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Abstract. *Total hydraulic resistance on an upland agricultural site may be influenced by several factors including standing vegetation. In this laboratory study, Darcy-Weisbach roughness coefficients were measured for corn, cotton, sorghum, soybeans, sunflower, and wheat vegetation. Experimental variables used in this investigation in addition to crop type included plant population, row spacing, row orientation, and flow rate. For some of the experimental tests, a single row of vegetation was oriented within a flume parallel to the principal flow direction. For the remainder of the tests, rows of vegetation were placed perpendicular to the flow using row spacings and plant populations recommended by crop management specialists. Measurements of discharge rate and flow velocity were used to calculate roughness coefficients for Reynolds number values ranging from approximately 550 to 22,000. Regression equations which relate roughness coefficients to plant population, row spacing, and Reynolds number were developed from the laboratory data. With the exception of wheat placed perpendicular to flow, roughness coefficients produced by standing vegetation were negligible. On upland agricultural areas, total hydraulic roughness will be influenced primarily by frictional drag over the soil surface, and residue and ground cover.* **Keywords.** *Hydraulics, Hydraulic roughness, Hydrologic modeling, Runoff.*

Resistance to flow on agricultural areas may be caused by frictional drag over the soil surface, standing vegetative materials, residue cover and rocks lying on the surface, raindrop impact, and other factors. Flow resistance in vegetated channels has received considerable attention (Chen, 1976; Fenzl and Davis, 1964; Kao and Barfield, 1978; Kouwen and Li, 1980; Kouwen et al., 1981; Temple, 1982; Temple et al., 1987; Thompson and Robertson, 1976; Turner et al., 1978), but most of this work has focused on flow through grasses.

Manning roughness coefficients for wheat and sorghum planted in diversion terraces were measured by Ree (1958). Ree and Crow (1977) determined Manning roughness coefficients for cotton, sorghum, and wheat located in vegetated waterways. In both of these studies, relatively large flow rates were used and thus the results cannot be applied to most overland flow conditions.

Darcy-Weisbach roughness coefficients for selected populations of wheat planted in different row spacings were measured by Turner et al. (1978). The authors report that most flow through vegetation is a mixture of laminar and turbulent flow. The density of vegetation was found to affect hydraulic resistance and reduce the available cross-section for flow.

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Engman (1986) described previous studies involving roughness coefficients on upland agricultural areas. Runoff plot data originally collected for erosion studies were used to identify hydraulic roughness coefficients. Friction factors were presented in a tabular format with a description of various surfaces and land uses.

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

Gilley et al. (1991 and 1992) performed laboratory studies to measure roughness coefficients for surfaces covered with crop residue, or gravel and cobble materials. The laboratory data were used to derive regression equations for predicting roughness coefficients based on surface cover and Reynolds number. The objective of this investigation was to develop regression equations for estimating Darcy-Weisbach roughness coefficients for selected standing crop materials. This information could be combined with previously obtained data to estimate total hydraulic resistance on cropland areas.

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):

$$f = \frac{8\,g\,R\,S}{V^2} \tag{1}$$

where

g = acceleration due to gravity

S = average slope

V = flow velocity

Hydraulic radius, R, is defined as:

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

where A is cross-sectional flow area and P is wetted perimeter. For a rectangular flume with flow width w:

$$R = \frac{w\,y}{w + 2\,y} \tag{3}$$

where y is flow depth.

Reynolds number, Rn, is used to describe flow characteristics, and is given as:

$$Rn = \frac{V\,R}{\upsilon} \tag{4}$$

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

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

$$Rn \cong \frac{q}{\upsilon} \tag{5}$$

where flow rate per unit width, q, is given as:

$$q = \frac{Q}{w} \tag{6}$$

and Q is flow rate.

The continuity equation for flow is defined as:

$$Q = V\,A \tag{7}$$

For a rectangular flume, water depth is given as:

$$y = \frac{Q}{V\,w} \tag{8}$$

In this study, water depth was determined indirectly using equation 8 and measurements of Q, V, and w.

Experimental Procedures

Effects of corn, cotton, sorghum, soybeans, sunflower, and wheat stalks on hydraulic roughness were examined in this investigation. After plant materials had been collected, they were placed in an oven and dried. For each type of plant material, 10 randomly selected stalks were used for characterizing diameter. Mean stalk diameter and the standard deviation among measurements are shown in table 1.

