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Darcy–Weisbach roughness coefficients for overland flow

John E. Gilley, Dennis C. Flanagan, Eugene R. Kottwitz, Mark A. Weltz

Abstract

Analysis of surface runoff on upland areas requires identification of hydraulic roughness coefficients. Procedures were identified for estimating total hydraulic roughness for rill and interrill areas on both croplands and rangelands. Equations were presented to determine roughness coefficients for: (a) rills; (b) gravel and cobble materials; (c) surface residue on croplands; (d) interrill areas; (e) plants on cropland areas; and (f) rangeland areas. Experimental procedures used to determine the roughness coefficients were summarized. Finally, future needs for estimating roughness coefficients were identified.

Introduction

Analysis of surface runoff on upland areas requires identification of hydraulic roughness coefficients. Roughness coefficients are used in the calculation of flow velocity and the routing of runoff hydrographs. Understanding and properly modelling upland flow hydraulics is also essential in developing process-based erosion models.

Meyer-Peter & Müller (1948) suggested that the Darcy–Weisbach roughness coefficient for open channels be composed of two components, f_g and f_b, which denote roughness coefficients associated with grain roughness and bed-form roughness, respectively. It has been assumed that f_g and f_b are additive, with the total roughness coefficient, f, representing their sums or

$$f = f_g + f_b. \tag{2.1}$$

Several subsequent investigators utilized this concept, including Einstein & Barbarossa (1952), Engelund (1966), Alam & Kennedy (1969) and Lovera & Kennedy (1969).

Shen & Li (1973) used the concept of additive roughness for use with overland flow. They assumed the total roughness coefficient under rainfall conditions to be the sum of f_{wo}, the roughness coefficient without rainfall, and f_{ra}, the added roughness coefficient due to rainfall, or

$$f = f_{wo} + f_{ra}. \tag{2.2}$$

Regression analysis was performed by Shen & Li (1973) to identify empirical equations for estimating f_{ra}. Rainfall was found to influence total hydraulic resistance significantly primarily on smooth surfaces with small discharge rates. For most overland-flow conditions, rainfall would be expected to have a minimal effect on total hydraulic resistance.

Laboratory measurements of roughness coefficients on surfaces covered with sand or gravel were made by Woo & Brater (1961), Emmett (1970), Phelps (1975) and Savat (1980). Similar tests were performed on natural landscapes by Dunne & Dietrich (1980), Roels (1984), Abrahams et al. (1986) and Parsons et al. (1990). In these studies, a significant correlation was established between Reynolds number and roughness coefficient.

Roughness coefficients were also significantly influenced by flow depth. For flow depths less than the height of the roughness elements, roughness coefficients increase with greater Reynolds number. Once roughness elements are submerged, their ability to retard overland flow is reduced as flow depth becomes larger. As a result, the roughness coefficient usually decreases with an increasing Reynolds number.

A comprehensive review of previous studies involving evaluation of roughness coefficients on agricultural and natural areas was provided by Engman (1986). Hydraulic roughness coefficients were developed from runoff data originally collected for erosion studies on experimental plots. Roughness coefficients were presented in a tabular format with a description of various surfaces and land uses.

Equations for estimating total hydraulic resistance on cropland and rangeland areas are presented below. Procedures are identified for estimating roughness coefficients caused by several factors. Roughness coefficients computed for these individual factors can be added to obtain total hydraulic resistance for a particular site.

Hydraulic equations

Overland-flow hydraulics

The Darcy–Weisbach equation is frequently used to model hydraulic characteristics of overland flow. Under uniform flow conditions, the Darcy–Weisbach roughness coefficient, f, is given as

$$f = \frac{8gRs}{V^2} \tag{2.3}$$

where g is acceleration due to gravity, s is average slope, V is mean flow velocity, and hydraulic radius, R, is defined as

$$R = \frac{A}{P} \tag{2.4}$$

where A is cross-sectional flow area and P is wetted perimeter (Chow 1959). For a rectangular flow geometry

$$R = \frac{by}{b+2y} \tag{2.5}$$

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

The continuity equation is defined as

$$Q = VA \tag{2.6}$$

where Q is flow rate. For a rectangular channel, water depth is given as

$$y = \frac{Q}{Vb}. \tag{2.7}$$

Reynolds number, Re, which is used to express the ratio of inertial forces to viscous forces is given as

$$Re = \frac{VR}{\nu} \tag{2.8}$$

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

Investigation of the correlation between roughness coefficient and Reynolds number requires the determination of shallow flow depths existing under field conditions. Since it may be difficult to identify the soil–water interface for eroding situations, direct measurement of flow depth may not be possible.

