FLOW VELOCITY AND WETTED PERIMETER EFFECTS ON FURROW INFILTRATION

T. J. Trout
MEMBER
ASAE

ABSTRACT

Infiltration theory and previous studies show that furrow infiltration increases with wetted perimeter. This effect can strongly influence water distribution along furrows. Stagnant blocked-furrow measurements on Portneuf silt loam soil supported this relationship. However, both recirculating infiltrometer and field-scale measurements showed no consistent infiltration:wetted perimeter relationship. The infiltrometer data, collected using a wide range of flow rates on a wide range of slopes, did show infiltration inversely related to flow velocity. This relationship results from the effect of flow on soil aggregate breakdown, particle movement, and depositional seal formation. Because both velocity and wetted perimeter increase with flow rate, their opposing effects on infiltration can result in little apparent effect when flow rates change. These interactions strengthen the inverse relationship between infiltration and furrow slope.

KEYWORDS. Irrigation, Infiltration, Furrows, Models.

INTRODUCTION

Furrow infiltration is a complex process that is difficult to model deterministically. Consequently, an empirical, opportunity time-based infiltration function, such as the Kostiakov equation, is usually used in irrigation models. The equation parameters for a given field and irrigation are usually based on average measurements or conditions for the field, implying uniform infiltration capacity throughout a field. However, in addition to soil-based infiltration variability, the irrigation process creates spatially-varying conditions that can affect infiltration capacity. Wetted perimeter and flow velocity vary across a furrow-irrigated field and may influence infiltration. These parameters are functions of flow rate, furrow slope, and roughness, which can be quantified. Thus, if the effects of wetted perimeter and flow velocity on infiltration are known, the influence of the flow rate, slope, and roughness on infiltration can be predicted, resulting in improved irrigation models.

Several investigators have found that furrow infiltration varies directly with furrow wetted perimeter. Fangmeier and Ramsey (1978) measured nearly proportional decreases in infiltration with wetted perimeter resulting from decreasing flow rate in precision-made furrows. Using a two-dimensional infiltration computer model, Samani (1983) predicted a direct relationship with a negative second derivative. Blair and Smerdon (1985) measured a direct relationship with a positive second derivative in four unreplicated stagnant blocked furrow measurements. Izadi and Wallender (1985) found positive correlations between infiltration rate and wetted perimeter in both stagnant and flowing blocked furrow tests but cumulative infiltration was correlated with wetted perimeter only in the stagnant tests. Izadi and Wallender (1985), Strelkoff and Sousa (1984), and Freyberg (1983) predict how varying wetted perimeter might affect infiltration.

Modelers of surface irrigation processes have recently begun to incorporate some type of infiltration versus wetted perimeter relationship in their furrow irrigation models. The USDA-Soil Conservation Service furrow irrigation design procedure assumes infiltration rate increases linearly with (but less than proportional to) wetted perimeter (USDA-SCS, 1983). In recent versions of the Surface Irrigation Simulation Model (SIRMOD) developed at Utah State University, infiltration is modeled as a power function of wetted perimeter (USU, 1989). The surface irrigation simulation model (SRFR) developed by Strelkoff allows selection of an infiltration rate relationship that is proportional to wetted perimeter and considers the varying opportunity times along the perimeter (Strelkoff, 1990; Strelkoff and Sousa, 1984).

Furrow infiltration rates can be greatly affected by surface sealing (Segeren and Trout, 1991). Erosion theory predicts that sediment detachment, and thus the sediment particles available to form a seal, increases with flow shear which is related to the square of the flow velocity (Trout and Neibling, 1993). Eisenhauer et al. (1983), using laboratory flume tests, found that the rate of seal formation increased with flow velocity. Brown et al. (1988) proposed that flow velocity increases increase seal formation which decreases infiltration. However, several researchers have measured higher infiltration in flowing furrow tests than with stagnant blocked furrow tests (Nance and Lambert, 1970; Fangmeier and Ramsey, 1978; Bautista and Wallender, 1985; Izadi and Wallender, 1985). Published studies have not quantified the relationship between flow velocity and furrow infiltration. Irrigation simulation models presently being used do not assume an effect of flow velocity on infiltration.

The objective of this study was to measure, under field conditions, the steady-state effects of wetted perimeter and flow velocity on furrow infiltration.

Article was submitted for publication in November 1991; reviewed and approved for publication by the Soil and Water Div. of ASAE in May 1992. Presented as ASAE Paper No. 86-2573.

The author is **Thomas J. Trout**, Agricultural Engineer, USDA-ARS, Soil and Water Management Unit, Kimberly, ID.

PROCEDURES

In flowing furrows, both wetted perimeter and flow velocity vary with the flow rate, bed slope, and roughness. Varying either parameter independent of the other in order to determine the individual effects on infiltration is difficult. Consequently, three approaches were taken to attempt to quantify the individual effects. A recirculating infiltrometer was used to apply a wide range of flow rates to furrows constructed on a wide range of slopes in order to statistically separate the effects of wetted perimeter and flow velocity. Second, the independent effect of wetted perimeter was measured in stagnant blocked furrows. Third, field-scale infiltration measurements were made to verify the infiltrometer results.

In the infiltrometer tests, both the wetted perimeter and flow rate were maintained constant after the short initial period; thus, only the effects under steady-state conditions were evaluated. Infiltration by Portneuf silt loam in southern Idaho quickly approaches and is dominated by the final or steady-state rate such that variation in initial infiltration is less important than variation in the final rate.

