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Darcy-Weisbach Roughness Coefficients for Surfaces with Residue and Gravel Cover

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Abstract. *Several types of hydraulic resistance factors may be present on upland agricultural areas. It is not known whether roughness contributions from individual elements are additive or if interactions between resistance factors may occur. In this study, Darcy-Weisbach roughness coefficients were measured on surfaces containing corn-soybeans, sorghum-cotton, and sunflower-wheat residue in addition to gravel cover. Varying rates of flow were introduced into a flume in which residue and gravel materials were securely attached. Roughness coefficients were calculated from measurements of discharge rate and flow velocity for Reynolds number values varying from approximately 1,200 to 13,000. The laboratory data were then used to identify the contribution to total hydraulic resistance provided by the different types of resistance elements. For most of the experimental treatments, the addition of smaller diameter residue materials (soybeans, cotton, or wheat) to surfaces containing larger resistance elements (corn, sorghum, or sunflower) did not significantly affect hydraulic resistance. However, smaller diameter residue materials did influence hydraulic resistance when they substantially increased the total volume of resistance elements. Existing roughness coefficient values were not significantly affected by the presence of gravel materials with diameters similar to the larger residue materials. The experimental results suggest that total hydraulic resistance cannot be predicted by simply adding the contributions provided by individual resistance elements. When estimating total hydraulic resistance on upland agricultural areas, the relative size, number, and volume of resistance elements must be considered.* ***Keywords.*** *Flow resistancy, Hydraulics, Hydraulic roughness, Hydrologic modeling, Runoff.*

Resistance to flow on upland agricultural areas may be caused by raindrop impact, frictional drag over the soil surface, residue cover and gravel lying on the surface, and standing vegetation. Total hydraulic resistance may be influenced by each of these elements. Roughness coefficient values must be properly estimated if upland flow hydraulics are to be accurately characterized.

Shen and Li (1973) examined the effects of raindrop impact on flow resistance over a smooth surface. A set of regression equations was presented for relating Darcy-Weisbach roughness coefficients to rainfall intensity and Reynolds number. For most upland agricultural areas, the effects of raindrop impact on flow resistance are expected to be minimal.

Previous studies involving roughness coefficients on upland areas were described by Engman (1986). Hydraulic roughness coefficients were identified using runoff plot data originally collected for erosion studies. Friction factors were presented in a tabular format with a description of various surface characteristics and land uses.

Liong et al. (1989) developed a simple method for assigning roughness coefficients to overland flow segments in kinematic wave models. The proposed method was found to work well on a gauged basin. This procedure may also be useful in estimating hydrographs for ungauged watersheds.

Runoff plot data from simulated rainfall plots were used by Weltz et al. (1992) to estimate hydraulic roughness coefficients for native rangelands. A subfactor-based regression technique was developed to identify roughness coefficients for shallow overland flow. An effective Darcy-Weisbach roughness coefficient is presented which incorporates the effects on hydraulic resistance of raindrop impact, soil texture, random roughness, rocks, litter, canopy, and basal plant cover.

Laboratory measurements of roughness coefficients on surfaces covered with sand or gravel were made by Woo and Brater (1961), Emmett (1970), Phelps (1975), and Savat (1980). Similar tests were performed under field conditions on natural landscapes by Roels (1984), Abrahams et al. (1986), and Abrahams and Parsons (1991). Roughness coefficients decreased with increasing Reynolds number in most of these studies. Once roughness elements were submerged, their ability to retard overland flow was reduced as the depth of overland flow became greater.

Gilley et al. (1990) measured hydraulic characteristics of rills at 11 sites located throughout the eastern United States. Roughness coefficients of rills were related to Reynolds number using regression techniques. A field experimental study was conducted by Gilley and Finkner (1991) to determine roughness coefficients on interrill areas. Regression equations were derived for estimating Darcy-Weisbach roughness coefficients based on random roughness and Reynolds number.

Gilley et al. (1991) conducted a laboratory study to measure Darcy-Weisbach roughness coefficients for

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selected residue materials. Varied rates of flow were introduced into a flume in which selected amounts of residue were securely attached. The laboratory data were used to derive regression equations for relating roughness coefficients to Reynolds number and either percent residue cover or residue rate.

