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Furrow Irrigation Water-Quality Effects on Soil Loss and Infiltration

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ABSTRACT

Irrigation-induced erosion is a serious problem in the western USA where irrigation water quality can vary seasonally and geographically. We hypothesized that source-water electrical conductivity (EC) and sodium adsorption ratio (SAR = Na/[(Ca + Mg)/2]$^{0.5}$, where concentrations are in millimoles of charge per liter) affect infiltration and sediment losses from irrigated furrows, and warrant specific consideration in irrigation-induced erosion models. On a fallow Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid), tail-water sediment loss was measured from trafficked and nontrafficked furrows irrigated with waters of differing quality. Treatments were the four combinations of low or high EC (0.6 and 2 dS m^{-1}) and low or high SAR (0.7 and 12 [mmol$_c$ L^{-1}]$^{0.5}$). Slope is 1%. Twelve irrigations were monitored. Each furrow received two irrigations. Main effects for water quality, traffic, and first vs. second irrigations were significant for total soil loss, mean sediment concentration, total outflow, net infiltration, and advance time. Average tail-water soil losses were 2.5 Mg ha^{-1} from low EC/low SAR furrows, 4.5 Mg ha^{-1} from low EC/high SAR furrows, 3.0 Mg ha^{-1} from high EC/high SAR furrows; and 1.8 Mg ha^{-1} from high EC/low SAR furrows. Elevating water EC decreased sediment concentration from 6.2 to 4.6 g L^{-1}, but increasing SAR increased sediment concentration from 6.2 to 8.7 g L^{-1}. Net infiltration decreased 14% in high SAR compared with low SAR treatments. Soil loss increased 68% for second irrigations, and net infiltration fell 23% in trafficked furrows, but water-quality effects were the same. Water quality significantly influenced infiltration and erosion processes in irrigated furrows on Portneuf soils.

Of the estimated 250 million ha irrigated worldwide, at least 60% is surface irrigated. Soil erosion from irrigation, especially furrow irrigation, contributes to nonpoint-source pollution (Hajek et al., 1990) and is a serious threat to crop productivity in many regions (Carter, 1993).

Agricultural research has focused primarily on rainfall-induced soil erosion, with comparatively little attention to furrow-irrigation-induced erosion. A common assumption has been that erosion in rills is mechanistically equivalent to that in irrigated furrows. While shear produced by concentrated flow causes soil detachment and entrainment in both, there are several important differences: (i) rill phenomenon often includes an additional force, raindrop impact, which detaches and transports adjacent soil particles to the rill stream; (ii) a furrow stream initially advances over dry soil, resulting in rapid wetting and destabilization of dry, low-cohesion soil aggregates and increased furrow erosion losses (Kemper et al., 1985), whereas rill soils are prewetted by precipitation; (iii) downstream flow rates decrease in furrows as water infiltrates, but increase in rain-fed rills owing mainly to tributary inflow, hence, furrow flow rates and potential erosion losses are greater in the upper reaches of a furrow, not in the lower reaches as for rills; and (iv) salinity and sodicity of rainwater are uniformly low, while irrigation water quality can vary widely, geographically and temporally, even within short distances and short intervals.

Few studies have attempted to determine how irrigation water quality influences furrow erosion, although this information may be necessary to understand and model erosion processes in surface irrigated systems.

Three main factors influencing furrow erosion are the shear stress of flowing water on the furrow perimeter, cohesivity of soil particles (which affects the stability and size-distribution characteristics of furrow soil), and stream transport capacity (Kemper et al., 1985; Trout and Neibling, 1993). Water quality may influence flow shear by controlling furrow intake and, hence, down-furrow flow rate. In soil column studies, SAR and EC of infiltrating water reduced soil permeability and infiltration rate (Fireman and Bodman, 1939; Quirk and Schofield, 1955; Frenkel et al., 1978). The most significant impact has been shown to be on depositional seal formation (Shainberg and Singer, 1985; Brown et al., 1988). Soils were more sensitive to water quality impacts when mechanical disruption (i.e., flow shear) accompanied water application (Quirk and Schofield, 1955; Oster and Schroer, 1979). The extent of water-quality impact on soil permeability was shown to depend on soil texture (Frenkel et al., 1978); clay mineralogy (McNeal and Coleman, 1966); presence of soluble soil minerals (Shainberg et al., 1981), soil binding agents, Al and Fe oxides, and organic matter (Goldberg et al., 1988); Na/K ratio of soil saturation extracts (Robbins, 1984); and constancy of irrigation water quality (Oster and Schroer, 1979). Sinclair et al. (1992) measured no effect on intake when they applied $CaCl_2$-treated water (SAR not specified) to furrows in hard-setting sandy loam soils. Their gravimetric sampling scheme, however, was limited in extent and may have inadequately represented soil water conditions. Evans et al. (1990) measured season-long intake rates using a recirculating furrow infiltrometer. Furrow intake was higher for more saline water treatments, even when irrigating with high SAR waters (EC = 9.2 dS m^{-1} and SAR >100 vs. EC = 0.1 and SAR = 0.97).

Furrow irrigation water quality affected soil cohesivity by altering clay dispersion (Velasco-Molina et al., 1971; Frenkel et al., 1978; Malik et al., 1992; Shainberg et al., 1992) and aggregate stability characteristics (Smith et al., 1992). Irrigating with high-SAR water increased double-layer thickness and zeta potential of soil colloids, leading to aggregate destabilization and enhanced chemical dispersion (Malik et al., 1992), especially when soil aggregates were exposed to the mechanical disturbance provided by flow shear (Peele, 1936; Oster and Schroer, 1979). The resulting soil structure was less cohesive and

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Abbreviations: EC, electrical conductivity; SAR, sodium adsorption ratio; ESP, exchangeable sodium percentage.

Table 1. Properties of Portneuf soil (plow layer).