RECIRCULATING INFILTROMETER TESTS

Recirculating infiltrometer tests were conducted during 1985 and 1986 on two fields of Portneuf silt loam in the Kimberly, Idaho, area. Tests were conducted on previously unirrigated non-wheel (uncompacted) furrows spaced 1.1 m apart. The 6 m long furrow test sections were constructed at various angles to the prevailing field slope to create furrows in close proximity with a wide range in bed slope.

In the 1985 tests, water was applied to four sets of ten parallel furrows. Furrow slopes varied from 0.005 to 0.015 m/m and flow rates of 6, 12, 20, 30, and 50 L/min. were applied to each set. In the 1986 tests, five sets of six parallel furrows were formed at different angles on a field with a 0.016 m/m prevailing slope. Resulting furrow bed slopes ranged from 0.002 to 0.016. Flow rates of 6, 12, 20, and 30 L/min were applied to each set of furrows.

Irrigation water was applied with a recirculating infiltrometer which recycled water through the furrow section. The recycling system, described by Blair and Trout (1989) and Trout (1991), was designed using a low-speed screw pump to recycle the water and eroded sediment in a way that minimized aggregate breakdown of sediment. A downstream weir was used to maintain uniform normal flow depth in the test section. The initial furrow flow rate was low (about 6 L/min.) so that the test section initially wet up at a slow, uniform rate of about 3 m/min to approximate field conditions. Flow was then gradually increased over a five minute period to the desired rate. Ten-hour cumulative infiltration, Z, and final (basic) infiltration rate, I, were determined from the decrease in continuously recorded water depth in the 600 L infiltrometer supply tank.

Slope of the flowing water surface was measured during the tests with a manometer. Flow cross-sectional shape was measured two meters from the inflow and outflow ends with a profilometer (ASAE, 1989) near the end of each test. Average flow cross-sectional area, A, and furrow wetted perimeter, P, were calculated from the profilometer data. The average flow velocity, V, was calculated as the flow rate, Q, divided by A. The average shear the flow exerts on the perimeter, T (Pa), was calculated from the tractive force equation:

$$T = \rho g R S \tag{1}$$

where

ρ = the density of water (1000 kg/m^3)
g = gravitational acceleration (9.81 m/s^2)
R = the furrow hydraulic radius = A/P (m), and
S = the furrow water surface slope (m/m).

Although the shear is related to the average flow velocity squared, it was measured in a different way, and was therefore considered as an alternative parameter for velocity effects.

One-half liter water samples were collected from the recirculating flow 15 min and 1 h after the tests began for gravimetric determination of sediment concentration. Since all sediment originating from the test section was continuously recycled by the flow through the section, sample sediment concentration represents the amount of sediment moving through the section, and concentration times storage volume in the recycling system (about 20 L) represents net eroded mass. The average of the two measurements was used to represent sediment movement during the first hour.

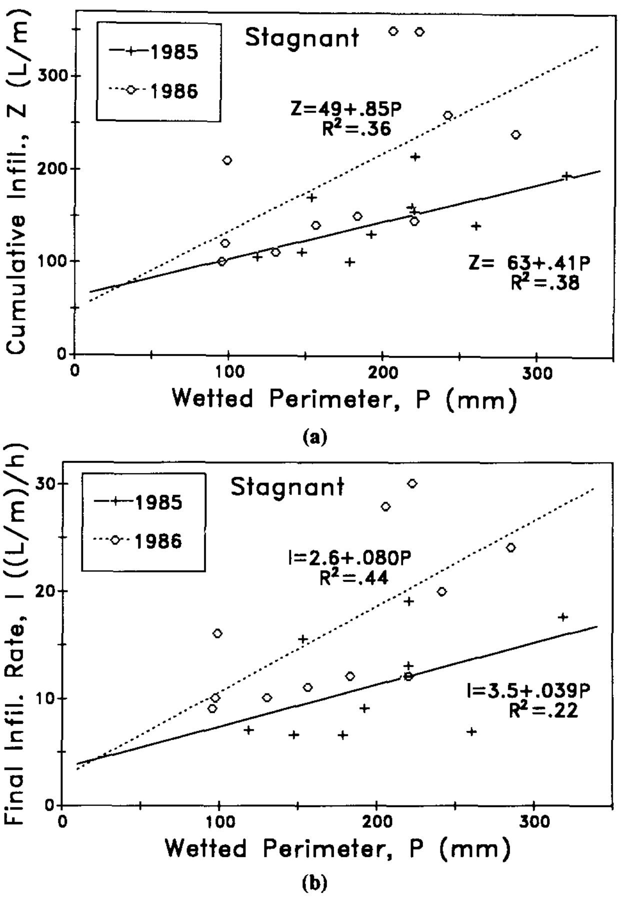
STAGNANT BLOCKED FURROW TESTS

Stagnant blocked furrow tests were also conducted at the recirculating infiltrometer sites. The furrows were aligned perpendicular to the prevailing slope to create uniform water depth and wetted perimeter conditions in each test section. The 1.5 m long sections were filled to various target depths over about 3 min and water levels were maintained with a Marriotte siphon supply tank. Infiltration during the ten-hour tests was calculated from the volume decrease in the supply tank. Wetted perimeter was calculated from furrow cross-sectional profiles measured at two places in each section.

FIELD TESTS

Field-scale infiltration tests were conducted in 1984, 1985 and 1986 near Kimberly and in 1986 at the Colorado State University Fruita Research Farm in the Grand Valley in western Colorado. The Idaho tests were on Portneuf soil planted to dry beans. The 1.1 m spaced furrows were 160 m long on a 0.007 m/m slope. Twelve consecutive non-wheel track furrows were divided into four replications of three flow rate treatments. The constant inflows to the Idaho furrows were set at 100%, 150%, and 200% of the rate required to complete advance in about four hours. Irrigation application continued for 12 h. Data were collected during four or five seasonal irrigations each year.

