FURROW FLOW VELOCITY EFFECT ON HYDRAULIC ROUGHNESS

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INTRODUCTION

The friction force that resists the movement of water in conduits is a function of the irregularity and roughness of the conduit surface. Kruse et al. (1965) and Heermann et al. (1969) found that the hydraulic resistance in irrigation furrows is a function of the logarithm of the ratio of the absolute roughness to the hydraulic radius. They successfuly modeled hydraulic smoothness (inverse of resistance), defined as the flow velocity V divided by the shear velocity V^*, by an equation developed by Sayre and Albertson (1961)

$$\frac{V}{V^*} = 6.06 \cdot \log\left(\frac{R}{\chi}\right) \quad (1)$$

where R = hydraulic radius (m); χ = a roughness parameter (m); and $V^* = \sqrt{gRS}$ with g = gravitational constant (9.81 m/s^2); and S = the friction slope that, for uniform flow, is equivalent to the channel bed slope (m/m). They also successfully related χ to the perimeter roughness

$$\chi = 28.3\sigma^{1.66} \quad (2)$$

where σ = the standard deviation of equally spaced measurements of roughness height along a longitudinal profile of the furrow bed (m).

Because actual roughness of earthen channels is difficult to measure, and χ has not been widely calibrated, uniform flow in furrows is most commonly modeled by the older Manning's equation. In Manning's equation, the hydraulic section, $AR^{2/3}$, required to carry a uniform flow on a given slope is proportional to the roughness coefficient, n

$$AR^{2/3} = \frac{nQ}{S^{1/2}} \quad (3)$$

where A = flow cross-sectional area (m^2); and Q = flow rate (m^3/s). The Chezy and Darcy-Weisbach uniform flow equations use similar empirical roughness coefficients.

Furrow roughness is generally considered to vary with such factors as tillage, soil type, residue management, and crop growth. Under traditional clean-tillage practices, until the growing plants extend into the flowing water, furrow roughness is created primarily by soil aggregates on the perimeter and irregularities in furrorw shape. Since soil aggregate size, shape, and placement can be altered by the flowing water, the flow can change the

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roughness. Although this relationship is recognized, it has not been quantified, and furrow roughness is generally assumed to be spatially uniform and temporally constant for any given irrigation.

Furrow perimeter roughness and shape change as soil particles and small aggregates break loose, move, and are redeposited by the flowing water. The change is generally toward smoother perimeters. Dry soil aggregates break down as they are quickly wetted by the advancing furrow stream. The shear force of the flowing water also breaks down aggregates. The resulting small aggregates and particles slough to the bed of the furrow where they roll and saltate along the bed until they deposit in a crack or behind a larger aggregate. As the larger cracks and voids fill, the bed load moves further and continues to break down, filling smaller voids in the furrow perimeter. These small particles are held in place both by gravity and by water tension within the soil at the perimeter (Brown et al. 1988). The result is smoothing of the furrow perimeter.

The amount of roughness change depends on the preceding condition, determined primarily by soil type, preceding cultivations, and irrigations or rainfall; the soil aggregate stability; and the forces applied. The hydraulic force that detaches and transports particles is represented by the shear, related to the square of the flow velocity. Consequently, the amount of roughness change should relate the velocity. The objective of this study is to determine the relationship between flow velocity and furrow roughness, so that the spatial variation in roughness as a function of flow rate and slope can be predicted. With this information, furrow hydraulic models can more closely mimic the physical system.

METHODS

A wide range of furrow flow velocities and flow depths was created in furrows on a small field plot by varying both the furrow slope and flow rate. Slope was varied by forming parallel sets of 6-m-long furrow sections at several angles to the predominant slope. Actual slope of the flowing water surface was measured during each test by determining the water surface elevation difference 0.5 m from the two ends of the section with a water manometer. Slopes ranged from 0.002 to 0.016 m/m. A range of constant flow rates from 6 to 50 L/min was applied to each set of furrows with a recirculating infiltrometer. The tests were carried out over two years on three fields located near the USDA-ARS Research Center near Kimberly, Idaho. The Portneuf silt-loam soil at the site has low aggregate stability and is highly erodible.

Furrows were formed in recently tilled soil with a narrow shovel followed by a triangular drag (boat), as is the practice in the area. The initial furrow shape was roughly triangular with 1:1 side slopes and a rounded bottom, but the shape rapidly evolved with water flow to a power function shape with 4:1-to-8:1 top width to flow depth ratios. Furrow cross-sectional-flow shape was measured after 6 hr of irrigation with a profilometer (rill meter) as per ASAE standards ("Evaluation" 1989) with 10 mm diameter PVC rods on 20 mm centers. The water surface and furrow-perimeter elevations were measured 2 m from each end of the furrow sections. The flow cross-sectional area and wetted perimeter were calculated by linearly interpolating between the measured elevations.