Darcy-Weisbach roughness coefficients for selected gravel and cobble materials were measured by Gilley et al. (1992) in a laboratory investigation. Measurements of flow rate and flow velocity were used to calculate roughness coefficients. Regression equations which relate roughness coefficients to surface cover and Reynolds number were derived from the laboratory data.

Gilley and Kottwitz (1994) determined Darcy-Weisbach roughness coefficients for selected standing vegetation. Laboratory measurements were used to derive regression equations which relate roughness coefficients to plant population, row spacing, and Reynolds number. In general, flow resistance caused by standing vegetation was found to be minimal.

Most of the previous studies concerning roughness coefficients on agricultural areas have focused on a single resistance element. On some upland areas, total hydraulic roughness may be influenced by resistance factors provided by a variety of roughness elements. Data are lacking for situations where hydraulic roughness may be derived from more than one factor. It is not known whether roughness contributions are additive or if interactions may be involved. In this study, Darcy-Weisbach roughness coefficients were measured on surfaces containing two types of crop residue and gravel cover.

Hydraulic Equations

The Darcy-Weisbach equation has been widely used to describe flow characteristics. Under uniform flow conditions, the Darcy-Weisbach roughness coefficient, f, is given as (Chow, 1959)

$$f = (8\ g\ R\ S) / V^2 \tag{1}$$

where

g = acceleration due to gravity
S = average slope
V = flow velocity
R = hydraulic radius, which is defined as:

$$R = A / P \tag{2}$$

where

A = cross-sectional flow area
P = wetted perimeter

For a rectangular flume with flow width w:

$$R = (w\ y) / (w + 2\ y) \tag{3}$$

where y is the flow depth. For overland flow conditions where flow width is much greater than flow depth, hydraulic radius can be assumed to be approximately equal to flow depth.

Reynolds number, $\mathcal{R}$, is also used to describe flow characteristics, and is given as:

$$\mathcal{R} = (V\ R) / \nu \tag{4}$$

where ν is the kinematic viscosity. Kinematic viscosity can be determined directly from water temperature.

The continuity equation for flow is defined as:

$$Q = V\ A \tag{5}$$

where Q is the flow rate. For a rectangular flume, water depth is given as:

$$y = Q / (V\ w) \tag{6}$$

In this study, water depth was determined indirectly using equation 6 and measurements of Q, V, and w.

Experimental Procedures

Residue combinations employed in this study included corn-soybeans, sorghum-cotton, and sunflower-wheat. Each of these residue combinations, which commonly occur in crop rotations, contains materials with substantially different diameters. Branches and stems were removed from the residue materials and only stalks were used.

Gravel materials with diameters varying from 1.25 to 2.50 cm were also included in the experimental design. Gravel surfaces are found on many agricultural areas and gravel was therefore used. Because gravel elements are much shorter than residue stalks, the use of gravel allowed evaluation of a combination of different types of resistance elements.

Ten randomly selected residue and gravel elements were used for characterizing dimensions. Mean diameter measured with a dial caliper (0.001 in. precision) and length measured with a ruler (0.1 in. precision), and the standard deviations for the measurements, are shown in table 1. It can be seen from table 1 that the size of the gravel and larger diameter residue materials was similar.

Percentages of surface cover for each experimental treatment are also presented in table 1. For each residue-gravel treatment, three different cover conditions were

Table 1. Diameter, length, and surface cover for selected residue-gravel treatments

Residue- Gravel Treatment	Diameter (cm)*	Length (cm)*	Surface Cover (%) Cover Condition I	II	III
Corn-Soybeans-Gravel					
Corn	2.35 (0.34)	42.3 (10.8)	23	32	30
Soybeans	0.59 (0.11)	25.4 (7.6)	36	31	25
Gravel	2.13 (0.61)	2.1 (0.6)	29	23	24
Sorghum-Cotton-Gravel					
Sorghum	1.63 (0.24)	39.4 (7.0)	12	21	41
Cotton	0.86 (0.17)	25.6 (8.1)	54	35	14
Gravel	2.13 (0.61)	2.1 (0.6)	25	31	26
Sunflower-Wheat-Gravel					
Sunflower	2.59 (0.31)	46.9 (2.6)	11	23	36
Wheat	0.29 (0.05)	16.9 (1.1)	59	57	44
Gravel	2.13 (0.61)	2.1 (0.6)	13	7	8

* Standard deviation of measurements is shown in parentheses.

evaluated. Three laboratory test runs, in turn, were conducted for each cover condition.