Texture	Particle-size distribution			Dominant clay minerals†	Cation-exchange capacity	EC‡	Exchangeable Na percentage	pH	OM‡	Aggregate stability§
	Sand	Silt	Clay							
	g kg⁻¹				$cmol_c\ kg^{-1}$	$dS\ m^{-1}$	%		$g\ kg^{-1}$	%, w/w
Silt loam	100–170	650–700	180–200	I > > K = M > V	18–20	0.5–0.7	1.6–1.8	7.9–8.2	10–17	89

† Coarse clay fraction: I = illite, K = kaolinite, M = montmorillonite, V = vermiculite.
‡ EC = electrical conductivity (saturated paste extract); OM = organic matter.
§ From Lehrsch and Brown (1995).

more susceptible to detachment and transport forces of the furrow stream. Arulanandan et al. (1975) measured the fluid shear stress required to initiate erosion from a packed sample of a cohesive soil. At a given SAR, the soil critical shear stress increased as the EC of the eroding fluid increased. This laboratory study was unable to fully simulate field furrow conditions (e.g., it did not account for initial low soil water content of furrows or infiltration). Hence, the observed response of soil shear to changes in fluid EC may differ from that occurring in the field. Soil dispersion also decreased with increasing electrolyte concentration of the percolating solution (Quirk and Schofield, 1955), even when soil SAR was high (Velasco-Molina et al., 1971; Arora and Coleman, 1979; Shainberg et al., 1981).

Water chemistry may influence the sediment transport capacity of the furrow stream indirectly via impacts on flow shear (i.e., infiltration-induced flow rate effects), and by modifying the character of entrained soil particles and aggregates. Water quality affected flocculation, which determined the size and density of detached soil material (Arora and Coleman, 1979; Goldberg and Glaubig, 1987). Compared with dispersed suspensions, the aggregate-size distribution of flocculated suspensions was skewed toward larger sizes. However, Gregory (1989) reported that in flowing water, hydrodynamic shear increased floc breakage and limited maximum floc diameters to between 50 μm and several millimeters, depending on the strength of flow shear. The relatively greater number of large coalescent masses in flocculated suspensions requires greater energy for transport, settles faster, and is less likely to be entrained in the furrow stream. For example, increasing EC of irrigation water enhanced soil flocculation (Arora and Coleman, 1979) and increased settling rates of sediment suspended in water (Robbins and Brockway, 1978).

We hypothesized that irrigation water-quality impacts sediment loss from furrows via effects on soil erodibility, flocculation, and infiltration. Water with low EC and/or high SAR should promote dispersion and development of a slowly permeable surface seal. This would decrease infiltration and increase stream velocity. Greater stream velocities may stimulate detachment and sediment transport processes and increase soil loss from furrows. In addition, low EC and/or high SAR should weaken soil aggregates and decrease the soil's resistance to shear. Alternatively, high EC/low SAR water would improve aggregate strength, promote flocculation and develop a more permeable surface seal, stabilize infiltration, and inhibit soil removal and transport processes. Our objectives were to: (i) determine whether EC and SAR of inflowing water affects sediment loss from irrigated furrows, and (ii) relate furrow sediment loss to net infiltration and outflow.

METHODS

The study was conducted from July through mid-August 1991 near Kimberly, ID, on a 1.6-ha field of fallow Portneuf silt loam. Properties of the Portneuf soil are presented in Table 1. Slope is 1%. The previous potato (*Solanum tuberosum* L.) crop was harvested, the field was fall disked, and disked and roller-harrowed in the spring. Pre-(spring) and post-emergence (mid-July) herbicides were applied to control weeds. Irrigation water, diverted from the Snake River, was conveyed to furrow heads via gated pipe fitted with adjustable spigots.

Furrows approximately 20 cm deep were formed with 75° V-shaped implements attached to the tractor's rear tool bar. Furrow spacing was 0.76 m, and furrow length was 114 m. Furrows were established in mid-June. Unused furrows were cultivated and reformed in late July to prevent soil consolidation and to remove any weed residue.

Four water-quality treatments consisted of combinations of two EC and two SAR levels. The chemistry of water-quality treatments selected satisfied the following criteria: (i) EC and SAR levels were moderate relative to the entire range of irrigation water qualities available in the western USA, yet had demonstrated potential for altering soil properties (e.g., infiltration rate) in surface irrigation applications (Oster and Schroer, 1979); (ii) treatment levels were obtainable by simple amendment of local irrigation water, and (iii) treatment choices would permit preparation of low and high SAR waters that had similar EC. The targeted EC levels were low EC = 0.5 $dS\ m^{-1}$ and high EC = 2 $dS\ m^{-1}$. The targeted SAR levels were low SAR = 0.7 and high SAR = 12. The control treatment (low EC/low SAR) was untreated Snake River water, which is characterized in Table 2. Typically, the composition of untreated Snake River water is relatively stable during the period encompassed by the study, e.g., EC and SAR vary less than 8% (Carter et al., 1973). Water chemistry of furrow streams was adjusted by metering solutions of NaOH, $CaCl_2$, and NaCl into inflows. The NaOH solution was employed because it increased irrigation-water SAR levels with minimal

Table 2. Composition of untreated Snake River water (i.e., low electrical conductivity [EC] low [SAR] sodium adsorption ratio treatment).

Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-	EC†	SAR†	pH
$mmol_c\ L^{-1}$							$dS\ m^{-1}$	$(m\ mol_c\ L^{-1})^{0.5}$	
2.30	1.44	1.13	0.12	2.95	0.81	0.78	0.42	0.82	8.3

Table 3. Treatment tail-water characteristics.