The 300 m long Colorado furrow tests were conducted on Youngston clay loam on a 0.0055 m/m slope in a field planted to corn (0.75 m furrow spacing). Data were collected during irrigations no. 1 and no. 5. Six tractor wheel compacted and six alternate non-wheel furrows were divided into two replications of three flow rate treatments



(a)

(b)

Figure 1–Infiltration vs. wetted perimeter data and linear regression lines for the Idaho stagnant blocked furrow tests (R^2 - coefficient of determination). a) Cumulative infiltration at 10 h; b) Final infiltration rate.

during irrigation no. 1. The three flow rate treatments were not replicated in irrigation no. 5. The flow rates were selected to produce approximately 5%, 30%, and 60% runoff rates after 8 h.

Inflow rate was measured volumetrically with a 3.78 L bucket and outflow rate, with 60° V long-throated furrow flumes. Cumulative infiltration and infiltration rate were determined by volume balance (inflow-outflow). During the Colorado tests and the initial two Idaho tests in 1986, flow cross-sectional shape was measured with profilometers in each furrow at 1/6, 1/2, and 5/6 the distance from the inflow end and flow rate was also measured at the furrow mid-point. Average furrow wetted perimeter, flow rate, and flow velocity were calculated from these data.

In the Idaho tests, the final steady infiltration rate was reached quickly (within 2 h of advance completion) and thus was not sensitive to differences in infiltration opportunity time resulting from different inflow and advance rates. In the Colorado tests, steady infiltration rates were not reached during the tests. Thus uniform inflow rates were applied to the wheel furrows and to the non-wheel furrows until advance was complete (about 5 h) to establish fairly uniform advance and infiltration opportunity times. The inflows were then adjusted to the desired rates and final infiltration rate was measured following 3 h of additional flow duration. Cumulative infiltration in the Colorado tests ranged from 125 to 180 mm during irrigation no. 1 and averaged 50 and 120 mm during irrigation no. 5 in the wheel and non-wheel furrows respectively.

RESULTS

STAGNANT BLOCKED FURROW TESTS

Ten-hour cumulative infiltration, Z, and final infiltration rate, I, show similar increasing trends with P in the stagnant blocked furrow tests (fig. 1). All four relationships presented in figure 1 are statistically significant ($P = 0.05$). The steeper slopes in 1986 are the result of two tests with high infiltration. The stagnant tests support previously reported results of less-than-proportional increases in infiltration with wetted perimeter (see Introduction). Near the mean perimeter value, the relative infiltration change is 60 to 80% as large as the relative perimeter change, which is similar to that predicted by Samani (1983) but less than that measured by Fangmeier and Ramsey (1978).

RECIRCULATING INFILTROMETER TESTS

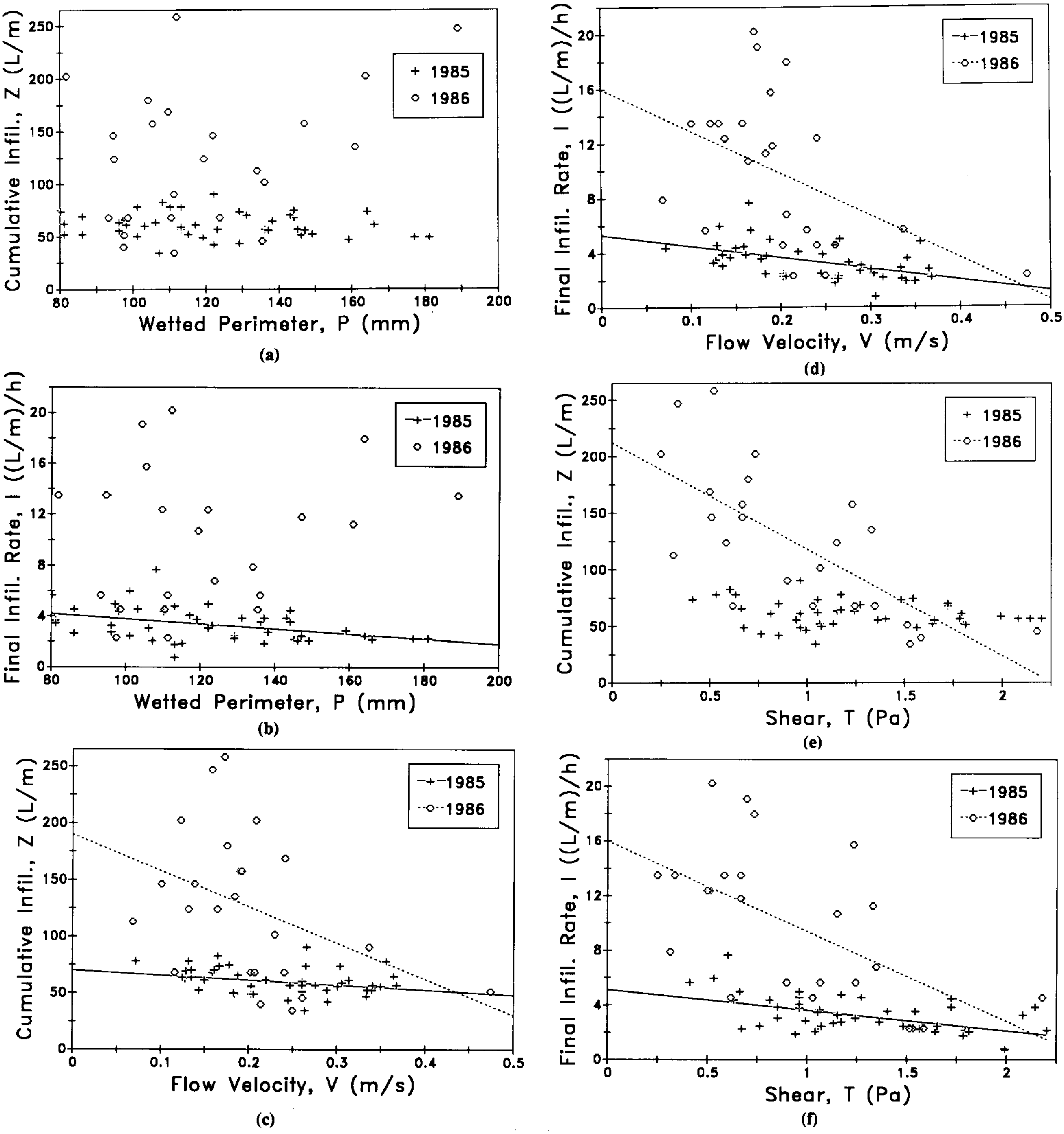
The recirculating infiltrometer data is shown in figure 2, and the linear regression parameters are listed in Table 1. The reason for the high infiltration variability in 1986 is not known. The relationships between both Z and I and wetted perimeter were poor in both years. The only significant linear relationship (I vs. P, 1985) was negative, which has no physical basis and likely resulted from intercorrelation of wetted perimeter and flow velocity in 1985 ($r = 0.37$) and the negative correlation between infiltration and velocity. Wetted perimeter and velocity were not correlated in 1986 ($r = 0.06$).