As an example, for cover condition I on the corn-soybeans-gravel treatment, tests were first performed on a surface containing 23% corn residue. A 36% cover of soybean residue was then added, and the same testing procedure was repeated. Finally, a third series of runs was made with corn, soybeans, and a 29% cover of gravel material. By using this testing procedure, the contribution to total hydraulic resistance provided by each of the residue or gravel materials could be identified.

The percentage of surface cover was determined using a photographic grid procedure (Laflen et al., 1978). Residue and gravel cover were photographed using 35-mm color slide film. The slides were projected onto a screen on which a grid had been superimposed. The number of grid intersections over residue and gravel material were determined visually from the projected slides and surface cover was then calculated. Six measurements were averaged to obtain a mean surface cover value.

The residue materials were glued at both ends onto a section of reinforced fiberglass sheeting located within a flume. The residue elements were positioned perpendicular to the principal flow direction and were not allowed to overlap. One of the principal objectives of this study was to determine if different types of resistance elements significantly influenced total hydraulic resistance. Roughness elements positioned perpendicular to the principal flow direction would be expected to have the greatest effect on flow hydraulics. In addition, this orientation allowed a greater surface coverage than was possible using randomly spaced residue and gravel materials.

Gluing the residue elements to the fiberglass sheets allowed much greater velocities and Reynolds numbers than would be possible in the field. Certainly, idealized flow conditions were used in this laboratory study. Hydraulic conditions required to move unanchored residue materials are reported by Gilley et al. (1994).

The 0.91-m-wide, 7.31-m-long, and 0.279-m-deep flume was maintained at a slope of 1.35%. Water was supplied to the flume using a constant head tank. Two replicate tests were run at eight flow rates ranging from approximately 1.01×10^{-3} to 1.26×10^{-2} m^3/s. Measurements of flow rate, obtained using a weighing tank, were made immediately before and after each test to ensure steady-state conditions. Reynolds number values varied from approximately 1,200 to 13,000. Water temperature was measured following flow rate determinations.

Once steady-state runoff conditions had become established, line sources of fluorescent dye were injected across the flume at downslope distances of 0.91 m and 7.01 m. A fluorometer and a stopwatch were used to determine elapsed time between the dye concentration peaks. Mean flow velocity was calculated by dividing the distance between the two line sources of dye (6.10 m) by the difference in travel time of the two dye concentration peaks. For each test sequence, three measurements of flow velocity were made.

Roughness coefficients for the fiberglass sheets that supported the residue and gravel materials were also identified. The experimental procedures used to measure roughness coefficients for the fiberglass sheets with and without residue and gravel materials were identical. Roughness coefficients induced by the bare fiberglass sheets at a given Reynolds number were subtracted from measurements obtained with the attached residue and gravel materials to determine hydraulic resistance caused by the residue and gravel materials alone.

Results and Discussion

Flow Mechanics

When developing theoretical flow concepts, Chow (1959) identified three basic types of flow over rough surfaces. Isolated-roughness flow exists when the roughness elements are so far apart that the wake and vortex at each element are completely developed and dissipated before flow reaches the next element. When the roughness elements are placed so close together that the wake and vortex at each element interfere with those developed at the following element, wake-interference flow results. Finally, quasi-smooth flow occurs when the roughness elements are so close together that the flow essentially skims the crest of the roughness elements.

The residue and gravel materials were placed perpendicular to flow. Thus, surface cover data could be used to identify the number of resistance elements present for a representative slope length. As an example, a 23% surface cover of corn (table 2) would provide 0.23 m of residue along a representative 1-m slope length. Since mean diameter for corn residue is 2.35 cm, approximately 10 residue elements would be present. Average spacing of the corn residue would be approximately 10 cm.