Thus, it may be necessary to determine water depth indirectly using Equation 2.7. Water depth can be substituted into Equation 2.5 to calculate hydraulic radius. Finally, roughness coefficient and Reynolds number values can be obtained from Equations 2.3 & 2.8, respectively.

Roughness coefficient equations

The total roughness coefficient for rills on croplands, f_r , can be represented as

$$f_r = f_{sr} + f_{rk} + f_{cr} + f_{st} \tag{2.9}$$

where f_{sr} is the roughness coefficient for rills, f_{rk} is the roughness coefficient for gravel and cobble materials. f_{cr} is the roughness coefficient for surface residue on croplands, and f_{st} is the roughness coefficient for plants on cropland areas. For rills on rangelands, the total roughness coefficient, f_{rr}, is given as

$$f_{rr} = f_{sr} + f_{rk} + f_{lt} + f_{pb} \tag{2.10}$$

where f_{lt} is the roughness coefficient for litter and organic residue on rangelands, and f_{pb} is the roughness coefficient for plants on rangeland areas. It can be seen from Equations 2.9 & 2.10 that two of the factors contributing to hydraulic roughness of rills are the same on cropland and rangeland areas.

The total roughness coefficient for interrill cropland areas, f_i, can be represented as

$$f_i = f_{si} + f_{rk} + f_{cr} + f_{st} \tag{2.11}$$

where f_{si} is the roughness coefficient for interrill areas. For interrill rangeland areas, the total roughness coefficient, f_{ir} . is given as

$$f_{ir} = f_{si} + f_{rk} + f_{lt} + f_{pb}. \tag{2.12}$$

Again, several of the same factors contribute to hydraulic resistance on interrill areas for both croplands and rangelands.

Equations 2.9-2.12 each contain four factors which may contribute to hydraulic roughness. Some of these factors may not be present at a given location. Even if a particular component is represented, its contribution to total hydraulic resistance may be minimal.

Roughness coefficients for rills

Experimental procedures

A field study was conducted by Gilley et al. (1990) at 11 sites located throughout the eastern United States to measure hydraulic characteristics of rills. The location, slope and particle size analysis of soils at the study sites are shown in Table 2.1. These soils were selected to cover a broad range of physical, chemical, biological and mineralogical properties. These properties resulted from diverse soil-forming factors acting through time, including climate, parent material, vegetation, biological activity and topography. Each soil is considered to be of regional or national importance.

Table 2.1 Location, slope and particle size analysis of selected soils used to measure roughness coefficients for rills.

Soil	Location		Slope	Particle size analysis % by weight		
	County	State	%	Sand	Silt	Clay
Caribou	Aroostook	Maine	6.4	47.0	40.3	12.7
Cecil	Oconee	Georgia	6.2	64.6	15.6	19.8
Collamer	Tompkins	New York	8.2	7.0	78.0	15.0
Gaston	Rown	North Carolina	5.9	35.5	25.4	39.1
Grenada	Panola	Mississippi	6.7	2.0	77.8	20.2
Lewisburg	Whitley	Indiana	9.6	38.5	32.2	29.3
Manor	Howard	Maryland	9.8	43.6	30.7	25.7
Mexico	Boone	Missouri	3.8	5.3	68.7	26.0
Miami	Montgomery	Indiana	6.4	4.2	72.7	23.1
Miamian	Montgomery	Ohio	8.8	30.6	44.1	25.3
Tifton	Worth	Georgia	5.5	86.4	10.8	2.8

The study areas were located on uniform slopes having relatively homogeneous soil characteristics. Either corn or small grains had been planted the previous year. Preparing the study areas for testing required removing all surface residue and then moldboard ploughing 3–12 months before the tests were conducted. After ploughing, the sites were disked lightly and maintained free of vegetation either by tillage or by application of herbicide. The study areas were disked immediately preceding testing. Two plots, 3.7 m across the slope by 10.7 m long, were established at each site using sheet metal borders. The plots were raked by hand prior to testing to provide a uniform surface.