The measured relationships between Z and I and flow velocity were significant and negative in both years. In all cases, the relationship with V was much better than with P. The 1986 infiltration versus velocity coefficients of determination were greatly increased (although the predictive relationships were little affected) by the one data point at the highest measured velocity. Infiltration also varied negatively with shear. The shear relationships were similar to those with velocity, and in 1986, the correlations were better than with velocity (reason unknown).

Multiple linear regressions of infiltration with P and V and with P and T were tested (Table 1). Adding P and/or the cross product to the regression model did not significantly improve the relationships and did not eliminate the negative relationship between infiltration and P in 1985.

Both P and V increase with increasing flow rate. Thus, the poor relationship between infiltration and flow rate in three of four cases and negative correlation in three of four cases is not unexpected (Table 1). The signs of the regression coefficient depend on the relative influence of P and V on infiltration. With increasing slope, V increases but P decreases, which results in the measured consistent negative correlations between infiltration and slope.

Sediment concentration in the infiltrometer recirculating flows correlated well with shear and fairly well with V (Table 2). The negative intercepts and positive coefficients



(a)

(b)

(c)

(d)

(e)

(f)

Figure 2–Cumulative infiltration at 10 h and final infiltration rate vs. wetted perimeter, flow velocity, and shear for the Idaho recirculating infiltrometer tests and linear regression lines for the significant (P = 0.05) relationships. Linear regression parameters are presented in Table 1. a) Cumulative infiltration vs. wetted perimeter; b) Final infiltration rate vs. wetted perimeter; c) Cumulative infiltration vs. flow velocity; d) Final infiltration rate vs. flow velocity; e) Cumulative infiltration vs. shear; f) Final infiltration rate vs. shear.

of the linear regressions indicate either a critical shear and velocity required to initiate sediment movement (Meyer, 1964) or a concave upward curve (positive second derivative) of the actual relationships, as proposed by Kemper et al. (1985). Both Z and I correlated negatively with sediment concentration. This indicates that seal formation increases with sediment concentration under the conditions tested. This link provides a physical explanation for the effect of velocity and shear on infiltration.

FIELD TESTS

In the three years of field-scale tests in Idaho (13 irrigations at two sites), no significant relationships were determined between infiltration rate and flow rate, and even the trends were erratic (fig. 3a). Infiltration tended to increase with flow rate in 40% of the tests, it tended to decrease in 20%, and no trend was evident in the remaining 40%. In 1986, furrow cross-section was

TABLE 1. Linear regression infiltration relationships for the recirculating infiltrometer data

		1985 (N* = 44)			1986 (N* = 24)		
Dependent Variable	Independent Variable	Intercept a	Coeff. b	R²†	Intercept a	Coeff. b	R²†
Z (L / m)	P (mm)	69	−0.07	0.02	26	0.82	0.11
	V (m / s)	70	−44	0.09‡	190	−320	0.17‡
	T (Pa)	66	−4.9	0.04	212	−94	0.50‡
	P and V	72	−0.021	0.10	94	0.77	0.27
			−42‡			−310‡	
	P and T	70	−0.042	0.05	122	0.74	0.60
			−4.1			−92‡	
	Q (L / min)	66	−0.22	0.08	124	0.004	0.01
	S (m / m)	64	−410	0.02	211	−11000	0.54‡
I [(L / m) / h]	P (mm)	5.8	−0.02	−0.16‡	5.3	0.038	0.03
	V (m / s)	5.3	−8.3	0.25‡	16	−31	0.22‡
	T (Pa)	5.1	−1.5	0.27‡	16	−6.6	0.35‡
	P and V	6.4	−0.013	0.30	12	0.033	0.24
			−6.8‡			−30‡	
	P and T	6.3	−0.012	0.32	12	0.32	0.37
			−1.2‡			−6.5‡	
	Q (L / min)	4.5	−0.047	0.30‡	12	−0.1	0.04
	S (m / m)	4.3	−107	0.09‡	16	−750	0.34‡

* N = sample size.
† R^2 = coefficient of determination.
‡ Statistically significant at P = 0.05.