The ratio of spacing to diameter provides an estimate of the distance between residue elements in relation to roughness height. It can be seen from table 2 that a 23% cover of corn residue provides roughness elements spaced at distances approximately four times the roughness height. Thus, isolated roughness flow would appear to exist for this experimental condition, and for each of the other treatments where a single type of residue material was present.

When soybean or cotton residue was added to a surface which contained corn or sorghum residue, the spacing between residue elements generally decreased. Because of smaller residue diameters, however, ratios of spacing to diameter, in general, continued to be relatively high. As a result, isolated-roughness flow appears to have also been present for those experimental treatments which used soybean and cotton residue.

Because of their small diameter, a large number of wheat residue elements were necessary to obtain required surface cover values. Relatively small values of the ratio of spacing to diameter were identified for the wheat residue treatments. Thus, wake-interference flow would be expected for those experimental treatments which used wheat residue.

Gravel materials were added to each of the surfaces as a final experimental treatment. The size of the gravel materials was similar to the larger diameter residue materials. The relatively large spacing between gravel materials (table 2) would imply that their presence did not substantially affect existing flow conditions.

Table 2. Surface cover, spacing, ratio of spacing to diameter, and volume of selected resistance elements

Residue-Gravel Treatment	Surface Cover (%)	Spacing (cm)	Ratio of Spacing to Diameter	Volume of Resistance Elements (cm^3)
Corn-Soybean-Gravel				
Corn	23	10.2	4.34	4250
Soybeans	36	1.64	2.78	1670
Gravel	29	7.34	3.45	4850
Corn	32	7.34	3.12	5910
Soybeans	31	1.90	3.22	1430
Gravel	23	9.26	4.35	3840
Corn	30	7.83	3.33	5540
Soybeans	25	2.36	4.00	1160
Gravel	24	8.88	4.17	4010
Sorghum-Cotton-Gravel				
Sorghum	12	13.6	8.34	1540
Cotton	54	1.59	1.85	3650
Gravel	25	8.52	4.00	4180
Sorghum	21	7.76	4.76	2690
Cotton	35	2.46	2.86	2360
Gravel	31	6.87	3.23	5180
Sorghum	41	3.98	2.44	5250
Cotton	14	6.14	7.14	946
Gravel	26	8.19	3.85	4350
Sunflower-Wheat-Gravel				
Sunflower	11	23.5	9.07	2240
Wheat	59	0.492	1.70	1340
Gravel	13	16.4	7.70	2170
Sunflower	23	11.3	4.36	4680
Wheat	57	0.509	1.76	1300
Gravel	7	30.4	14.3	1170
Sunflower	36	7.19	2.78	7320
Wheat	44	0.659	2.27	1000
Gravel	8	26.6	12.5	1340

When determining the volume of the resistance elements, a cylindrical cross-section was assumed for both the residue and gravel materials. The volume of resistance elements was calculated on a meter-squared basis. As an example, a 23% cover of corn (table 2) would provide 0.23 m^2 of cover. Since corn residue has a 2.35 cm diameter, effective residue length was 9.79 m. When this value was multiplied by cross-sectional area (4.34 cm^2), a 4250 cm^3 residue volume was obtained. The effect of volume of resistance elements on flow mechanics will be discussed later.

Effects of Additional Crop Residue on Roughness Coefficients

Darcy-Weisbach roughness coefficients at varying Reynolds numbers for selected residue covered surfaces are shown in figures 1, 2, and 3. Relatively small quantities of corn, sorghum, and sunflower residue (23, 12, and 11%, respectively), and relatively large amounts of soybean, cotton and wheat residue (36, 54, and 59%, respectively) were used in these three experimental tests. Increased hydraulic resistance caused by the addition of the smaller diameter residue materials should have been most apparent for these surface cover conditions.