Irrigation water treatment	Sample number	EC† mean	EC† SD	SAR† mean	SAR† SD	pH mean	pH SD
		- dS m^{-1} -		($m\ mol_c\ L^{-1})^{0.5}$			
low EC/low SAR	49	0.5	0.1	0.9	0.2	8.6	0.1
high EC/low SAR	71	2.1	0.9	0.5	0.1	7.5	0.3
low EC/high SAR	54	0.7	0.4	9.1	7.6	9.2	0.7
high EC/high SAR	73	1.7	0.7	9.3	3.9	7.4	0.1

† EC = electrical conductivity; SAR = sodium adsorption ratio.

influence on EC (via the reaction: $Na^+ + OH^- + Ca^{2+} + HCO_3^- \rightleftarrows CaCO_3\downarrow + CO_2\uparrow + Na^+ + H_2O$).

Either peristaltic pumps or constant-head discharge devices were utilized to introduce salt solutions into furrow inflows beneath gated-pipe spigots. Metering rates were checked periodically throughout each irrigation. Eighteen to 24 tailwater samples were randomly collected from furrow treatments during each irrigation. Soluble Ca, Mg, and Na in the samples were determined by atomic-absorption spectrophotometry, and EC was measured with a conductivity meter. These measurements indicated that tail-water EC was very close to target values, but SAR in runoff water of high SAR treatments was often closer to nine than our target value of 12 (Table 3). The SAR of the low EC/high SAR treatment (NaOH added) was more variable than other treatments. The greater variation was probably related to the simultaneous reaction that occurred during solution addition (see above), and may have resulted from differing reaction rates or endpoints present in each furrow system.

The study employed a split-plot experimental design. Each replicated block consisted of four plots representing the four water-quality types. Each plot was split into a wheel-trafficked (one tractor pass) and non-wheel-trafficked furrow subplot. The response from each subplot was taken as the mean of the three furrows. Subplots received two irrigations. The second irrigation occurred 7 to 9 d after the first. Furrows were not disturbed between irrigations. For statistical purposes, the two irrigation events were referenced as *irrigation episode*. Interaction effects between irrigation episode (first vs. second irrigations) and treatments were examined by including irrigation episode as a split of the subplot. The experiment was repeated in a new block six times (six replicates) from July through mid-August. The entire data set included complete measurements from 288 irrigated furrows. Values from three furrows were averaged for each subplot response, so the statistical data set includes 96 responses: (6 replicates) × (4 water qualities) × (2 traffic types) × (2 irrigations) = 96.

Surface soils were sampled for soil water content before each irrigation. Inflow rate was 19 L min^{-1} for all irrigations except for the initial irrigation in the last three repetitions; inflow was increased to 23 L min^{-1} during these irrigations to promote more rapid furrow stream advance across the drier surface soils in these plots. Inflow and outflow rates were measured, and runoff samples collected for each furrow during each irrigation. Irrigation and runoff initiation times were noted in all irrigations. Furrow runoff rate was measured using calibrated, long-throated flumes (Bos et al., 1984) installed near furrow outfalls. Outflows were measured and runoff samples collected at 30-min intervals during the first 1 to 3 h of an irrigation; once outflows stabilized, samples were taken hourly.

One-liter runoff samples were collected from the flume outlet. Sediment concentration in tail-water samples was measured using the Imhoff cone technique (Sojka et al., 1992), in which 30-min settled-sediment volume is correlated with sediment weight. Three Imhoff-cone sediment samples were collected from each treatment in each irrigation. These were filtered, and the papers dried and weighed, to provide sediment mass values for calibration of sediment volume to mass correlation functions.

Table 4. Significance of *F* values from analysis of variance on measured responses.

Source of variation	Sediment loss	Total inflow	Total outflow	Net intake	Mean concentration of sediment	Advance time
Model (overall *F* test)	**	NS	**	**	**	**
Water quality (TRT)	**	–	**	**	**	**
Traffic (TR)	**	–	**	**	**	**
Irrigation episode (IE)	**	–	**	**	**	**
TRT × TR	NS	–	NS	NS	NS	NS
TRT × IE	*	–	NS	NS	NS	NS
TR × IE	NS	–	**	NS	NS	NS
TRT × TR × IE	NS	–	NS	NS	NS	NS

*, ** Significant F-value at 0.05 and 0.01 probability levels, respectively; NS = not significant at the 0.05 level.

The computer program FUROFIGR (Lentz and Sojka, 1994) expedited analysis of furrow irrigation data. Analysis indicated that Imhoff calibration functions for treatments and irrigation episodes were unique. Therefore, separate calibration functions were computed for furrows from each different treatment/irrigation episode combination. This version of FUROFIGR assumed constant inflow, outflow, and sediment concentration during each measurement period. Total inflow, outflow, and sediment losses were summed across all periods. Net infiltration was the difference between total inflow and total outflow, and mean sediment concentration was the ratio of total sediment loss to total outflow. Furrow advance time was the number of minutes required for inflowing water to initially traverse the entire dry furrow length. Analysis of variance compared treatment effects. Mean separations in tables and error bars in treatment-comparison figures were obtained from confidence intervals derived from pairwise Student's *t*-tests ($\alpha = 0.10$). A 0.10 significance level was used to offset the lack of power associated with the conservative *t*-test.

RESULTS AND DISCUSSION

Analysis of variance (Table 4) showed that water quality, irrigation episode, and traffic significantly affected total tail-water soil loss, total outflow, net infiltration, mean tail-water sediment concentration, and advance time. Significant interactions were a water quality × irrigation episode effect on soil loss and a traffic × irrigation episode effect on total outflow.