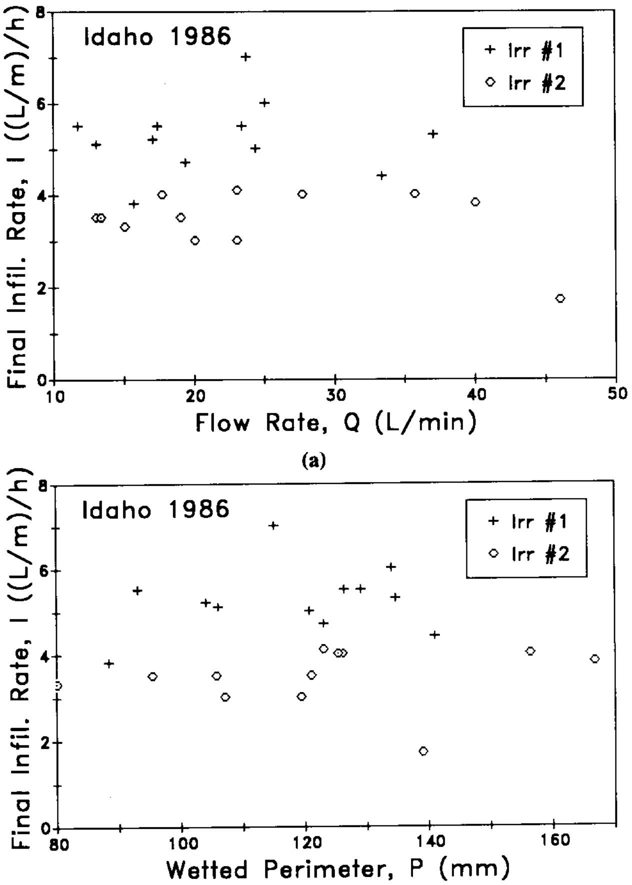
measured and P, V, and T calculated, but correlations between both Z and I and these factors were very poor (fig. 3b). The effects of P and V could not be separated from the field test data since slope could not be varied. Therefore, these results that indicate the absence of relationships are not conclusive but indicate that P and V effects may tend to cancel each other.

In the Colorado field tests (fig. 4), infiltration rate was weakly positively correlated with flow rate (R^2 = 0.19) and wetted perimeter (R^2 = 0.22). This indicates that, for the Colorado soil and conditions, infiltration is more sensitive to P than V. This is likely due to the Colorado soil being either less erosive or less prone to surface sealing. Sediment concentration in the tailwater from the Colorado furrows appeared high, but was not measured.

TABLE 2. Linear regression relationships between average sediment concentration in the first hour, C, and flow velocity, V, flow shear, T, final infiltration rate, I, and cumulative infiltration, Z, for the recirculating infiltrometer data

		1985 (N = 29)			1986 (N = 22)		
Dependent Variable	Independent Variable	Intercept a	Coeff. b	R²	Intercept a	Coeff. b	R²
C(g / L)	V(m / s)	−6.4	57	.30*	−1.0	24	.15
C(g / L)	T(Pa)	−8.2	13	.47*	−3.5	7.7	.47*
I((L / m) / hr)	C(g / L)	4.14	−0.71	.21*	11.7	−.45	.20*
Z(L / m)	C(g / L)	65.4	−.58	.18*	143	−5.3	.23*

* Statiscally significant at P = .05
N = sample size.
R^2 = coefficient of determination



(a)

(b)

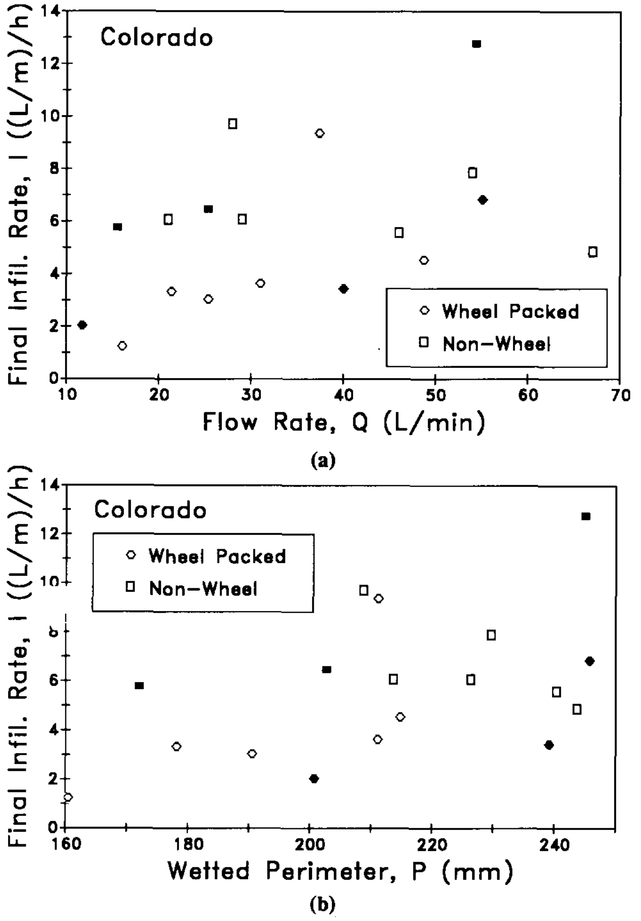
Figure 3–Final infiltration rate vs. average flow rate [graph (a)] and wetted perimeter [graph (b)] for the 1986 Idaho field-scale tests.

