate stabilization) and infiltration-inhibiting (viscosity) influences of WSPAM. These same factors may also be responsible for WSPAM's substantial but equally variable effects on furrow irrigation uniformity. In two of the four years, WSPAM increased mean net furrow infiltration in the lower section and reduced it in the upper section relative to the control furrows. This effect could not be explained by the greater inflow rate and shorter advance time of the WSPAM treatments. The application of WSPAM holds considerable potential for managing water infiltration in soils, but better understanding is needed of the factors and processes influencing its field infiltration effects.

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NOMENCLATURE

ANOVA = analysis of variance

InfRtau = average near-steady furrow infiltration rate per unit area

Pg = WSPAM treatment derived from a granular product

Pe = WSPAM treatment derived from an emulsion product

Vinfadv = infiltration volume at the end of the furrow advance phase

Vinftau = furrow infiltration volume at the common opportunity time

WSPAM = water-soluble polyacrylamide