The furrow flows were recycled through the test section by lifting the water from a downstream sump to a small return reservoir with a low-rotations-per-minute (RPM) Archimedes screw (Blair and Trout 1989; Trout

1990). Water then flowed by gravity through a hose to a 60° V-notch furrow flume at the upstream end of the furrow section. This system was specifically designed so that all sediment running off the test section would be recycled to the head end with minimal disturbance of the small sediment aggregates. Flow rate was controlled by a valve at the return reservoir outlet and measured in the flume. The water level in the return reservoir was held constant by a water supply reservoir configured as a Mariotte syphon. Water depth at the downstream end of the furrow section was kept at a near-normal flow depth with an adjustable weir at the sump inlet. The initial flow rate for all furrow sections was about 6 L/min, to allow the furrow stream to advance at the rate of 3 m/min, after which rates were increased to the desired rate.

Average flow velocity was calculated as the flow rate divided by the average flow cross-sectional area. The χ parameter and Manning's roughness coefficient were calculated from (1) and (3), respectively, using the measured flow rate and slope, and the average of the two measured flow areas and wetted perimeters for each test section.

RESULTS

Both χ and n decreased significantly with increasing flow velocity (Figs. 1 and 2). The decreasing scatter with increasing velocity may be the result of the increasing influence of the flow, or equivalently, the decreasing influence of initial conditions, on the channel roughness. The variation in χ, when combined with (2) indicates that absolute roughness σ decreases from 3.5 to 1.5 mm as V increases from 0.1 m/s to 0.3 m/s.

Eq. (1) assumes hydraulic resistance varies with relative roughness, and thus with hydraulic radius. The experimental procedure allowed the effects of V—which affects absolute roughness—and R, to be separated. For this data set, there was no relationship ($r^2 < .01$) between hydraulic resistance and R. The χ parameter may vary with furrow shape (Kruse et al. 1965). Trout (1991) showed that, for the measured furrows, the shape of the flow cross sections did not vary consistently with flow rate and slope, and thus would not affect the relative variation in χ.

Fig. 3 shows photographs of typical furrow sections after 6 hr of irrigation with a range of flow rates ($S = 0.007$). Average flow velocities in the sections varied from 0.15 m/s to 0.30 m/s. The rough perimeters of the furrows with low flow rates, and the smooth, more prismatic channels of the high flow rate furrows are evident.

Although a straight line fits most of the n versus V data fairly well (Fig. 2), the velocity extremes indicate a concave-upward relationship. The roughness should have a finite value at zero velocity, and asymptotically approach a base value at high velocity. Consequently, an exponential relationship with an offset was fitted to the data. A power function relationship, shown in Fig. 2, also fit the data well, but is not applicable at very low velocities.

ANALYSIS OF RESULTS

Because both roughness and flow velocity were calculated from the measured cross-sectional flow area, area measurement errors could have influenced the relationship between roughness and velocity. For example, a 25% overestimate of area results in a 20% underestimate of velocity, a 45% overestimate of n, and, for average conditions, a 250% overestimate of χ. Thus, area-measurement error would tend to create an inverse relationship between roughness and velocity. Although flow area at each cross section

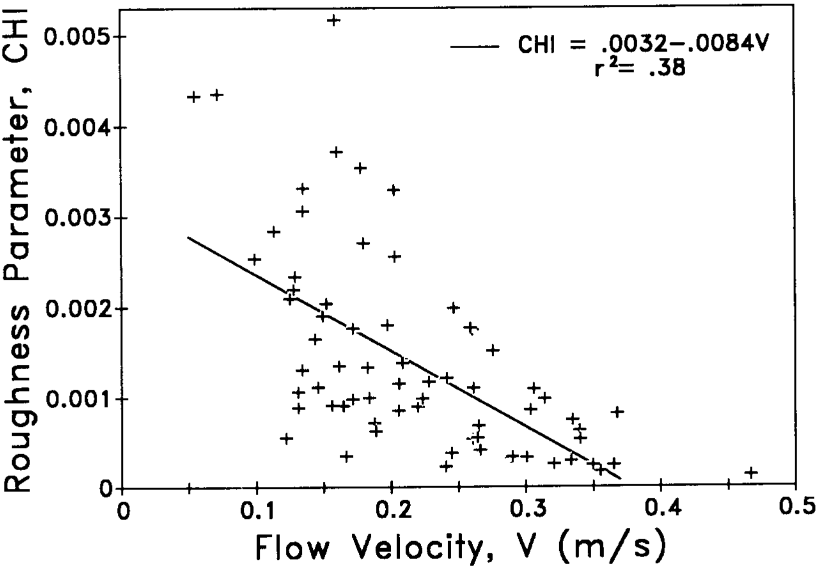

FIG. 1. Sayre-Albertson χ Roughness Parameter versus Flow Velocity Data and Best-Fit Linear Regression Line