A portable rainfall simulator designed by Swanson (1965) was used to apply rainfall at an intensity of approximately 57 mm h^{-1}. The first rainfall application (initial run) of 1 h duration occurred at existing soil-water conditions. A second rainfall simulation run (wet run) was conducted approximately 24 h later, again for a duration of 1 h. A final, very wet rainfall application was applied within one hour after completion of the wet run.

After steady-state conditions had become established during the very wet rainfall application, inflow was added at the top of each plot to simulate greater slope lengths. Flow addition for each of four inflow increments occurred only after steady-state runoff conditions for the previous inflow increment had become established and selected hydraulic measurements had been made. A trough extending across the bottom of each plot gathered runoff, which was continuously measured using an HS flume with stage recorder. Steady-state runoff conditions were determined using the stage recorder and HS flume. A thermometer was used to measure water temperature, and flow width was determined using a ruler.

To determine rill discharge, a bromide solution of known concentration was continuously injected into each rill at a constant rate (Replogle et al. 1966). Runoff samples containing the diluted bromide solution were collected at the point where each rill discharged into the collection trough. Samples of approximately 800 ml were obtained using polyethylene bags. The concentrations of diluted bromide in each of these samples were determined later using an ion analyser. From measurements of the bromide injection rate and concentration, and diluted concentration, rill discharge rate was determined.

Mean flow velocity in each rill was measured using a fluorometer (Hubbard et al. 1982). A slug of dye was injected into the rill and the time required for the concentration peak to travel a known distance to a downstream point was identified. A time-concentration curve resulted from continuous pumping of runoff from the rill through the fluorometer flow cell. Due to the symmetrical shape of the dye concentration curve, the velocity associated with the peak concentration was assumed to equal mean flow velocity. Mean flow velocity was obtained by dividing travel distance by time of travel.

Roughness coefficient equations

The regression equations shown in Table 2.2 relate roughness coefficients calculated using Equation 2.3 to Reynolds number values obtained from

Table 2.2 Regression equations for roughness coefficients for rills versus Reynolds number.

Soil	Regression coefficients* a	Regression coefficients* b	Coefficient of determination r^2
Caribou	4.99×10^3	−1.120	0.825
Cecil	9.72×10^2	−0.874	0.702
Collamer	1.14×10^2	−0.670	0.678
Gaston	2.57×10^2	−0.767	0.702
Grenada	3.41×10^2	−0.695	0.601
Lewisburg	8.75×10^2	−0.889	0.614
Manor	6.01×10^3	−1.120	0.879
Mexico	5.27×10^5	−1.850	0.860
Miami	1.51×10^2	−0.621	0.816
Tifton	2.36×10^4	−1.240	0.731
All soils combined**	1.35×10^3	−0.934	0.655

* Regression coefficients a and b are used in the equation

$$f_{sr} = a\,(Re)^b$$

where f_{sr} is the roughness coefficient for rills and Re is Reynolds number.

** For the "All soils combined" analysis, Darcy-Weisbach roughness coefficients ranged from 0.17 to 8.0 while Reynolds number varied from approximately 300 to 10,000.

Equation 2.8. Regression coefficients are reported for each of the individual soils and for all soils combined. The fluorometer that was used to measure flow velocity was not functioning properly during most of the run on the Miamian soil. As a result, information from this site was omitted from Table 2.2.

Analyses of all soils combined provided roughness coefficient values ranging from 0.17 to 8.0, while Reynolds number varied from 300 to 10,000. Results from the all soils combined analysis can be used to estimate roughness coefficients for rills from the equation

$$f_{sr} = \frac{1350}{Re^{0.934}} \qquad (2.13)$$

Roughness coefficients for gravel and cobble materials

Experimental procedures
Gilley et al. (1992) performed a laboratory study to measure roughness coefficients for gravel and cobble materials. The diameters of gravel and

Table 2.3 Diameter, surface cover and shape factor for gravel and cobble surfaces.