DISCUSSION

WETTED PERIMETER

Porous media flow theory dictates that, for most conditions, two-dimensional infiltration from furrows should increase with wetted perimeter. Infiltration from furrows in homogeneous soils (without interference from neighboring furrows) should increase with P at a decreasing rate (negative second derivative) as the infiltration geometry converts from that of two-dimensional flow from a line source to predominately one-dimensional flow. As furrow width increases and lateral flow at the edges becomes relatively less important, the relationship becomes linear. Such a relationship is supported by the stagnant blocked furrow tests, the results of the numerical model of Samani et al. (1983), and most of the field data presented by Fangmeier and Ramsey (1978). For the practical range, this relationship can be modeled either by a straight line with a positive intercept as is done by the USDA-SCS (1983), or with a power function (Blair and Smerdon, 1985) with an exponent smaller than one.

The only case in which infiltration would be expected to increase at an increasing rate with P is when the soil permeability of the furrow side walls is higher than that of the bed. This condition can occur when sediment



(a)

(b)

Figure 4–Infiltration rate after 8 h vs. average flow rate [graph (a)] and wetted perimeter [graph (b)] for the Colorado field-scale tests. Solid symbols are data from the fifth irrigation.

deposition on the bed forms a seal while sloughing from the furrow side walls maintains a more permeable surface. Akram et al. (1981) reported such variable permeability in small irrigation channels.

The effect of P on infiltration should decrease with infiltrated volume (and thus infiltration opportunity time) because reduction in the capillary potential gradient reduces the magnitude of horizontal flow. Wetting pattern overlap between adjacent furrows likewise decreases the effect of P. The effect of non-homogeneities, such as surface seals or subsurface restrictive layers, is too complex to generalize but merits analysis by numerical models.

Results of the flowing furrow infiltrometer tests failed to show the expected relationship between infiltration and wetted perimeter, in spite of the wide P range tested. Experimental factors (intercorrelation between P and V in 1985 and data variability in 1986) may account in part for this lack of correlation. Data from field-scale tests also failed to show a relationship between infiltration and P, although velocity effects and the strong P versus V intercorrelation could have masked the relationship. The lack of correlation between infiltration and P under flowing conditions is an important result that counters existing theory, results from stagnant water tests, and previously reported results.

VELOCITY

The flowing infiltrometer data consistently showed infiltration to be negatively correlated with V and T. This relationship is most likely the result of the measured effect of the flow on sediment movement and of sediment movement on creation of a low-permeability seal on the furrow perimeter. Sediment movement and surface seal formation vary with the soil and conditions. Portneuf silt loam has low aggregate stability, erodes easily, and forms relatively low permeability surface seals (Segeren and Trout, 1991). Soils which are more stable and less erosive will likely have a weaker infiltration versus velocity relationship.

The recirculating infiltrometer may have accentuated the effect of sediment movement on infiltration by recirculating the eroded sediment. Low sediment concentrations in the recirculating water at the end of the tests indicated that most eroded sediment eventually deposited on the furrow perimeter. In flowing furrows, sediment deposits unevenly due to changing flow rates and slopes along furrows and deposition lag times (Trout and Neibling, 1993). Also, some sediment is discharged from the end of the furrows. Thus, the velocity effect may not be as strong from data representing field conditions as from infiltrometer tests. However, the lack of correlations between infiltration and P or Q in the Idaho field tests indicate that some effect is counteracting the expected effect of wetted perimeter on infiltration and the V effect is the most likely cause.

The 1986 data indicate that shear is a better parameter than average flow velocity to describe the flow effect on infiltration. This agrees with the common usage of shear to describe both flow erosiveness and sediment transport capacity (Trout and Neibling, 1993). Shear is related to the square of the flow velocity, resulting in strong intercorrelation between T and V. However, a portion of the shear, as calculated by the tractive force equation, is absorbed by form resistance due to irregular, non-prismatic channel perimeters and obstacles such as large aggregates and plant residue. Therefore, average flow velocity is conceptually preferable to total shear to describe infiltration effects. Partitioning shear between surface resistance, which affects particle detachment and movement, and form resistance would make shear a good parameter, but is difficult.

The data obtained was inadequate to define the shape of the relationship between infiltration and V or T. Infiltration has a finite value at zero flow velocity, as represented by the stagnant test results, and V may have little effect on infiltration until a critical shear with sufficient energy to move soil particles is reached. Infiltration then should decrease with increasing flow velocity, particle movement, and seal formation. The rate of decrease should diminish and infiltration should approach a base value at high velocity, both because increasing seal thickness results in diminishing infiltration decreases and because increasing velocity increases sediment carrying capacity and reduces deposition of fine particles. In fact, high velocity flows with sufficient energy to erode away furrow bed seals increase infiltration (Brown et al., 1988). In the range of decreasing infiltration, an exponential relationship with a negative exponent can be used to model the expected effect. A reasonable assumption is that velocity effects on infiltration are multiplicative rather than additive, resulting in the infiltration rate as influenced by other factors such as P being proportionally modified upward or downward by the effect of velocity.

CONSEQUENCES

Relating infiltration to P and V allows infiltration to be related to the furrow flow rate, Q, roughness (hydraulic resistance), n, and slope, S. Channel hydraulics relationships used in surface irrigation models can make this linkage. Under uniform flow conditions, if a furrow shape is assumed, a generalized relationship can be developed between these parameters and P and V and thus with infiltration. By Manning's uniform flow equation (in base SI units):

$$Q = \left(\frac{1}{n}\right) A \times R^{2/3} S^{1/2} \qquad (2)$$

If a power-function relationship is assumed between A and P:

$$A = aP^{u} \qquad (3)$$

where

a and u are empirical coefficients dependent on furrow shape, then, as derived by Trout (1991):

$$P = a_p \left(Q \frac{n}{\sqrt{S}}\right)^{3/(5u-2)} \qquad (4)$$

and

$$V = a_v Q \left(Q \frac{n}{\sqrt{S}}\right)^{-3u/(5u-2)} \qquad (5)$$

where

$a_p = a^{-5/(5u-2)}$

$a_v = a^{2/(5u-2)}$

Trout (1991) measured a = 0.1 and u = 2 for the cross sections of the furrows used in this study. Note that with these equations and coefficients, a 75% decrease in Q along a furrow results in a 40% P decrease and a 29% V decrease.