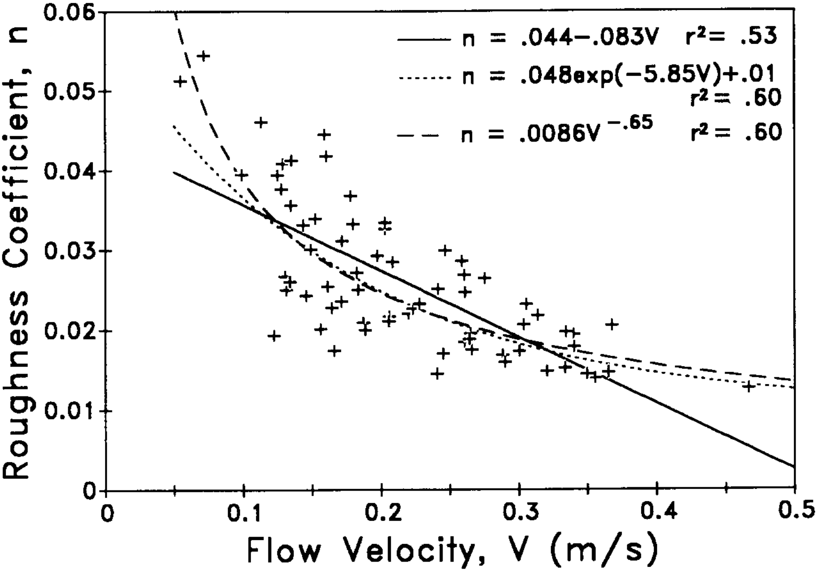

FIG. 2. Manning's Roughness Coefficient versus Flow Velocity Data and Linear, Exponential, and Power Function Best-Fit Regression Lines

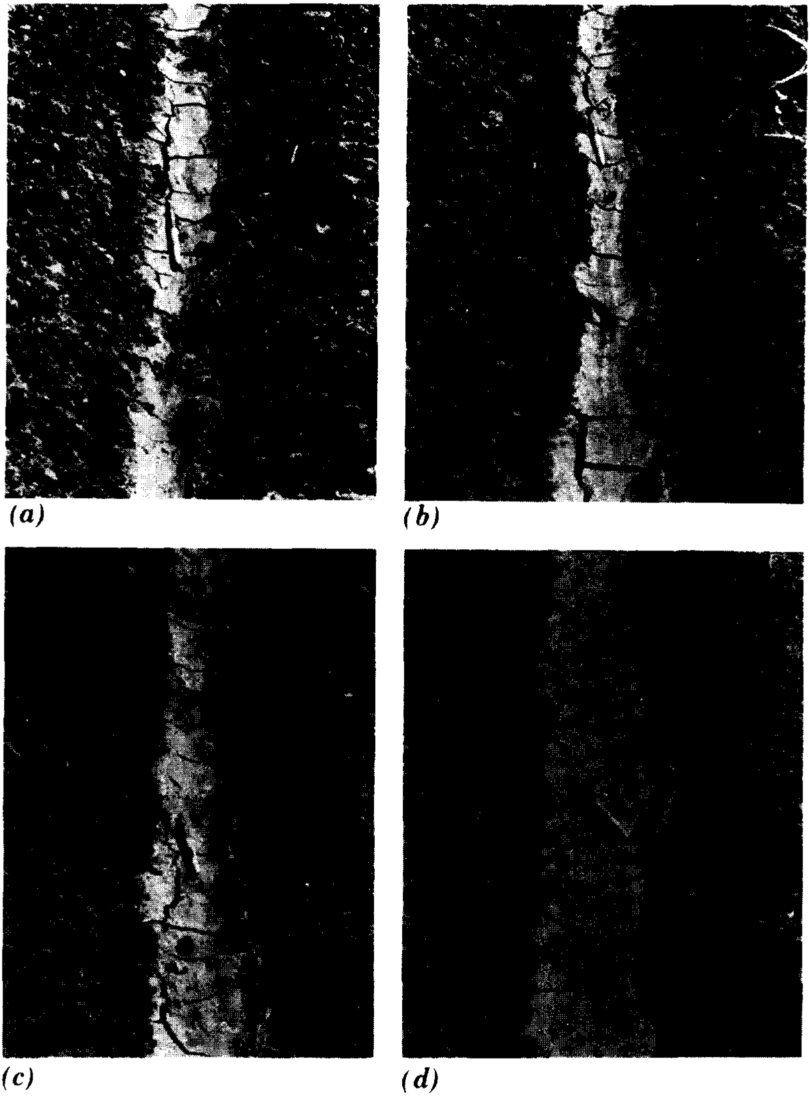

FIG. 3. Furrows after 6 hr of Irrigation on Freshly Tilled Soil with Range of Flow Rates: (*a*) 6 L/min; (*b*) 12 L/min; (c) 20 L/min; (*d*) 30 L/min