Diameter cm	Surface cover %	Shape factor*
0.25 - 1.27	6, 15, 37, 66, 90	0.51
1.27 - 2.54	7, 13, 32, 61, 90	0.52
2.54 - 3.81	4, 16, 32, 56, 80	0.49
3.81 - 12.70	6, 17, 33, 61, 89	0.47
12.70 - 25.40	9, 13, 24, 61, 83	0.52

* Shape factor, *SF*, is given as (Guy 1969)

$$SF = c \,/\, (ab)^{0.5}$$

where a = longest axis, b = intermediate axis and c = shortest axis

cobble materials used in the investigation are shown in Table 2.3. The gravel material, varying in size from 0.25 to 12.70 cm, was removed from a rangeland site near Tombstone, Arizona. Cobble material, with dimensions of 12.70–25.40 cm, was obtained near Lincoln, Nebraska.

Shape factors (Guy 1969) determined from measurements on 10 samples from each of the size classes are shown in Table 2.3. Shape factors provide a relative estimate of the physical configuration of gravel and cobble material. Little variation in shape factor was found between size classes. For natural sediments with much smaller diameters, a shape factor of 0.7 is typical (Guy 1969).

Gravel and cobble materials were glued in a random orientation onto a section of reinforced fibreglass sheeting located within a flume. Surface cover values for each of the size classes are shown in Table 2.3. The percentage of surface cover was obtained using a photographic grid procedure (Laflen et al. 1978). Gravel and cobble materials on the fibreglass sheets were photographed using 35 mm colour slide film. The slides were projected onto a screen on which a grid had been superimposed. The number of grid intersections over gravel and cobble material was determined visually from the projected slides, and surface cover was then calculated.

The flume, which was 0.91 m wide, 7.31 m long and 0.279 m deep, 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 selected flow rates. Flow rate was determined immediately before and after each test to confirm steady-state conditions. Water temperature was measured following flow rate determinations.

Reynolds number values varied from approximately 500 to 16,000. Uniform flow conditions were difficult to maintain on the gravel- and cobble-covered surfaces for Reynolds numbers less than approximately 500. For Reynolds numbers greater than 16,000, little variation in roughness coefficient values was found.

Once steady-state runoff conditions had become established, line sources of fluorescent dye were simultaneously injected across the flume at downslope distances of 0.91 and 7.01 m. A fluorometer was used to determine time of travel of 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 fibreglass sheets supporting the gravel and cobble materials were also identified. The experimental procedures used to measure roughness coefficients for the fibreglass sheets with and without gravel and cobble material were identical. Roughness coefficients induced by the bare fibreglass sheets at a given Reynolds number were subtracted from measurements obtained with gravel and cobble material to determine hydraulic resistance caused by the gravel and cobble material alone.

Tests were also conducted to measure total hydraulic roughness for three distributions of size classes. The purpose of these tests was to validate the addition of roughness coefficients for individual size classes to obtain total hydraulic roughness. The percentage of surface cover contributed by each size class for each distribution is shown in Table 2.4.

Roughness coefficient equations

Darcy–Weisbach roughness coefficients at varying Reynolds number for gravel material with dimensions of 2.54-3.81 cm are shown in Figure 2.1. The trends

Table 2.4 Percent cover for selected size classes used in validation test series for gravel and cobble surfaces.

Diameter	Percent cover in test series		
cm	1	2	3
0.25 - 1.27	21	3	16
1.27 - 2.54	31	11	9
2.54 - 3.81	14	18	38
3.81 - 12.70	13	28	11
12.70 - 25.40	9	30	15
Total cover	88	90	89

presented in Figure 2.1 are characteristic of all but the largest size class of gravel and cobble material. For the experimental results shown in Figure 2.1 with surface covers of 56 and 80%, water depth was usually greater than the height of the gravel material. As a result, Darcy-Weisbach roughness coefficients consistently decreased as Reynolds number became larger. In contrast, water depths at lower Reynolds numbers for the test runs with surface cover values of 4, 16 and 32% were typically less than the height of the gravel material. As a result, roughness coefficients initially increased with Reynolds number. Once flow depth exceeded roughness element height, roughness coefficients became smaller as Reynolds number increased.