As previously proposed, cumulative infiltration, Z, can be represented as an increasing linear function of P with a positive exponent:

$$Z(P) = k_{po} + k_p P \qquad (6)$$

where k_{po} and k_p are the intercept and slope of the relationship (both positive).

If Z is an exponential function of velocity:

$$Z(V) = Z_o \exp\left[k_v \left(V - V_c \right) \right] \qquad (7)$$

where

Z_o = the projected infiltration at $V = 0$,

V_c = the critical velocity above which particle movement and velocity effects commence, and

k_v = the coefficient (negative) describing the rate of infiltration decrease with velocity.

Equation 7 is only valid for $V \geq V_c$. For $V < V_c$, $Z = Z_o$. Assuming the P and V effects are multiplicative and k_{po} and k_p are derived at V = 0, equations 6 and 7 can be combined:

$$Z(P,V) = \left(k_{po} + k_p P \right) \exp\left[k_v \left(V - V_c \right) \right] \qquad (8)$$

Combining equations 4 and 5 with equation 8 allows infiltration variations with Q and S to be projected, as was done in figures 5 and 6. In the figures, a = 0.1, u = 2, and, for the solid lines, n = 0.025. The infiltration coefficients used were 50 L/m and 500 L/m^2 for k_{po} and k_p respectively, which were taken from the stagnant test data, and $V_c = 0$. In figure 5, velocity effects are ignored ($k_v = 0$). In figure 6, $k_v = -2$ s/m which results in a 33% decrease in infiltration with a 0.2 m/s V increase, which agrees with 1985 data.

Figure 5 demonstrates the strong potential influence of P on infiltration as Q varies, and thus the importance of including this relationship when predicting water distribution along a furrow. For a moderately sloped furrow (S = 0.006) with 40 L/min inflow and 25% runoff, 25% less water is infiltrated at the tail end than at the head end under steady flow conditions and the resulting low quarter distribution uniformity (DU) only due to P effects is 0.87. This non-uniformity is often larger than that created by infiltration opportunity time differences.

Figure 6 demonstrates how the influence of V decreases the infiltration variation. For the above conditions, only 16% less water is infiltrated at the tail compared to the head end and the resulting DU is 0.92.

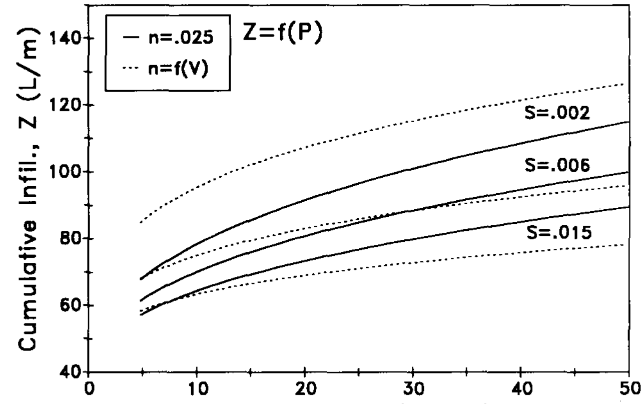


Figure 5–Variation of furrow infiltration with flow rate and furrow slope when infiltration increases linearly with wetted perimeter (from eq. 8 with $k_v = 0$).

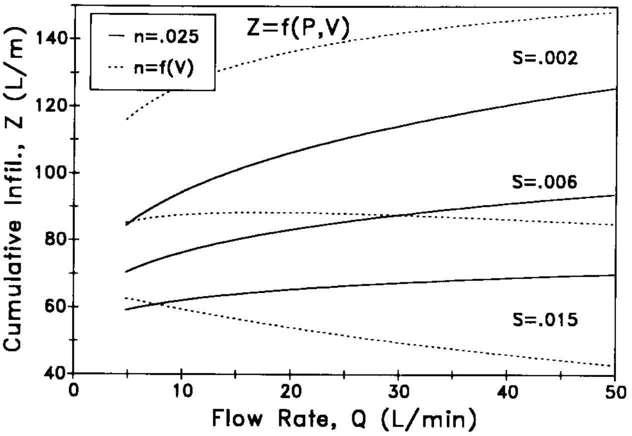


Figure 6–Variation of furrow infiltration with flow rate and furrow slope when infiltration increases linearly with wetted perimeter and decreases exponentially with flow velocity (from eq. 8).

In both the infiltrometer and field tests, P did not vary as much as expected with Q, and furrow perimeters were noticeably smoother when V was high. The same erosion and sediment deposition processes that create the perimeter seal also smooth the perimeter and reduce hydraulic resistance, resulting in an inverse relationship between roughness and velocity. Trout (1992) modeled the n versus V relationship determined from data collected during the recirculating infiltrometer tests with a power function:

$$n = 0.0086V^{-0.65} \qquad (9)$$

By this relationship, n increases from 0.021 to 0.034 as Q decreases from 40 to 10 L/min (S = 0.006). When this relationship is inserted into equations 4 and 5, the dotted-line relationships shown in figures 5 and 6 result. The perimeter smoothing with V decreases the influence of Q and increases the influence of S on P. The variation in velocity with Q and S is increased. As a result, infiltration increases less with increasing Q and more with decreasing S.