Water-Quality Effects

The water-quality effect on total furrow soil loss was examined separately for each irrigation episode because of the significant interaction of water quality × irrigation episode on sediment loss. The soil loss pattern in response to water-quality treatments was similar in both irrigations (Fig. 1A and 2A), but treatment effects were slightly larger for the second irrigation (Table 5). In the second irrigation, sediment loss for control (low EC/low SAR) furrows was 2.9 Mg ha^{-1}, and all soil loss mean separations were significant (Table 5). For both irrigation episodes, soil losses from high EC/low SAR treatments were 67 to 72% of control losses. Low EC/high SAR

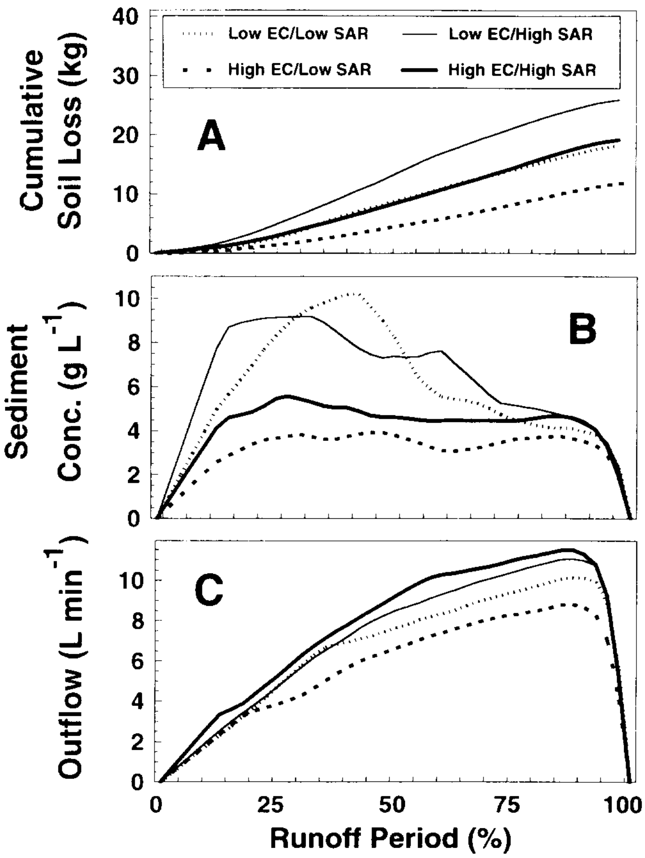

Fig. 1. Influence of irrigation water quality on: (A) cumulative soil loss; (B) mean sediment concentration; and (C) outflow during the first irrigation. Plotted values are means of all furrows included in each water-quality treatment. (Note *y* axis scale differences with Fig. 2.)

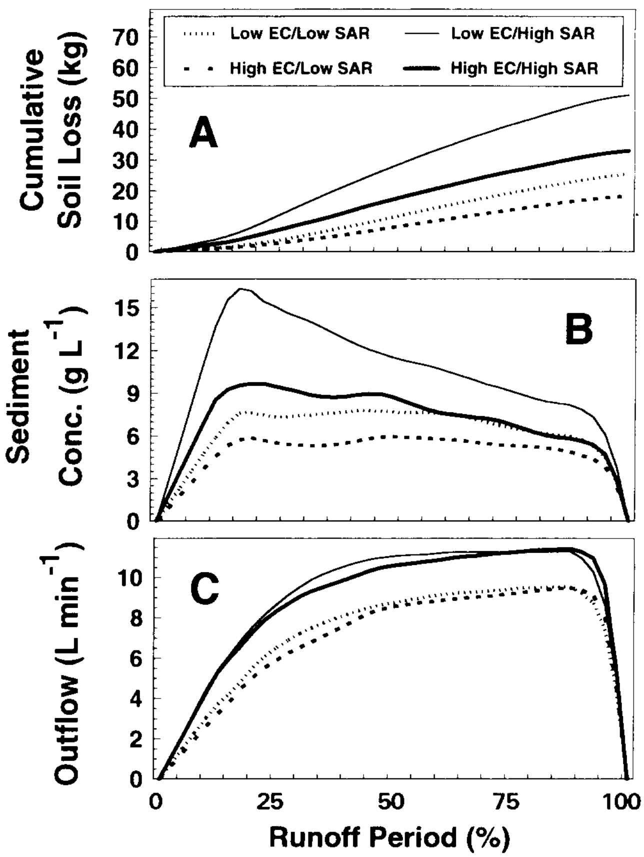

Fig. 2. Influence of irrigation water quality on: (A) cumulative soil loss; (B) mean sediment concentration; and (C) outflow during the second irrigation Plotted values are means of all furrows included in each water-quality treatment. (Note *y* axis scale differences with Fig. 1.)

treatment soil losses were 1.43 to 2.03 times those of controls, and high EC/high SAR soil losses were 1.04 to 1.31 times control amounts.

The response of mean sediment concentration to water-quality treatments was similar to that of total soil loss (Fig. 1B and 2B). Sediment concentration was greatest in low EC/high SAR, smallest in high EC/low SAR irrigated furrows, and intermediate for the control (low EC/low SAR) and high EC/high SAR furrows (Table 5). Total outflow, net infiltration, and furrow advance were without water-quality interactions, thus treatment values from all irrigations were analyzed together (Table 6). In general, total outflow was 25% greater, net infiltration was 14% less, and furrow advance was 19% faster for high SAR than for low SAR treatments.

For these irrigation waters, the impacts of increased EC on sediment concentration and soil loss were the opposite of those observed when SAR increased (Fig. 1 and 2). Elevating water EC reduced the total sediment loss and mean sediment concentration in runoff, but had little effect on net infiltration or rate of furrow advance (Tables 5 and 6). Conversely, increasing the SAR of the irrigation water increased total sediment loss and the mean sediment concentration in outflow, reduced net infiltration, and increased the rate of furrow advance. Increasing both EC and SAR resulted in lower soil loss than occurred when SAR alone increased (Tables 5 and 6). These results strongly support our hypothesis.

Clay Dispersion

Low EC/high SAR irrigation water enhanced chemical dispersion and destabilization of soil aggregates in furrow

Table 5. Effect of water quality on furrow soil loss in each irrigation.