Hydraulic measurements were made for rows oriented both parallel and perpendicular to the flow. For the parallel configuration, a single row of crop material was placed in the center of the flume along its entire length. Two row spacings were examined, each with two in-row plant densities, for the runs made with rows perpendicular to the flow. Tests were conducted using two plant populations for each crop material. Crop management specialists recommended the plant population values which were used.

Except for wheat, individual stalks of plant material were glued onto a section of reinforced fiberglass sheeting located within the flume. To help stabilize the plant materials at higher flow rates, the stalks were placed over small diameter nails that had been secured to the fiberglass sheets. Clumps of wheat containing several stems were also placed at desired locations within the flume. Plant material and roots that had been located below the surface were removed from the wheat clumps. The plant population values for wheat shown in table 1 represent individual wheat stems.

Tests were conducted using a flume 0.91 m wide, 7.31 m long, and 0.279 m deep. A slope gradient of 1.35% was arbitrarily selected. Further analysis is needed to identify the effect of other slopes on resistance coefficients.

Water was supplied to the flume using a constant head tank. Two replicate tests were run at 10 flow rates ranging from approximately 7.32×10^{-4} to 2.52×10^{-2} m^3/s. A weighing tank was used to measure flow rate immediately before and after each test to ensure steady-state conditions. Water temperature was identified following flow rate determinations.

Reynolds number values varied from approximately 550 to 22,000. Maintaining uniform flow conditions was difficult for Reynolds numbers less than 550. For Reynolds numbers greater than 22,000, substantial variations in roughness coefficient values were sometimes found between replicate tests.

Line sources of fluorescent dye were injected across the flume at downslope distances of 0.91 m and 7.01 m, once

Table 1. Stalk diameter, plant population, and row spacing for selected crops

Crop Material	Stalk Diameter* (cm)	Plant Population† (stalks/m of row)	Row Spacing‡ (m)
Corn	2.74 (0.290)	3.28; 6.56	0.762; 1.02
Cotton	1.11 (0.310)	3.28; 13.1	0.508; 1.02
Sorghum	1.81 (0.340)	6.56; 23.0	0.762; 1.02
Soybeans	0.635 (0.086)	16.4; 29.5	0.381; 0.762
Sunflower	2.78 (0.152)	3.28; 6.56	0.381; 0.762
Wheat	0.310 (0.071)	93.4; 197	0.178; 0.356

* The standard deviation of measurements is shown in parentheses.

† The same two plant populations were used for both parallel and perpendicular flow.

‡ Two row spacings, each with two in-row plant populations, were employed for perpendicular flow.

steady state runoff conditions had become established. Time of travel of the dye concentration peaks was determined using a fluorometer and stop watch. 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 between the two dye concentration peaks. Three measurements of flow velocity were made for each flow rate. For a given flow rate, differences in flow velocity measurements were found to be minimal.

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

RESULTS AND DISCUSSION

For many engineering problems, the upper and lower limits of selected parameters must be identified. In this investigation, maximum hydraulic resistance occurred when the plant materials were located perpendicular to flow. In contrast, minimum hydraulic resistance resulted when flow occurred parallel to the roughness elements.

PARALLEL FLOW

Roughness coefficient values for crop materials placed parallel to flow are presented in table 2. It can be seen from table 2 that for soybeans (the material with the largest resistance values) Darcy-Weisbach roughness coefficients ranged from 1.9×10^{-3} to 3.1×10^{-2}. Under most field conditions, roughness coefficient values of this magnitude would have a minimal effect on overland flow hydraulics.

If it is necessary to predict roughness coefficients, regression equations shown in table 2 can be used. These equations relate Darcy-Weisbach roughness coefficients to plant population and Reynolds number. Separate equations were developed for each of the individual crops using all available data points. To estimate resistance coefficients for other crop materials, the regression equation derived for the crop used in this study having similar characteristics should be employed.

Table 2. Regression equations for Darcy-Weisbach roughness coefficients vs. plant population and Reynolds number for rows parallel to flow