Water depths were usually smaller than the height of the roughness elements for cobble materials having a diameter of 12.70-25.40 cm. As a result, Darcy-Weisbach roughness coefficients generally increased with Reynolds number (Fig. 2.2). However, the surfaces with 61 and 83% cover showed a substantial reduction in roughness coefficient values at the highest Reynolds number, where flow depth exceeded the height of many of the roughness elements.

Regression equations that relate roughness coefficients for gravel and cobble materials to percentage cover and Reynolds number are shown in Table 2.5. Regression relations are presented for five selected size classes with dimensions ranging from 0.25 to 25.40 cm. Use of the regression equations shown in Table 2.5 requires information on the percentage of the ground surface covered with gravel and cobble materials. If ground cover percentages are available for the separate size classes shown in Table 2.5, then the individual regression equations can be used. If only total ground cover is known, the friction coefficient for gravel and cobble materials can be estimated using a generalized

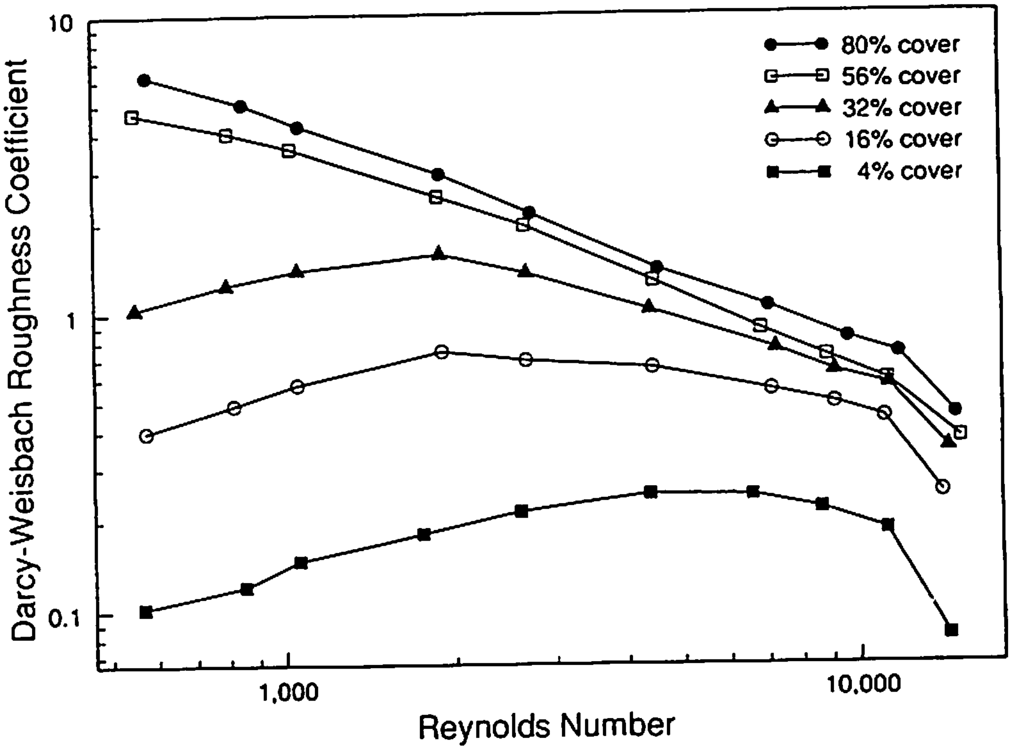

Figure 2.1 Darcy-Weisbach roughness coefficients vs. Reynolds number for gravel material with a diameter of 2.54 to 3.81 cm.

regression equation. Data for gravel and cobble materials having a diameter range of 0.25–12.70 cm were combined to obtain

$$f_{rk} = \frac{2.16(percentage\ cover)^{0.953}}{Re^{0.550}}. \qquad (2.14)$$

Equation 2.14 was derived using roughness coefficient values ranging from 0.05 to 7.8.

Information on the size distribution of surface material obtained on the basis of mass may be more readily available and easier to obtain. Gilley et al. (1992) made measurements of the mass of gravel or cobble material corresponding to a given surface cover. This data was used to develop regression equations for relating surface cover for a given size class to gravel or cobble mass.