	First irrigation				Second irrigation			
	Low SAR†		High SAR		Low SAR		High SAR	
Measured response	Low EC†	High EC	Low EC	High EC	Low EC	High EC	Low EC	High EC
Total soil loss, Mg ha^{-1}	2.1 b‡	1.4 c	3.0 a	2.2 b	2.9 c	2.1 d	5.9 a	3.8 b
Mean sediment conc., g L^{-1}	5.4 b	3.7 c	6.5 a	4.8 b	7.0 b	5.4 c	10.9 a	7.6 b

† EC = electrical conductivity; SAR = sodium adsorption ratio.
‡ Means within a row and irrigation episode with dissimilar letters are significantly different ($P < 0.10$); each value is the mean of 36 furrows.

Table 6. Overall influence of water quality on furrow flow rate and infiltration.

Measured response	Low SAR†		High SAR	
	Low EC‡	High EC	Low EC	High EC
Total inflow, mm	107‡	107	106	107
Total outflow, mm	40 b§	36 bc	47 a	48 a
Net infiltration, mm	67 ab	71 b	59 a	59 a
Furrow advance, min	59 ab	63 a	51 bc	48 c

† EC = electrical conductivity; SAR = sodium adsorption ratio.
‡ Mean separations were not appropriate because of a nonsignificant ANOVA; each value is the mean of 72 furrows.
§ Means within a row with dissimilar letters are significantly different ($P < 0.10$).

streams. This was evident from both the Imhoff cone samples and their calibration functions, which related settled sediment volume to mass of sediment per liter. Turbidity of the Imhoff cone supernatant (after settling for 30 min) was greater in low EC/high SAR samples than in high EC/low SAR samples, signifying greater clay dispersion and clay content in the low EC/high SAR sediment. Furthermore, the slope of the calibration function for low EC/high SAR samples (0.73) was significantly less ($P < 0.05$) than that for samples from the low EC/low SAR treatment (0.84), indicating that the bulk density of the low EC/high SAR settled sediment was less than that of the low EC/low SAR treatment. We attributed its low bulk density to the dispersed, less consolidated condition of the low EC/high SAR sediment.

That irrigation water having an SAR of ≈ 9 and EC of ≈ 0.7 would promote clay dispersion may be surprising for two reasons. First, clay dispersion is a function of a soil's ESP; it's possible that the soil in the furrow did not equilibrate with the source water during the irrigation, thus soil ESP would have been less than the water's SAR value. Patience and numerous leaching volumes are required to equilibrate soil in a laboratory column with infiltrating water. However, erosion and infiltration (sealing) are soil surface and furrow-stream phenomena, therefore, it is the impact of water chemistry on surface soil that is most critical. The kinetic energy conditions and soil/water ratios occurring in the surface 2 millimeters and flow-suspended sediment of irrigated furrows differ markedly from those present at the soil surface in column experiments. Mixing and redistribution of surface soil caused by flow shear and low soil/water ratios of furrow-stream suspensions may have accelerated the equilibration process in furrows relative to laboratory columns. If furrow soils did not equilibrate with applied water, then water-quality impacts on furrow processes in subsequent irrigations could be greater than that observed here.

A second concern is that the salt concentration of the low EC/high SAR water (≈ 7 mmol$_c$ L^{-1}) was enough to mask any dispersing effects of the water's higher SAR (Table 3). Shainberg et al. (1980) reported that infiltrating water with a salt concentration of 2 mmol$_c$ L^{-1} prevented clay dispersion in soil columns when water SAR ≤ 10. However, the influence of EC and SAR on clay dispersion, infiltration, or hydraulic conductivity varies with soil type, and other researchers reported that clay dispersion can occur with SAR = 10 source water at electrolyte concentrations of ≤ 10 mmol$_c$ L^{-1} (Curtin et al., 1994; Frenkel et al., 1978; Goldberg and Forster, 1990).

While the pH of the low EC/high SAR tail water was 1 to 1.8 units higher than for other treatments (Table 3), the pH effect on clay dispersion–flocculation was considered to be slight. Goldberg and Forster (1990) reported that the critical coagulation concentration value of soil clay suspensions with SAR ≤ 25 was unchanged when the suspension pH was increased from 7.5 to 9.5.

When furrows were irrigated with low EC/high SAR waters, rapidly wetted aggregates were destabilized and sediment was readily detached and transported, resulting in high in-stream dispersed sediment concentrations, compared with furrows irrigated with low SAR water. Greater stream sediment concentrations lead to enhanced soil loss, particularly since outflows were also greater in high SAR treatments than low SAR waters (Table 6).

An increase in EC promotes clay flocculation and settling of suspended sediments in irrigation water (Robbins and Brockway, 1978). Settling of flocculated particles produces an open, more porous depositional seal than that produced by dispersed systems (Southard et al., 1988). The percentage of water-stable aggregates can be raised by elevating water EC (Smith et al., 1992). Increased Ca levels stabilize the microaggregate fraction (Peele, 1936). Thus, a greater proportion of larger and more stable aggregates are present that are more resistant to transport forces than smaller aggregates and primary particles. Furthermore, increasing the EC of the eroding fluid increases soil resistance to shear forces (Arulanandan et al., 1975). Water-quality impacts on soil aggregation could fully explain the sediment concentration and soil loss effects we observed. However, water-quality treatments also affected infiltration and, hence, runoff rates (given equivalent inflow rates used across treatments). This suggests that soil erosion was also influenced by induced changes in furrow stream hydraulics, although not measured.

Surface Seal and Infiltration Relationships

For Portneuf soil, the surface seal that forms during irrigation and erosion of furrows is instrumental in controlling furrow infiltration (Segeren and Trout, 1991). Evidence of seal formation and its effect on infiltration and runoff can be seen in outflow–duration curves (Fig. 1C and 2C). Those from the first irrigation (Fig. 1C) show a more gradual rate of increase in outflow, with steady state nearly achieved by irrigation's end (95% of maximum outflow occurred at 80% runoff). In contrast, those from the second irrigations (Fig. 2C) show a more rapid rise to steady state (95% of maximum outflow at 50% runoff). The first response resembles that produced when infiltration and seal development are initiated together, while the second is indicative of an infiltration event initiated after a soil seal has already formed (Moore, 1981). Though surface antecedent soil water content for second-irrigation furrows was greater than that for the first (15 vs. 10% water content by weight), this probably had a smaller impact on the shape of outflow–duration curves than seal formation. Moore

(1981) showed that whether surface seals were developing or had already formed, a change in initial soil water content tends to shift the soil infiltration rate–duration curve rather than alter its shape. Thus, the change in outflow–duration curve shape observed in the first and second irrigation most likely resulted from differences in seal development.

