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Influence of Irrigation Water Properties on Furrow Infiltration: Temperature Effects

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ABSTRACT

For surface irrigation, the rate and spatial characteristics of infiltration processes influence crop productivity, water use efficiency, and erosion potential of stream flows. A change in infiltration rate alters furrow stream flow velocity and shear, and hence irrigation-induced erosion. Furrow irrigation models may be improved if they can account for the influence of water properties on these processes. Water temperature may influence furrow infiltration by altering fluid viscosity. We conducted laboratory soil column intake (constant head), and field recirculating furrow infiltrometer experiments, to determine whether irrigation water temperature significantly altered infiltration. The soil was Portneuf silt loam (coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcids). Soil column intake increased by 0.8 to 3.0 percent per degree C. This increase was not significantly different from that observed for furrows, 2.0 to 2.9% deg.⁻¹. While more field studies are needed, these data show that diurnal and seasonal changes in irrigation water temperature can significantly alter furrow infiltration and stream flow. These effects may help explain observed field-infiltration variability. Inclusion of temperature algorithms in furrow irrigations models may increase their predictive accuracy.

INTRODUCTION

Timely and adequate amounts of infiltrated water are critical for optimal crop production. For irrigated agriculture, the rate and spatial characteristics of water application and infiltration influence crop productivity, water use efficiency, and erosion potential of runoff water. Furrow irrigation applies water to upper field locations; relying on gravity to draw the water across the field via furrows or corrugates formed in previous tillage operations. Furrow infiltration rate determines to a significant extent the size, wetted perimeter, flow velocity, and shear of the furrow stream. These affect downstream infiltration rates, the magnitude of resulting flow-induced soil detachment, and subsequent sediment transport across and off the field. Computer models designed to simulate irrigation-induced erosion need to account for furrow infiltration phenomenon to accurately describe furrow hydraulic effects on sediment detachment and transport.

Properties of the irrigation water influence furrow infiltration processes. In part, this results from its effects on

depositional seal formation. In irrigation furrows, seals form in response to rapid wetting, flow shear, and chemical soil dispersion (Kemper et al., 1985; Shainberg and Singer, 1985). These processes breakdown and disperse soil aggregates and increase turbidity in the furrow stream, which encourages formation of a tight, slowly permeable depositional seal. The seal reduces infiltration rates. The impact force of raindrops does not contribute to seal formation in furrows (Shainberg and Singer, 1985).

Water Quality Influences on Furrow Infiltration

Laboratory soil column or permeameter studies have examined water quality influences on saturated hydraulic conductivity. Typically, the soils were wetted slowly from the column bottom and disturbance to surfaces was minimized. These conditions do not fully duplicate those occurring in irrigation furrows. Nevertheless, the studies indicated that flow of ponded water through soils increased with increasing electrical conductivity, EC (Fireman and Bodman, 1939; Quirk and Schofield, 1955; Oster and Schroer, 1979), decreasing sodium adsorption ratio, $[SAR=Na/((Ca + Mg)/2)]^{0.5}$, where concentration is in mmol. L⁻¹ (Xiao et al., 1992), and decreasing turbidity (Ragusa et al., 1994).

Several factors were found to influence the degree to which water quality affects soil permeability, including the soluble soil mineral content (Shainberg et al., 1980), concentration of soil cementing materials, Al and Fe oxides and organic matter (Goldberg et al., 1988), soil saturation extract Na/K ratio (Robbins, 1984), soil texture (Frenkel et al., 1978), clay mineralogy (McNeal and Coleman, 1966), and sequence of irrigations having varying water chemistries (Oster and Schroer, 1979; Chawla et al., 1983). Oster and Schroer (1979) concluded that irrigation water quality had a greater effect on infiltration than the chemistry of the soil column because of its alteration of surface soil characteristics.

Field infiltration studies commonly observe large differences (>10%) between furrows. This is caused by variations in furrow slope, roughness, wetted perimeter, and flow velocity across a field. Despite the difficulties such variation poses for field investigations, several field studies have confirmed results observed in the laboratory. Brown et al. (1988) concluded that, for silt loam soils, water infiltration rates in furrows supplied with low-sediment water were 50 to 100% higher than furrows supplied with sediment-enriched irrigation water. A recirculating furrow

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infiltrometer study on similar soil showed a 66% reduction in cumulative infiltration when furrow stream sediment concentration increased from 1 to 100 g L⁻¹ (Trout et al., 1995). A field study on these silt loam soils showed that increasing irrigation water EC from 0.07 to 0.17 S m⁻¹ or decreasing SAR from 9.3 to 0.5 resulted in a 20% increase in cumulative furrow infiltration (Lentz et al., 1996a).