Crop Material	f Value Range	Regression Coefficients* h	i	j	k	Coeff. of Deter. (r^2)
Corn	1.8×10^{-3} 8.1×10^{-2}	3.69×10^{-3}	-1.63×10^{-3}	1.38×10^{-6}	-6.97×10^{-3}	0.505
Cotton	1.0×10^{-4} 3.0×10^{-2}	9.44×10^{-4}	-1.38×10^{-2}	1.80 × 10–7	8.74×10^{-3}	0.669
Sorghum	5.0×10^{-4} 9.4×10^{-2}	1.61×10^{-3}	-3.93×10^{-2}	1.14×10^{-6}	2.13×10^{-2}	0.724
Soybeans	5.0×10^{-3} 5.9×10^{-2}	9.60×10^{-4}	-1.57×10^{-2}	1.14×10^{-6}	1.39×10^{-4}	0.712
Sunflower	3.0×10^{-3} 8.9×10^{-2}	8.23×10^{-3}	-5.82×10^{-2}	1.05×10^{-6}	8.81×10^{-3}	0.663
Wheat	1.1×10^{-1} 2.2	7.33×10^{-3}	-3.08	2.66×10^{-5}	3.34×10^{-1}	0.864

* Regression coefficients h, i, j, and k are used in the equation f = h (plant population) + i (row spacing) + j (Reynolds number) + k for plant population reported as stalks/m, row spacing given in m, and Reynolds number values ranging from approximately 550 to 22,000.

Table 3. Regression equations for Darcy-Weisbach roughness coefficients vs. plant population, row spacing, and Reynolds number for rows perpendicular to flow

Crop Material	f Value Range	Regression Coefficients* a	b	c	Coeff. of Deter. (r^2)
Corn	2.0×10^{-4} 2.5×10^{-2}	-1.55×10^{-4}	9.60×10^{-7}	-1.08×10^{-3}	0.673
Cotton	4.0×10^{-4} 9.4×10^{-3}	5.72×10^{-4}	-8.78×10^{-8}	7.00×10^{-4}	0.715
Sorghum	3.0×10^{-4} 1.2×10^{-2}	-1.11×10^{-4}	4.74×10^{-7}	1.57×10^{-3}	0.650
Soybeans	1.9×10^{-3} 3.1×10^{-2}	1.65×10^{-4}	8.94×10^{-7}	-2.98×10^{-3}	0.600
Sunflower	2.0×10^{-4} 2.0×10^{-2}	7.05×10^{-4}	6.96×10^{-7}	-2.33×10^{-3}	0.711
Wheat	3.0×10^{-4} 2.4×10^{-2}	-2.01×10^{-5}	6.90×10^{-7}	3.35×10^{-3}	0.688

* Regression coefficients a, b, and c are used in the equation f = a (plant population) + b (Reynolds number) + c for plant population reported as stalks/m, and Reynolds number values ranging from approximately 550 to 22,000.

PERPENDICULAR FLOW

The range in roughness coefficient values for the rows of plant stalks placed perpendicular to flow are shown in table 3. Larger hydraulic resistance was obtained when the rows of plant materials were oriented perpendicular to flow. Wheat stalks produced Darcy-Weisbach roughness coefficient values of 0.11 to 2.17, the largest of any of the crop materials. All other plant materials produced Darcy-Weisbach roughness coefficients less than 0.1.

Darcy-Weisbach roughness coefficients at varying Reynolds numbers for rows of wheat stalks placed perpendicular to flow are shown in figure 1. It can be seen from figure 1 that roughness coefficient values for wheat generally increased with Reynolds number. For each of the experimental runs, flow depth was less than the height of the crop materials. As a result, the total effective surface area of the resistance elements increased with flow rate, causing greater hydraulic resistance.

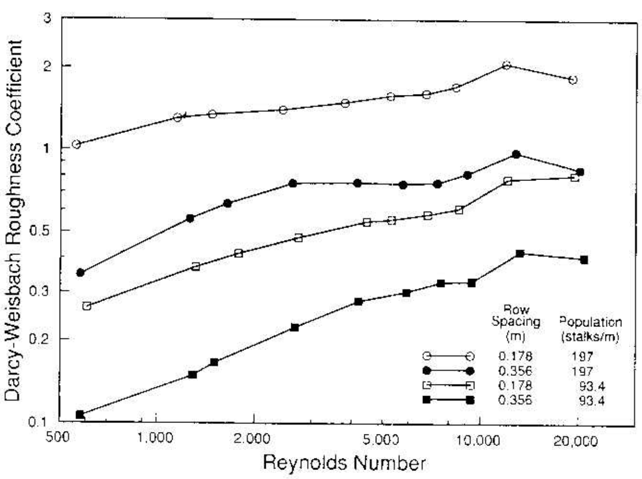

Figure 1–Darcy-Weisbach roughness coefficients vs. Reynolds number for wheat rows perpendicular to flow.