An infiltration rate comparison between irrigated furrows having normal and subnormal seal development (unpublished furrow infiltrometer data) indicated that permeability of the developing seals tends to exert control over furrow infiltration rate very early in Portneuf irrigations (in the first 5–10 min. of an infiltration event). These data, which were corroborated with in-furrow hydraulic resistance measurements (Segeren and Trout, 1991), suggest that an imbibition-induced decline in soil water potential gradient exerts a smaller influence on furrow infiltration rate than does soil surface permeability in Portneuf soils.

Early in the first irrigation (0–20% runoff period), all treatments showed a parallel rapid increase in outflow induced by the formation of a depositional layer and attendant abruptly decreasing infiltration rates (Fig. 1C). Later, the slope of the outflow curve decreased noticeably, but this occurred sooner in the irrigation for low SAR treatments (20–35% of runoff) than for high SAR treatments (45–55% of runoff). We hypothesize that the parallel rapid increase in outflow for all water-quality treatments was caused by the initial development of a depositional layer with restricted permeability. The subsequent slope change noted above may reflect the accumulation of differences in processes or factors controlling infiltration. Seal-forming processes under the high EC/low SAR treatment no longer produced the previous steeply declining infiltration rates (i.e., increasing outflow rates) because more complete blockage of the depositional layer's open and porous structure was not as easily accomplished by the small quantities of undispersed colloidal materials available, or by soil aggregates themselves, which were generally too large to enter soil pores. In contrast, under the low EC/high SAR treatments, the depositional seal developed, and its permeablility declined, at a fairly uniform rate throughout the irrigation, steadily reducing infiltration. Well-dispersed particles common under these conditions produced a depositional layer with smaller average pore size. Even then, small dispersed colloids could enter soil pores and penetrate several millimeters into the soil before lodging in and blocking soil pores. In this phase, continued colloid penetration maintained the steeply increasing outflow-rate curve of the low EC/high SAR treatment (Fig. 1C).

Furrow seal and infiltration processes apparently link irrigation water quality to stream erosivity. High SAR waters produced a significant reduction in furrow net infiltration and an increase in furrow outflow compared with low SAR counterparts (Table 6). We attributed this lower net infiltration to less permeable depositional seals formed in response to high SAR waters (Shainberg and Singer, 1985). The high SAR treatments also had the greatest soil loss, especially in the second irrigation

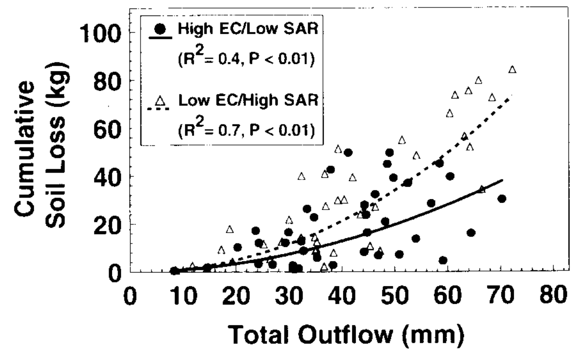

Fig. 3. Cumulative soil loss from nontrafficked furrows irrigated with waters of contrasting quality as a function of total outflow (both irrigations).

(Table 5). The inverse relationship between infiltration and furrow erosion was expected since decreased water intake produces an increase in flow velocity, which enhances flow shear, detachment, and sediment transport capacity of the furrow stream (Kemper et al., 1985). This infiltration–furrow erosion relationship was presented graphically in a preliminary analysis of our research results (Lentz et al., 1993). Increased soil loss was also attributed to the weakening of furrow aggregates and increased soil dispersion under low EC and/or high SAR conditions (Velasco-Molina et al., 1971; Arora and Coleman, 1979), which promoted sediment detachment processes in the furrow stream.

Increased EC alone had an inconsistent influence on furrow net infiltration, corroborating results of Sinclair et al. (1992). However, outflow–duration plots (Fig. 1C and 2C) suggest a trend toward increased infiltration with increased EC, especially for low SAR treatments.

Figures 3 and 4 compare high EC vs. high SAR effects on outflow and soil loss relationships. Note the curvilinear association between soil loss and outflow. In addition, soil loss in the high SAR system increased more sharply with outflow rate than did that in the high EC system. It appears that other factors besides outflow may be controlling soil loss in the high EC/low SAR treatment, i.e., soil cohesivity and aggregate stability. These data suggest that the EC effect on furrow soil

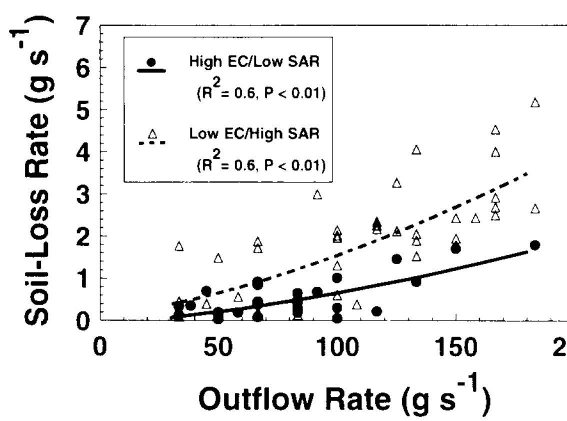

Fig. 4. Effect of irrigation water quality on soil loss rate vs. outflow rate relationships during the initial furrow runoff phase. Furrows are nontrafficked (both irrigations).