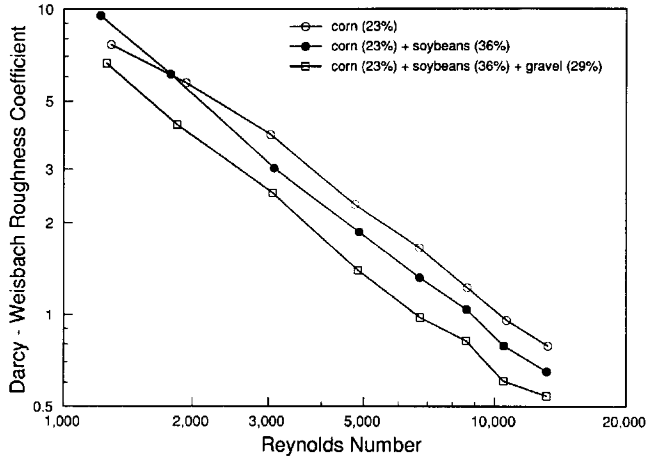

Figure 1–Darcy-Weisbach roughness coefficients as a function of Reynolds number for cover condition I on the corn-soybeans-gravel treatment.

It can be seen from figures 1, 2, and 3 that for a given surface condition, the Darcy-Weisbach friction factor usually decreased as Reynolds number became greater. As flow rates increased, water depths also became larger. As a result, surface roughness elements would be expected to have less of an effect on flow hydraulics at greater flow depths.

Measured Darcy-Weisbach roughness coefficients were evaluated using the paired student's t-test. This statistical evaluation was performed to determine if the addition of a different type of residue material to a surface already containing residue affected existing roughness coefficient values. Significant differences in measured Darcy-Weisbach roughness coefficients between residue-gravel treatments are noted in table 3. Differences in measured Darcy-Weisbach roughness coefficients within a given column for a particular cover condition are significant at the 5% level if the same letter does not appear.

The trends shown in figures 1 and 3 are characteristic of most of the experimental results. The addition of smaller-diameter residue elements to surfaces containing larger-diameter materials did not significantly affect roughness coefficient values. For these experimental treatments, a

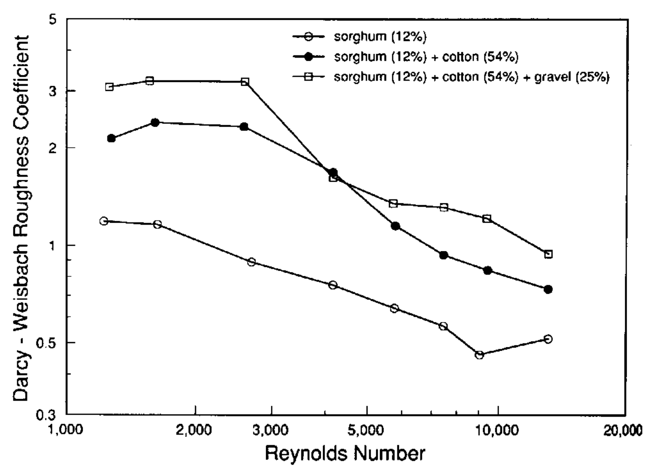

Figure 2–Darcy-Weisbach roughness coefficients as a function of Reynolds number for cover condition I on the sorghum-cotton-gravel treatment.

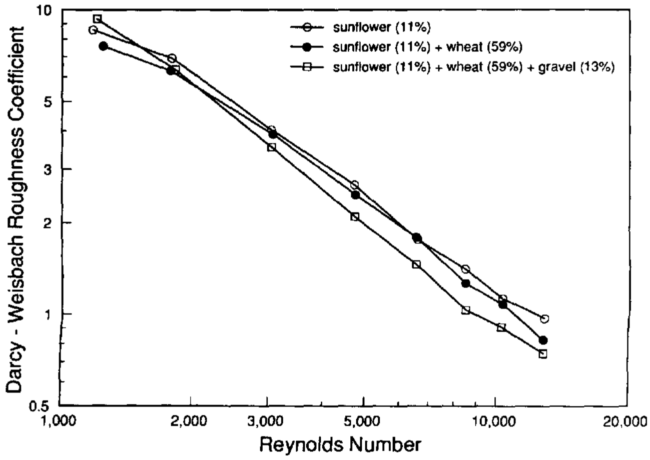

Figure 3–Darcy-Weisbach roughness coefficients as a function of Reynolds number for cover condition I on the sunflower-wheat-gravel treatment.

relatively large volume of residue material was present before the addition of other residue elements (table 2). Thus, the smaller diameter residue materials did not substantially affect total residue volume, or existing roughness coefficient values.