Irrigation water amendments can also alter infiltration into furrows. Additions of < 10 mg L⁻¹ polyacrylamide (PAM) to irrigation water increased furrow infiltration into newly formed silt loam furrows by up to 60% (Lentz et al., 1992; Lentz and Sojka, 1994; Trout et al., 1995). The PAM-induced infiltration increase at a given location is a function of the amendment concentration (Lentz et al., 1992), the molecular characteristics of polymer used (Lentz and Sojka, 1996, 1999), irrigation history (Sojka et al., 1998), water chemistry (Lentz et al., 1996b), and soil texture (Mitchell, 1990).

Potential Water Temperature Effects

Early soil column studies reported that soil hydraulic conductivity increased with soil column temperature and partly or entirely attributed the result to a decrease in soil water viscosity (Moore, 1940; Haridasan and Jensen, 1972). Hopmans and Dane (1985) related soil hydraulic conductivity (K_T) at temperature (T) using:

$$K_T = (\eta_{ref}/\eta_T)K_{ref} \quad [1]$$

where K_{ref} is hydraulic conductivity measured at a reference temperature, and η_{ref} and η_T denote the viscosity of water at the reference temperature and the soil temperature of interest. The influence of soil and water temperature on hydraulic conductivity increased with increasing volumetric water content (Haridasan and Jensen, 1972). This suggests that water transport (infiltration) through the wetted perimeters of soil lined water conveyance channels, such as irrigation furrows, should vary with water temperature. Mitchell et al. (1985) observed diurnal fluctuations in irrigation canal water levels that correlated closely with canal water temperature. However, effects of evaporation, runoff, and subsurface drainage into the canals may also have contributed to the observed diurnal variation.

Jaynes (1990) measured water infiltration in an isolated soil plot ponded under ~40 mm of quiescent tap water. The observations were made during a 120 h period, after 35 days of continual irrigation. An infiltration model that expressed hydraulic conductivity as a function of temperature succeeded in duplicating the diurnal temperature dependent infiltration rate shifts. Duke (1992) employed a computer simulation to evaluate temperature effects on furrow irrigation. Cumulative infiltration computed at a constant reference temperature, differed by 9 to 28% from cumulative infiltration values computed using actual furrow stream water temperatures.

To our knowledge, few if any field studies have measured the effect of irrigation water temperature on furrow infiltration. The inherently large infiltration variability observed among furrows, and interactions with other furrow processes, such as soil detachment, headcut

formation, and seal development may overshadow temperature impacts and render them insignificant. Our objective was to determine if irrigation water temperature significantly affects infiltration rates in flowing water systems such as irrigation furrows, where the soil at the soil-water interface is disturbed by flow shear forces.

MATERIALS AND METHODS

Laboratory and field experiments were used to examine temperature effects on infiltration into Portneuf silt loam (coarse-silty, mixed superactive, mesic, Durinodic Xeric Haplocalcids). Field measurements were made on a research plot near Kimberly, ID USA. The silt loam surface horizon had 100 g kg⁻¹ clay, 700 g kg⁻¹ silt, and 10 to 13 g kg⁻¹ organic matter, a cation exchange capacity of 190 mmol kg⁻¹, saturated-paste-extract EC of 0.07 S m⁻¹, exchangeable sodium percentage (ESP) of 1.5, pH of 7.7, and calcium carbonate equivalent of 5%.

The response of Portneuf soil columns 7.6 cm in diameter and 7.6 cm long to applied water was measured using a constant-head method (Klute and Dirksen, 1986). Undisturbed soils were extracted from the field in cylinders. Ponded water was held in similar cylinders attached above the soil cores using rubber sleeves. The constant-head device, soil columns, and water supply were placed in a plant growth chamber to permit testing at three different temperatures ranging between 7 and 33°C (Fig. 1). Infiltrating water and near-surface soil temperature in columns was adjusted to the target value before we ran each test. Infiltration rates were taken as the mean calculated during two to three 30 min monitoring periods. Soil column flow was measured before and after the soil surface was disturbed by stirring to a depth of 1 to 1.5 cm. Tap water used in trials had an EC of 0.08 S m⁻¹, SAR of 1.7 and pH of 7.2. We measured flow through nine individual soil columns, subjecting each to two thermal shifts during which temperature was elevated by 8-to-10°C. The resulting data set included 18 responses.