Table 7. Effect of irrigation episode on measured response where interactions were not present.

Measured response	First	Second
Soil loss, Mg ha^{-1}	2.2†	3.7
Mean sediment conc., g L^{-1}	5.1 b‡	7.7 a
Total inflow, mm	112†	103
Total outflow, mm	39†	47
Net infiltration, mm	73 a	56 b
Furrow advance, min	80 a	40 b

† Mean separations were not appropriate because of a significant interaction or nonsignificant ANOVA; each value is the mean of 144 furrows.
‡ Means within a row with dissimilar letters are significantly different ($P < 0.10$).

Table 8. Effect of traffic on measured response where interactions were not present.

Measured response	Non-wheel-trafficked	Wheel-trafficked
Soil loss, Mg ha^{-1}	2.2 b†	3.6 a
Mean sediment conc., g L^{-1}	5.6 b	7.2 a
Total inflow, mm	107‡	107
Total outflow, mm	37‡	49
Net infiltration, mm	70 a	58 b
Furrow advance, min	70 a	44 b

† Means within a row with dissimilar letters are significantly different ($P < 0.10$); each value is the mean of 144 furrows.
‡ Mean separations were not appropriate because of a significant interaction or nonsignificant ANOVA.

erodibility characteristics was more important than its influence on infiltration and furrow stream erosivity.

Irrigation Episode Effects

A significant interaction between water quality and irrigation episode was found. Compared with the initial irrigation, soil loss tended to be greater in second irrigations, but the difference was significant only for the low EC/high SAR treatment. The increase in soil loss for second irrigations compared with initial irrigations was 97% for low EC/high SAR and 73% for high EC/high SAR water, but only 40% for the low SAR waters. The influence of high SAR water on total soil loss was much more potent during the second irrigation. Overall, second-irrigation mean sediment concentration was 51% greater, net infiltration was 23% lower, and furrow advance 50% faster than in the first irrigation (Table 7).

Several factors contributed to these results. First, net infiltration in previously irrigated furrows was reduced, which increased total outflow (Table 7) and enhanced detachment and transport forces. Permeability in these soils was reduced owing to their consolidation and subsidence, and to formation of a surface crust. In addition, surface antecedent soil water content for second-irrigation furrows was 50% greater than when first irrigated. This resulted in a downward shift in the soil infiltration rate–duration curve (Moore, 1981), hence soils in the second irrigation absorbed water more slowly (shorter furrow advance time). Second, the first irrigation may have altered the chemistry of in-furrow surface soil, amplifying water-quality impacts on furrows in the second irrigation.

Traffic Effects

Compared with non-wheel-trafficked furrows, wheel-trafficked furrows in general had 64% greater total soil loss, 22% higher mean sediment concentration, 17% less net infiltration, and 34% faster furrow advance (Table 8). The compacted soils in trafficked furrows absorbed water less rapidly, produced higher runoff and stream velocities, and enhanced flow-induced erosion. Furthermore, the interaction of irrigation episode and traffic increased outflow significantly for non-trafficked furrows in the second irrigation. In the first irrigations, total outflow from trafficked furrows was already high because compaction had reduced net infiltration. Thus, the potential for increased outflow from second-irrigation trafficked furrows was reduced.

CONCLUSIONS

The EC and SAR of inflowing water significantly impact infiltration and erosion processes in irrigated furrows, supporting the hypothesis that water quality influences furrow-irrigation-induced soil loss via effects on both soil erodibility and furrow-stream erosivity (via infiltration effects). While the Portneuf soil is similar to many irrigated soils in the Pacific Northwest, it clearly is not representative of all soil types found in other irrigated regions. Chemistry of soils themselves will influence their susceptibility to water-quality impacts. For example, soils with relatively high ESP would be sensitive to low SAR water, but would be less sensitive to high SAR water than soils with low ESP. Soils high in organic C content would be less sensitive to high EC irrigation waters than soils with low organic C (Hiel and Sposito, 1993). However, the soil dispersion and aggregate stabilizing processes affected by irrigation water quality have been shown to be important for soils having a range of soil textures (Shainberg and Singer, 1985; Evans et al., 1990), clay contents (Malik et al., 1992), and clay mineralogy (Quirk and Schofield, 1955; Velasco-Molina et al., 1971; Arulanadan et al., 1975). Likely, many irrigated soils will be susceptible in some degree to water-quality impacts. Furthermore, water quality is not a constant in all irrigated agriculture. Farmers sometimes blend surface and well sources to meet volume demands, and surface water quality often changes seasonally as snowmelt is displaced by return flows and drainage in surface water sources. Therefore, the chemistry of irrigation water must be carefully considered when assessing irrigation-induced erosion. Mathematical models that describe irrigation processes and predict infiltration and erosion rates will need to account for water-quality effects on both soil erodibility and stream hydraulics parameters. Moreover, soil erosion parameters used to predict rainfall-induced erosion may be subject to error if (i) rainfall simulators were used to derive parameters, and (ii) chemistry of source water used in rainfall simulators differed from that of rainwater. Under certain circumstances, these considerations may provide an unexpected source of error in output derived from the Revised Universal Soil Loss Equation, Water Erosion Prediction Project, and other predictive technologies. More study is needed to define water-quality parameters to improve erosion prediction for a wide range of soils. Further study of water-quality erosion impacts under rainfall regimes may also be warranted, since the chemistry of raindrops involved in initial interrill and rill erosion high on the landscape may differ significantly from that of downstream waters, such as those flowing in ephemeral gullies, channels, and streams.

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REFERENCES

Arora, H.S., and N.T. Coleman. 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci. 127: 134–139.

Arulanandan, K., P. Loganathan, and R.B. Krone. 1975. Pore and eroding fluid influences on surface erosion of soil. J. Geotech. Eng. Am. Soc. Civ. Eng. 101:51–65.

Bos, M.G., J.A. Replogle, and A.J. Clemmons. 1984. Flow measuring flumes for open channel systems. John Wiley & Sons, New York.