The exception to this situation is shown in figure 2. For lower Reynolds number values, Darcy-Weisbach roughness coefficients for the sorghum residue were substantially less than values for corn and sunflowers shown in figures 1 and 3, respectively. It can be seen from figure 2 that a significant increase in hydraulic resistance resulted when a 54% cover of cotton residue was added to a surface containing only 12% sorghum residue. The existing volume of resistance elements more than tripled as a result of the additional cotton residue (table 2). Smaller diameter residue elements which substantially increase the total volume of resistance elements may affect total hydraulic roughness.

Table 3. The effects of crop residue and gravel cover on measured Darcy-Weisbach roughness coefficients*

	Cover Condition†		
Residue - Gravel Treatment	I	II	III
Corn - Soybeans - Gravel			
Corn	a	a	a
Corn + Soybeans	a	a	a
Corn + Soybeans + Gravel	a	a	a
Sorghum - Cotton - Gravel			
Sorghum	a	a	a
Sorghum + Cotton	b	ab	a
Sorghum + Cotton + Gravel	b	b	a
Sunflower - Wheat - Gravel			
Sunflower	a	a	a
Sunflower + Wheat	a	a	a
Sunflower + Wheat + Gravel	a	a	a

* Differences in measured Darcy-Weisbach roughness coefficients within a given column for a particular cover condition are significant at the 5% level (paired student's t-test) if the same letter does not appear.

† The percentage of residue and gravel cover for each cover condition is shown in table 1.

Effects of Gravel Cover on Roughness Coefficients

Figures 1, 2, and 3 show measured resistance coefficient values on surfaces containing both crop residue and gravel materials. The statistical effect of gravel cover on hydraulic roughness is also reported in table 3. The gravel materials used in this study were added to surfaces which contained a substantial residue cover.

It is apparent from figures 1 and 3 that roughness coefficient values for surfaces with corn-soybeans or sunflower-wheat residue were not significantly affected by gravel cover. The treatment with sorghum-cotton-gravel cover had slightly larger resistance values as shown in figure 2. However, it can be seen from table 3 that the addition of gravel materials did not significantly increase existing roughness coefficient values on any of the surfaces.

In this investigation, gravel materials were added to surfaces which already contained a substantial residue cover. The addition of gravel materials to surfaces with much smaller residue cover may have produced different results. In addition, use of much larger gravel materials may have affected roughness coefficient values.

Summary and Conclusions

Several types of resistance factors may be present on some upland agricultural areas. Each of the roughness elements may influence flow hydraulics. In this study, Darcy-Weisbach roughness coefficients were measured on surfaces containing two types of crop residue and gravel cover.

Experimental treatments included corn-soybeans-gravel, sorghum-cotton-gravel, and sunflower-wheat-gravel. The residue and gravel materials were glued perpendicular to flow, without overlap, onto fiberglass sheets that had been placed in a flume. Steady uniform flow conditions were then established at eight selected discharge rates. Darcy-Weisbach roughness coefficients were calculated from measurements of discharge rate and flow velocity for Reynolds numbers values varying from approximately 1,200 to 13,000.

For most of the experimental tests, the addition of smaller diameter residue materials (soybeans, cotton, or wheat) to surfaces containing larger resistance elements (corn, sorghum, or sunflower) did not significantly affect hydraulic resistance. The exception to this situation occurred when a 54% cover of cotton residue was added to a surface containing only 12% sorghum residue. For this cover condition, the existing volume of resistance elements more than tripled as a result of the addition of cotton residue. Smaller diameter residue elements which substantially increase the total volume of resistance elements may affect total hydraulic resistance.

The diameter of the gravel materials used in this study varied from 1.25 to 2.50 cm, which was similar to the larger residue materials. A substantial residue cover was present on the surfaces where the gravel materials were added. Therefore, existing roughness coefficient values were not significantly affected by the addition of the gravel materials.

When determining hydraulic resistance on an upland site, the relative size, number, and volume of the roughness elements must be considered. Total hydraulic resistance is not additive for different types of resistance elements and cannot be estimated by simply summing the contributions of individual resistance factors. For many upland conditions, total hydraulic roughness can be estimated from a single resistance factor. For other situations, the contribution of different types of resistance elements to total hydraulic roughness must be considered.

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