A recirculating furrow infiltrometer (Trout et al., 1995) was modified by inserting approximately 11 coils of 10 mm (outside diameter), copper tubing along the inside wall of the constant-head furrow-inflow supply reservoir (Fig. 2). This tube circulated temperature regulated water from a programmable recirculating water bath through the reservoir. A platinum resistance temperature sensor inserted into the supply reservoir near the outlet valve provided thermal feedback to the water bath, which was programmed to maintain the supply reservoir water at a preset temperature. A data logger and three copper-constantan thermocouple temperature sensors monitored main supply tank, furrow inflow water temperatures, and soil temperature (0.5 to 1.0 cm depth) at the wetted perimeter midway along the furrow. A sheath of fiberglass batting over the 16 L supply reservoir and 570 L main water supply tank slowed heat transfer to or from the atmosphere.

Infiltrometer runs were typically started in the morning using irrigation water that had cooled over night to a temperature between 9 and 14 °C. Inflows were set at 16.5 L min⁻¹ and continued for 2 to 6 h, enough time for the furrow infiltration rate to attain a steady state, all other factors being

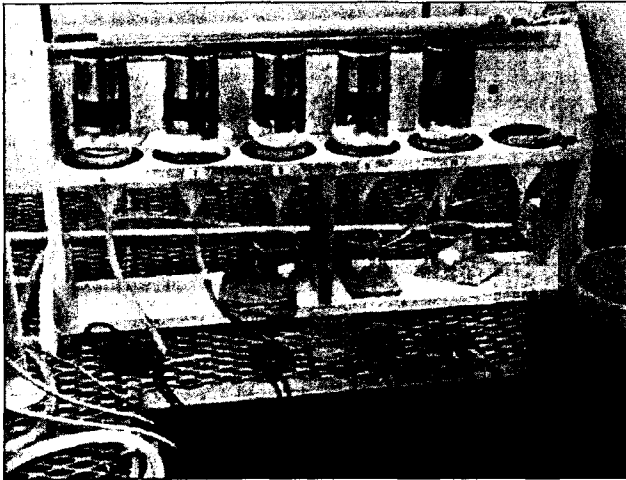


Figure 1. Constant head apparatus set up in plant growth chamber to measure the effect of temperature on hydraulic conductivity through soil columns.



Figure 2. Recirculating furrow infiltrometer used in field experiment with modifications that permit control and monitoring of stream temperatures. Note: The insulation batting over the furrow was needed only on cool days and was not used in this study.

invariant. The main supply tank water was then refilled with enough heated irrigation water to elevate furrow stream water temperatures by 5 to 20 °C. Monitoring continued for 2 to 4 h after altering furrow stream water temperatures. The experiment was repeated over several consecutive days on five individual furrows. The data set provided six furrow responses to temperature-shift events. Infiltration was computed for the furrow-wetted perimeter.

Soil column and field furrow response values were reported as mm h^{-1} , or percent, infiltration-increase per °C temperature change. A *t*-test was used for both the soil column and furrow studies to test the null hypothesis that infiltration increase was equal to zero. The mean infiltration-increase response from soil column and furrow intake experiments were compared using a *F*-test ($P = 0.05$).

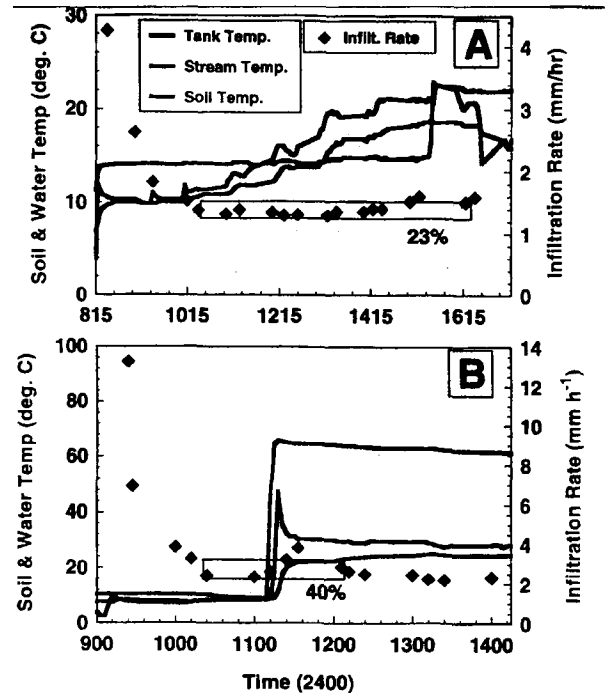


Fig. 3. Recirculating furrow infiltrometer output, main supply tank and furrow stream water temperature, and 0.5-1.0 cm furrow wetted perimeter soil temperature for two different furrows monitored on DOY 267 (A) and DOY 298 (B).