Laboratory data collected on the surfaces described in Table 2.4, which contained multiple size classes, were used to test the reliability of the regression equations. Roughness coefficients were first determined for each size class using information presented in Table 2.5. Roughness contributions for each of

Table 2.5 Regression equations for roughness coefficients for gravel and cobble materials vs. percentage cover and Reynolds number.

Diameter	Regression coefficients*			Coefficient of determination
cm	a	b	c	r^2
0.25 - 1.27	1.68×10^{1}	5.78×10^{-1}	7.09×10^{-1}	0.985
1.27 - 2.54	1.18×10^{1}	6.78×10^{-1}	6.67×10^{-1}	0.945
2.54 - 3.81	1.91	1.19	6.28×10^{-1}	0.943
3.81 - 12.70	1.11×10^{-1}	1.61	4.68×10^{-1}	0.944
12.70 - 25.40	1.25×10^{-5}	1.63	-5.68×10^{-1}	0.944
0.25 - 12.70**	2.16	9.53×10^{-1}	5.50×10^{-1}	0.672

* Regression coefficients a, b and c are used in the equation

$$f_{rk} = a\ (\text{percentage cover})^{b}\ /\ (Re)^{c}$$

where f_{rk} is the roughness coefficient for gravel and cobble materials and *Re* is Reynolds number.

** Data for gravel and cobble surfaces having a diameter range of 0.25–12.70 cm were combined to obtain a generalized regression equation. Darcy-Weisbach roughness coefficients for this generalized equation ranged from 0.05 to 7.8 while Reynolds number varied from approximately 500 to 16,000.

the five size classes were then added to find total hydraulic resistance for the given test series. Hydraulic roughness coefficients were determined for each Reynolds number value used in the laboratory tests.

Predicted versus measured roughness coefficients are presented in Figure 2.3. Close agreement between predicted and measured values was found for each test series. Linear regression analysis of predicted versus measured roughness coefficients yielded an r^2 value of 0.983. Thus, reliable estimates of roughness coefficients for gravel and cobble materials were obtained by adding the roughness contributions of individual size classes.

Roughness coefficients for surface residue on croplands

Experimental procedures

A laboratory study was conducted by Gilley et al. (1991) to identify roughness coefficients for selected crop residue materials. The types of residue used in the investigation included corn, cotton, peanut, pine needles, sorghum, soybeans, sunflower and wheat. Needles produced by ponderosa pine were