For a given row spacing, a greater number of stalks per meter of row length were found to substantially increase hydraulic resistance. An increased number of resistance elements produced greater stalk surface area, and larger roughness coefficients. Larger roughness coefficient values also resulted when the total number of plants per unit area were held constant, but row spacing was reduced. In other words, for a given number of plants per unit area, a larger number of rows, with fewer plants in each row, produced the greatest resistance to flow.

Separate regression equations were identified for each of the individual crops (table 3). If it is necessary to predict roughness coefficients for other crops, the regression relation derived for the crop used in this study having similar characteristics should be employed.

Temporal Changes in Roughness Coefficients

Crop rows are usually planted in a direction different from the principal slope direction. This situation may result in widely varying hydraulic conditions during a single runoff event. During the initial portion of the runoff event, flow would be expected to occur in the direction of the row, especially on areas where significant ridges are present. For some storms, flow depth may increase until the ridges are overtopped. For this portion of the runoff event, some of the runoff volume will travel in the direction of the principal slope and encounter greater flow resistance. Finally, late in the runoff event, runoff rate will decrease to a level less than that necessary to overtop the ridges and flow will again be expected to be in the direction of the row. Thus, hydraulic resistance values may change substantially during a single runoff event.

Stalk diameter may change significantly during the growing season. Stalks from mature crops collected after harvest were used in this experimental study. Thus, roughness coefficients reported in this investigation represent an upper limit for the given crop material. Resistance values may be minimal at the beginning of the cropping season, and increase substantially by crop maturity.

On some agricultural areas, crops are planted in the bottom of large ridges. As the crops mature, the fields are cultivated and the size of the ridges are reduced. In preparation for harvest, the ridges are completely removed, and a nearly uniform surface is established. For this particular management system, the direction of overland flow can be seen to change substantially during the cropping season.

Relative Importance of Standing Vegetation

Several factors may influence total hydraulic resistance on upland areas. In estimating a composite roughness coefficient, the relative contribution of each of these factors should be evaluated. For a particular site, one or two resistance mechanisms may predominate, and the others can be neglected.

For many cropland conditions, the contribution to total hydraulic roughness caused by standing crop materials will be negligible. Resistance to flow is induced by a bare soil surface. Darcy-Weisbach roughness coefficients varying from approximately 0.1 to 7 were determined by Gilley and Finkner (1991) on a recently planted surface for Reynolds number values ranging from approximately 20 to 6,000. For Reynolds numbers varying from approximately 300 to 10,000, Darcy-Weisbach roughness coefficients within rills ranged from approximately 0.2 to 8 (Gilley et al., 1990).

Crop residue or gravel and cobble materials in contact with the surface can also have a substantial impact on flow hydraulics. Darcy-Weisbach roughness coefficients varying from approximately 0.6 to 7 were measured by Gilley et al. (1991) on a surface with a 70% cover of wheat residue at Reynolds number values ranging from approximately 500 to 20,000. In comparison, an 80% cover of gravel material with 2.54 to 3.81 cm diameter produced Darcy-Weisbach roughness coefficients of approximately 0.5 to 7, for Reynolds numbers varying from approximately 600 to 16,000. Thus, with the exception of wheat located perpendicular to the principal flow direction, roughness coefficients caused by standing crops are in most cases small enough to be considered negligible.

Summary and Conclusions

Hydraulic roughness coefficients are used to analyze surface runoff on upland areas. Total hydraulic resistance at a site may be caused by several factors. Roughness coefficients for selected standing crop materials were measured in this investigation.

Experimental variables used in this study included crop type, plant population, row spacing, row orientation, and flow rate. Selected amounts of corn, cotton, sorghum, soybeans, sunflower, and wheat stalks were secured to a fiberglass sheet located within a flume. A single row of plant material was oriented parallel to flow in some of the experimental tests. For the remainder of the tests, rows of plant material were placed perpendicular to the flow using row spacings and plant populations recommended by crop management specialists. Darcy-Weisbach roughness coefficients were then identified under steady, uniform flow conditions for a wide range of discharge rates.

Regression equations were developed which related roughness coefficients to plant population, row spacing and Reynolds number. Separate equations were derived for each of the crop materials, for flow occurring both parallel and perpendicular to the roughness elements. The regression equations can be used for Reynolds number values varying from approximately 550 to 22,000.

Several factors may contribute to hydraulic resistance on upland areas. The relative contribution of each of these factors to a composite roughness coefficient should be considered. Roughness coefficients induced by standing crop materials were found in general to be much less than hydraulic roughness values caused by other resistance mechanisms such as crop residue on the soil surface, or gravel and cobble materials.

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