RESULTS AND DISCUSSION

Infiltration and flow through soil columns stabilized within approximately 30 min after the temperature shift had been completed. Measured infiltration rates from field furrows were less stable, partly because furrow conditions were dynamic. Infiltration may have responded to other furrow processes that were less directly linked to thermal changes; e.g. depositional seal formation, changes in channel configuration, or emergence of macropores. Measurement fluctuations also resulted from the somewhat cyclic nature of the water supply and recirculating processes of the infiltrometer, although these were minimized by integrating measurements over an appropriate period.

Recirculating infiltrometer results show that increasing irrigation water temperature produced both short (Fig. 3B) and long-term (Fig. 3A) increases in furrow infiltration. Typically, an initial rise in water temperature produced an immediate increase in furrow infiltration, followed 0.5 to 1.5 h later by a decrease in infiltration rate (See Fig. 3B, 11:15). This suggests that rising water temperatures may also instigate or enhance other furrow processes that partially or completely compensate for decreasing water-viscosity effects on infiltration. Because furrow infiltration on

Portneuf silt loam soils is controlled by the conductivity of the depositional seal (Segeren and Trout, 1991), it is likely that any compensating process acts upon the soil-water interface.

Increasing irrigation water and wetted-perimeter temperatures significantly increased ponded infiltration/conductivity through both furrows and soil columns (Table 1). The increase in soil column flow produced by increasing water temperatures was 2.0% deg.⁻¹, and was not significantly different ($P=0.24$) from that for furrows, 2.3% deg.⁻¹.

Initial infiltration rates for individual soil columns ranged from 0.8 to 20.8 mm h⁻¹, while initial steady-state infiltration rates for furrows ranged from 1.3 to 3.2 mm h⁻¹ (Table 1). The greater range for soil columns reflects the

Table 1. Infiltration rates of soil columns and furrows before changing soil and water temperature, and resulting increase in infiltration in response to the new temperature conditions.

Soil Test Method	Infiltration Range (mm h ⁻¹)	Infiltration Increase (mm h ⁻¹ deg. ⁻¹)		Infiltration Increase (% of initial deg. ⁻¹)	
		Range	Mean	Range	Mean
Column	0.8 - 20.8	0.01 - 0.47	0.08*a [†]	0.8 - 3.0	1.99* [†] a
Furrow	1.3 - 3.2	0.03 - 0.07	0.05*a	2.0 - 2.9	2.3*a

* Response significant, i.e. nonzero mean ($P = 0.05$)

† Similar letters indicate non-significant differences between Column and Furrow responses ($P < 0.05$).

irrigation water viscosity. In this respect our results are similar to those of Haridasan and Jensen (1972). In fact, measured infiltration rate increases were lower than predicted, which suggests that temperature conditions influence other furrow processes that potentially counteract viscosity-induced infiltration effects.

The temperature of surface-source irrigation inflows in southern Idaho can vary by as much as 10 °C during the season, and include a similar range in diurnal variation (R.D. Lentz, unpublished data). Furthermore, furrow stream temperature can increase as water crosses the field -- by as much as 22 °C as measured along 500 m furrows on a sunny summer day in Colorado (Duke, 1992). This study shows that such water temperature changes can lead to very significant fluctuations in furrow infiltration rate, and should be considered in mathematical models that predict furrow hydraulics and resulting erosion. These temperature effects may also help explain observed furrow infiltration variability. These results have implications for furrow irrigation water management as well. For example, farmers wishing to furrow irrigate long, nearly flat fields could increase the rate of furrow advance and hence application uniformity by starting their irrigation in the evening rather than the morning. With little solar heating, evening-started furrow streams would remain cooler, infiltration would be minimized, and stream-flow maximized.

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small size of each soil sample monitored and the large variation in number and continuity of pores, particularly macropores, present in soil cores. The infiltration increase produced by rising water temperature was greater for soil columns with high initial infiltration rates. This explains why the range for infiltration increases reported for soil columns was greater than that for field furrows. This proportionality between temperature effect and initial soil column infiltration rate is correctly described by the relationship modeled in Eq. [1]. Equation [1] predicts that the infiltration increase (% of initial infiltration rate deg.⁻¹) would range between 3.1 and 3.5 % deg.⁻¹ for these soil columns. Thus, the infiltration rate increases observed in this study may be entirely accounted for by changes in

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