Darcy-Weisbach Roughness Coefficient

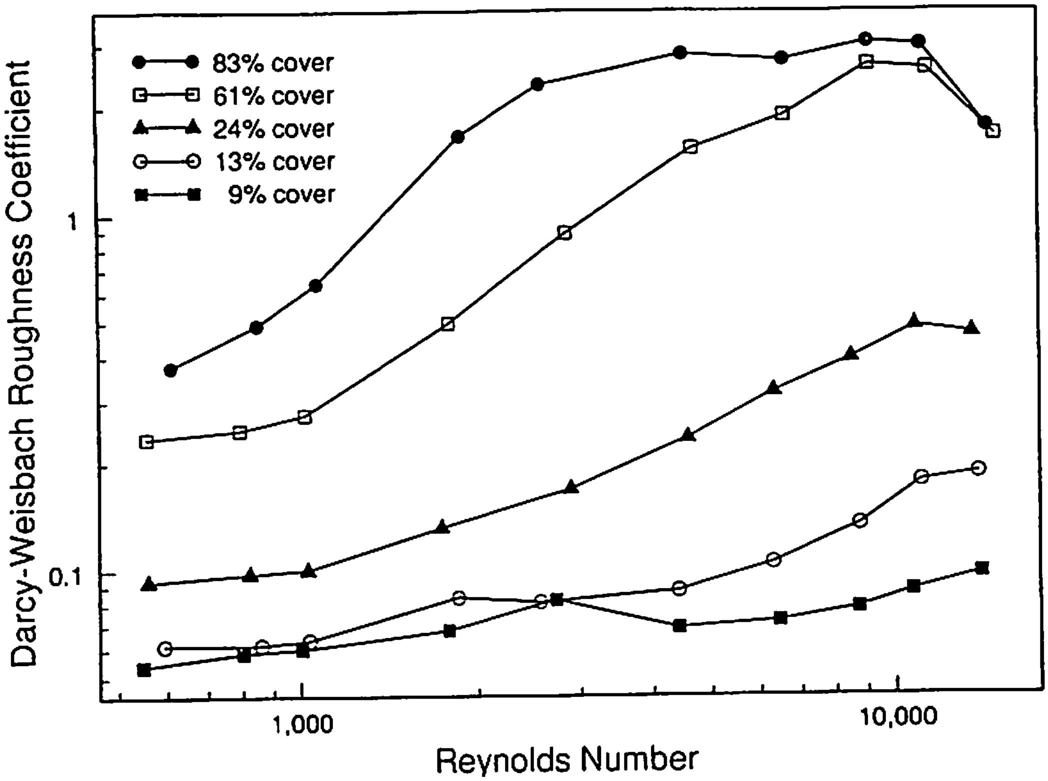

Figure 2.2 Darcy-Weisbach roughness coefficients vs. Reynolds number for cobble material with a diameter of 12.7–25.4 cm.

used to obtain an estimate of roughness coefficients on forested areas. After the residue materials had been removed from the field, they were placed in an oven and dried. For each residue type, 10 separate residue elements were randomly selected for measurement of residue dimensions. Mean residue diameters and lengths are shown in Table 2.6.

A measured mass of residue material was glued in a random orientation onto a section of reinforced fibreglass sheeting. For each residue type, five residue rates were selected. All of the residue materials, except pine needles and wheat, were applied at rates equivalent to 2, 4, 6, 8 and 10 t ha^{-1}. Rates equivalent to 0.75, 2, 4, 6 and 8 t ha^{-1} were used for pine needles, while wheat straw was applied at rates equivalent to 0.25, 0.50, 1, 2 and 4 t ha^{-1}. Since pine needle and wheat residue elements had smaller diameters than the other residue materials, they furnished greater surface cover at a given residue rate.

The percentage of surface cover provided at a given residue rate (Table 2.6) was obtained using the photographic grid procedure (Laflen et al. 1978) described previously. Testing procedures used to measure roughness coefficients for crop residues were similar to those used for gravel and cobble