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

Carter, D.L. 1993. Furrow irrigation erosion lowers soil productivity. J. Irrig. Drain. Eng. Am. Soc. Civ. Eng. 119:964–974.

Carter, D.L., C.W. Robbins, and J.A. Bondurant. 1973. Total salt, specific ion, and fertilizer element concentrations and balances in the irrigation waters of the Twin Falls Tract in southern Idaho. USDA-ARS Western Region Publ. ARS-W-4.

Curtin, D., H. Steppuhn, and F. Selles. 1994. Clay dispersion in relation to sodicity, electrolyte concentration, and mechanical effects. Soil Sci. Soc. Am. J. 58:955–962.

Evans, R.G., C.J. Smith, J.D. Oster, and B.A. Myers. 1990. Saline water application effects on furrow infiltration of red-brown earths. Trans. ASAE 33:1563–1572.

Fireman, M., and G.B. Bodman. 1939. The effect of saline irrigation water upon the permeability and base status of soils. Soil Sci. Soc. Am. Proc. 4:71–77.

Frenkel, H., J.O. Goertzen, and J.D. Rhoades. 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42:32–39.

Goldberg, S., and H.S. Forster. 1990. Flocculation of reference clays and arid-zone soil clays. Soil Sci. Soc. Am. J. 54:714–718.

Goldberg, S., and R.A. Glaubig. 1987. Effect of saturating cation, pH, and aluminum and iron oxide on the flocculation of kaolinite and montmorillonite. Clays Clay Miner. 35:220–227.

Goldberg, S., D.L. Suarez, and R.A. Glaubig. 1988. Factors affecting clay dispersion and aggregate stability of arid-zone soils. Soil Sci. 146:317–325.

Gregory, J. 1989. Fundamentals of flocculation. Crit. Rev. Environ. Control 19:185–230.

Hajek, B.F., D.L. Karlen, B. Lowery, J.F. Power, T.E. Schumacher, E.L. Skidmore, and R.E. Sojka. 1990. Erosion and soil properties. p. 23–39. *In* W.E. Larson et al. (ed.) Proc. Soil Erosion Productiv. Worksh., Bloomington, MN. 13–15 Mar. 1989. Univ. of Minnesota, St. Paul.

Heil, D., and G. Sposito. 1993. Organic matter in illitic soil colloids flocculation: I. Counter ions and pH. Soil Sci. Soc. Am. J. 57: 124–126.

Kemper, W.D., T.J. Trout, M.J. Brown, and R.C. Rosenau. 1985. Furrow erosion and water and soil management. Trans. ASAE 28: 1564–1572.

Lehrsch, G.A., and M.J. Brown. 1995. Furrow erosion and aggregate stability variation in a Portneuf silt loam. Soil Technol. 7:327–341.

Lentz, R.D., and R.E. Sojka. 1994. Automated Imhoff cone calibration and soil loss/infiltration analysis for furrow irrigation studies. p. 858–863. *In* D.G. Watson et al. (ed.) Computers in agriculture 1994. Proc. Int. Conf. Comput. Agric. 5th, Orlando, FL. 6–9 Feb. 1994. ASAE, St. Joseph, MI.

Lentz, R.D., R.E. Sojka, and D.L. Carter. 1993. Influence of irrigation water quality on sediment loss from furrows. p. 274–278. *In* Agricultural research to protect water quality. Proc., Minneapolis, MN. 21–24 Feb. 1993. Soil Water Conserv. Soc., Ankeny, IA.

Malik, M., M.A. Mustafa, and J. Letey. 1992. Effect of mixed Na/Ca solutions on swelling, dispersion and transient water flow in unsaturated montmorillonitic soils. Geoderma 52:17–28.

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

Moore, I.D. 1981. Effect of surface sealing on infiltration. Trans. ASAE 24:1546–1552.

Oster, J.D., and F.W. Schroer. 1979. Infiltration as influenced by irrigation water quality. Soil Sci. Soc. Am. J. 43:444–447.

Peele, T.C. 1936. The effect of calcium on the erodibility of soils. Soil Sci. Soc. Am. Proc. 1:47–58.

Quirk, J.P., and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163–178.

Robbins, C.W. 1984. Sodium adsorption ratio-exchangeable sodium percentage relationships in a high potassium saline-sodic soil. Irrig. Sci. 5:173–179.

Robbins, C.W., and C.E. Brockway. 1978. Irrigation water salt concentration influences on sediment removal by ponds. Soil Sci. Soc. Am. J. 42:478–481.

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

Shainberg, I., J.D. Rhoades, and R.J. Prather. 1981. Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. 45:273–277.

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

Shainberg, I., D. Warrington, and J.M. Laflen. 1992. Soil dispersibility, rain properties, and slope interaction in rill formation and erosion. Soil Sci. Soc. Am. J. 56:278–283.

Sinclair, P.J., T.S. Abbott, and A.R. Gilmour. 1992. Effects of furrow and water treatments on the absorption of water into beds of structurally unstable red-brown earths. Soil Tillage Res. 25: 245–261.

Smith, G.G., J.L. Foley, and R.J. Loch. 1992. Effects of electrical conductivity of water used in wetting and in wet sieving on measured aggregate water stability. Soil Technol. 5:177–184.

Sojka, R.E., D.L. Carter, and M.J. Brown. 1992. Imhoff cone determination of sediment in irrigation runoff. Soil Sci. Soc. Am. J. 56:884–890.

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

Trout, T.J., and W.H. Neibling. 1993. Erosion and sedimentation processes in irrigation. J. Irrig. Drain. Eng. Am. Soc. Civ. Eng. 119:947–963.

Velasco-Molina, H.A., A.R. Swoboda, and C.L. Godfrey. 1971. Dispersion of soils of different mineralogy in relation to sodium adsorption ratio and electrolytic concentration. Soil Sci. 111:282–287.