With the velocity effect on both roughness and infiltration included, S has a strong effect on infiltration, but Q has essentially no effect at moderate slopes and an inverse effect at steep slopes. This can explain the lack of a consistent relationship between infiltration and flow rate in the Idaho field tests (S = 0.007). The infiltration increase with flow rate measured on the Colorado field (S = 0.0055) is evidence that V exerts relatively less influence on infiltration and perhaps roughness than under Idaho conditions.

Although the relationships depicted in figures 5 and 6 depend on soil-specific coefficients, they indicate the potential importance of both wetted perimeter and flow velocity on furrow infiltration and water distribution, and demonstrate a method to quantify infiltration variability resulting from P and V effects. More research is required to verify the relationships for other soils and conditions.

CONCLUSIONS

- Furrow infiltration should increase less than proportionally with wetted perimeter if other factors are held constant.
- On highly-erodible Portneuf silt loam, infiltration is inversely related to flow velocity. This is likely the result of the effect of velocity on seal formation on the perimeter. The velocity effect masked the influence of wetted perimeter on infiltration in flowing furrows.
- Since both wetted perimeter and flow velocity increase with flow rate, the velocity effect on infiltration counteracts the wetted perimeter effect and can eliminate the influence of flow rate on infiltration in moderate-to-steeply sloped furrows.
- Both wetted perimeter and flow velocity variations can significantly influence water distribution in furrows, and their effects should be quantified on a range of soils and included in predictive models.

REFERENCES

Akram, M., W. D. Kemper and J. D. Sabey. 1981. Water levels and losses and cleaning in watercourses. *Transactions of the ASAE* 24(3):643-650.

ASAE Standards, 36th Ed. 1989. EP 419. Evaluation of furrow irrigation systems, 569-574. St. Joseph, MI: ASAE.

Bautista, E. and W. W. Wallender. 1985. Spatial variability of infiltration in furrows. *Transactions of the ASAE* 28(6):1846-1851.

Blair, A. W. and E. T. Smerdon. 1985. Effect of wetted perimeter on infiltration in furrows. In *Development and Management Aspects of Irrigation and Drainage Systems, Proceeding of the 1985 ASCE Irrigation and Drainage Specialty Conference*, 162-169. ASCE.

Blair, A. W. and T. J. Trout. 1989. Recirculating furrow infiltrometer design guide. Technical Report CRWR 223. Center for Research in Water Resources, College of Engr., Univ. of Texas at Austin.

Brown, M. J., W. D. Kemper, T. J. Trout and A. S. Humpherys. 1988. Sediment, erosion, and intake in furrows. *Irrigation Science* 9:45-55.

Eisenhauer, D. E., D. J. Steib, J. R. Duke and D. F. Heermann. 1983. Transient surface seal development with shallow overland flow. ASAE Paper No. 83-2051. St. Joseph, MI: ASAE.

Fangmeier, D. D. and M. K. Ramsey. 1978. Intake characteristics of irrigation furrows. *Transactions of the ASAE* 21(4):696-700.

Freyberg, D. L. 1983. Modeling the effects of time dependent wetted perimeter on infiltration from ephemeral channels. *Water Resources Research* 19(2):559-556.

Izadi, B. and W. W. Wallender. 1985. Furrow hydraulic characteristics and infiltration. *Transactions of the ASAE* 28(6):1901-1908.

Kemper, W. D., T. J. Trout, M. J. Brown and R. C. Rosenau. 1985. Furrow erosion and water and soil management. *Transactions of the ASAE* 28(5):1564-1572.

Meyer, L. D. 1964. Mechanics of soil erosion by rainfall and runoff as influenced by slope length, slope steepness, and particle size. Ph D. thesis, Purdue Univ., West Lafayette, IN.

Nance, L. A., Jr. and J. R. Lambert. 1970. A modified inflow-outflow method of measuring infiltration in furrow irrigation. *Transactions of the ASAE* 13(6):792-794, 798.

Samani, Z. A. 1983. Infiltration under surge irrigation. M.S. diss., Dept of Agricultural and Irrigation Engineering, Utah State University, Logan, UT.

Segeren, A. G. and T. J. Trout. 1991. Hydraulic resistance of soil surface seals in irrigated furrows. *Soil Science Society of America Journal* 55(640-656).

Strelkoff, T. and F. Souza. 1984. Modeling effect of depth on furrow infiltration. *J. of Irrig and Drainage Engr., ASCE* 110(4):375-387.

Strelkoff, T. 1990. SRFR: A computer program for simulating flow in irrigation furrows, basins, and borders. WCL Report 17. USDA-ARS Water Conservation Laboratory, Phoenix, AZ.

Trout T. J. 1991. Furrow geometric parameters. *J. of Irrig. and Drainage Engr., ASCE* 117(5):613-634.

Trout, T. J. 1992. Furrow flow velocity effect on hydraulic roughness. *J. of Irrig. and Drainage Engr., ASCE* 118(6):(In Press).

Trout, T. J. and W. H. Neibling. 1993. Erosion and sedimentation processes on irrigated fields. *J. of Irrig. and Drainage Engr., ASCE* 118:(In Press).

USDA – Soil Conservation Service. 1983. Furrow irrigation. Chapter 5. In *National Engineering Handbook*, Section 15 – Irrigation, 5-30. U.S. Government Printing Office.

Utah State University. 1989. The surface irrigation simulation model (SIRMOD) user's guide. Dept of Agri. and Irrig. Engr., Utah State Univ., Logan, UT.