was measured with ±10%, area is variable along a furrow, and determining the average area for the furrow section is less certain. The physical result of variable flow area is gradually varying, rather than the uniform flow assumed in the roughness calculation. The variability of the area was not measured in the present study, and thus the confidence limits of the area measurement cannot be quantified. The use of the average of two area measurements for each test section improved the accuracy. Measurement error probably strengthened the measured relationship between roughness and velocity, but is unlikely to have created the strong measured relationship. The sensitivity of calculated roughness-to-area errors is likely the cause of much of the data scatter.

The recirculating infiltrometer was designed to create flow and sediment conveyance conditions as near as possible to those that occur in a flowing furrow. However, all of the sediment movement conditions present in furrows could not be duplicated. In furrows, some flow distance is required for sediment transport to reach the equilibrium conditions created by the recycled flows in the infiltrometer. Also, some sediment is discharged from furrows with tailwater. Because much of the furrow smoothing and shape change is created by larger sediments which normally don't move far, and because the lag distances to near-equilibrium states is not long, these complexities should affect furrow roughness primarily after flow transitions, such as at the inflow end and after slope changes.

The silt-loam soil in the test plots had low aggregate stability and was highly erodible. Many aggregates disintegrated with only the wetting that occurred when the flow initially arrived. Sediment concentrations in furrow flows in the area commonly exceeded 1,000 mg/L. This soil smooths more rapidly and at lower velocities than more-stable soils. Consequently, for more-stable soils, the relationships depicted in Figs. 1 and 2 would likely shift to the right.

CONSEQUENCES

With a relationship between roughness and flow velocity, surface irrigation models can better describe the physical system. Flow rate decreases along a furrow as water infiltrates, and slope may vary spatially. Flow velocity decreases with both Q and S, so roughness would vary inversely with both factors. Furrow hydraulics models can determine flow velocities and apply the roughness to velocity relationship.

A generalized relationship between V, Q, S, and roughness is possible for some furrow shapes. For example, with Manning's equation and the constant-shape furrow cross section model described by Trout (1991)

$$V = k_1 Q^{1/4} n^{-3/4} S^{3/8} \quad \ldots\ldots (4)$$

where k_1 = empirical coefficient dependent on furrow shape. According to (4), if 75% of the inflow to a furrow is infiltrated along its length, the velocity will decrease by 30% from the inflow to the outflow end. A 60% slope decrease would cause a similar veocity decrease. These interactions are strengthened because the lower velocity results in higher roughness which, in turn, results in a further decrease in velocity. For example, for the tested soil, if V at the inflow end of the furrow were 0.2 m/s, the predicted n value would be 0.02 (Fig. 2). The 30% lower velocity at the tail due to the lower Q would result in 50% higher roughness (n = 0.03). However, the higher roughness would further decrease V by 25%, which would result in n = 0.038. The end result of these interactions is a roughness at the furrow tail end of more than twice that at the head. Doubling the roughness will increase the flow depth and wetted perimeter by 30%; and the cross-sectional area and thus surface storage by nearly 70% (assuming the constant-shape furrow cross section).

Ignoring these interactions between velocity and roughness can result in a significant error in predicted surface storage, which affects stream advance and recession; and in predicted wetted perimeter, which affects infiltration and water distribution. Considering the effect of spatially varying roughness on infiltration will increase predicted water-distribution uniformity (Trout 1992).

The present study considered only final roughness resulting from steady-state flow conditions. Furrow smoothing by water flow occurs over some time period, implying a temporal variation. In many soils, much of the decrease in roughness in a previously unirrigated furrow occurs soon after the flow is introduced. In the tested soils with low aggregate stability, most of the smoothing occurred within a few minutes of flow initiation. Thus, the temporal roughness change will affect the water depth and storage near the tip of the advancing stream, but will have little influence on the stream advance rate. Using the measured steady-state relationship between velocity and roughness will partially compensate for omitting this temporal variation since flow velocity is also low near the advancing stream tip.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = flow cross-sectional area (m^2);
g = gravitational constant (9.81 m/s^2);
k_1 = empirical shape coefficient;
n = Manning's roughness coefficient ($s/m^{1/3}$);
P = wetted perimeter (m);
Q = flow rate (m^3/s);
R = hydraulic radius = A/P (m);
r^2 = coefficient of determination;
S = energy gradient (m/m);
V = flow velocity (m/s);
V^* = shear velocity (m/s);
σ = measure of absolute roughness (m); and
χ = Sayre-Albertson roughness parameter (m).