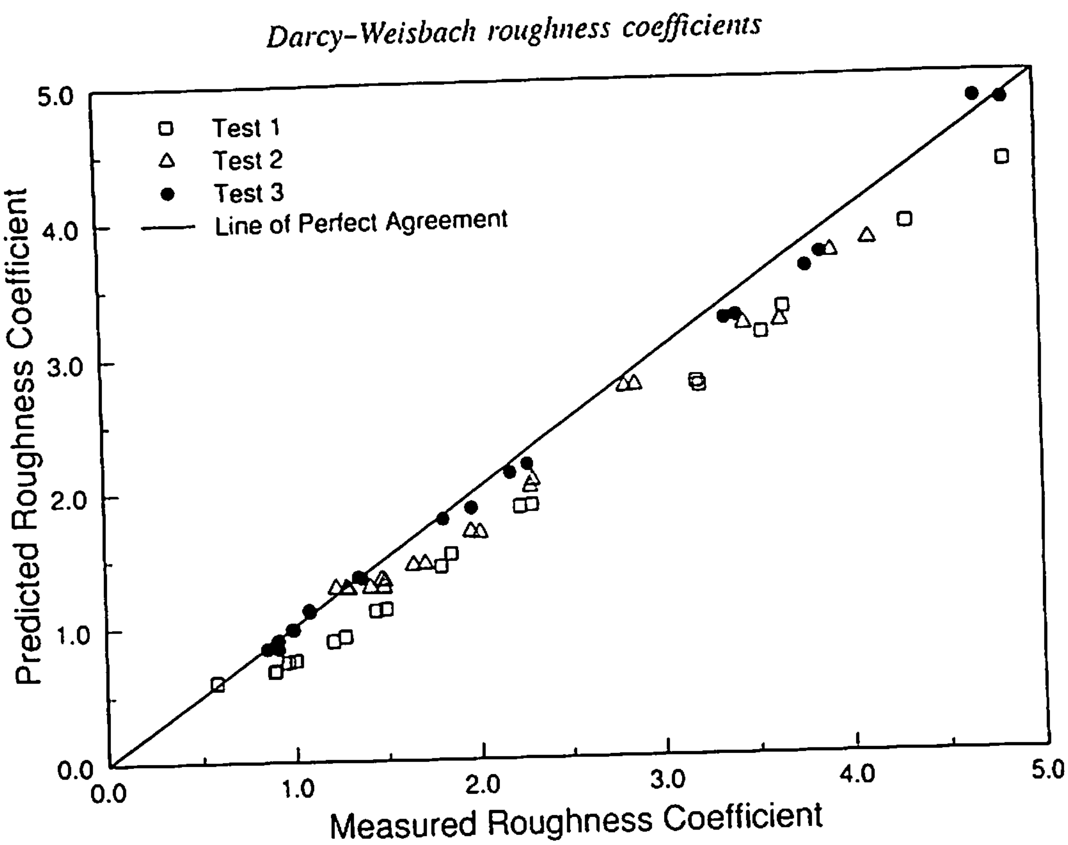

Figure 2.3 Predicted vs. measured Darcy-Weisbach roughness coefficients for surfaces containing gravel and cobble materials.

materials. Results reported here may be used for Reynolds number values ranging from approximately 500 to 16,000.

Roughness coefficient equations

Darcy-Weisbach roughness coefficients at varying Reynolds numbers for selected rates of wheat residue are shown in Figure 2.4. The trends presented in Figure 2.4 are characteristic not only of wheat residue but also of the other vegetative materials used in this investigation. Data presented in Figure 2.4 indicates that for a given residue rate, the Darcy-Weisbach friction factor usually decreased as Reynolds number increased.

The regression coefficients presented in Table 2.7 can be used to relate roughness coefficients for crop residue materials to percentage residue cover and Reynolds number. Regression coefficients are reported for selected residue types and for all residue types combined. Results for the all residue types combined analysis can be used to estimate the roughness coefficient for residue materials not used in this investigation using the relation

Table 2.6 Diameter, length, residue rate and surface cover of crop residue materials.

Residue type	Mean diameter cm	Mean length cm	Residue rate t ha^{-1}	Surface cover %
Corn	1.87	42.9	2 - 10	25 - 81
Cotton	0.73	36.2	2 - 10	12 - 50
Peanut	0.36	20.2	2 - 10	17 - 84
Pine needles	0.12	12.6	0.75 - 8	30 - 93
Sorghum	1.59	35.7	2 - 10	22 - 91
Soybeans	0.40	13.1	2 - 10	32 - 93
Sunflower	1.93	42.2	2 - 10	15 - 63
Wheat	0.30	19.4	0.25 - 4	26 - 99

$$f_{cr} = \frac{0.127(\textit{percentage cover})^{1.55}}{Re^{0.388}}. \qquad (2.15)$$

Roughness coefficient values varying from 0.17 to 18.7 were used in the derivation of Equation 2.15.

Information on the rate of residue present at a particular site may be more readily available than surface cover data. Regression equations relating roughness coefficients to residue rate and Reynolds number were presented by Gilley et al. (1991). Procedures for estimating surface cover from values of residue rate were also identified for the selected residue materials.

Roughness coefficients on interrill areas

Experimental procedures

Field tests to determine roughness coefficients for interrill areas were conducted by Gilley and Finkner (1991) at the University of Nebraska Rogers Memorial Farm located in Lancaster County, approximately 18 km east of Lincoln, Nebraska. The Sharpsburg silty clay loam at the site (fine, montmorillonitic, mesic Typic Argiudolls) formed on loess under prairie vegetation. Average slope at the location was 6.4%.

The experimental design for the study consisted of two randomized complete blocks, with the first block being located immediately upslope from the second.

Table 2.7 Regression equation for roughness coefficients for surface residue on croplands versus percent cover and Reynolds number.

Residue type	Regression coefficients* a	b	c	Coefficient of determination r^2
Corn	6.30×10^{-2}	1.53	2.34×10^{-1}	0.911
Cotton	8.88×10^{-2}	1.02	7.88×10^{-2}	0.731
Peanut	2.61×10^{-1}	1.56	5.06×10^{-1}	0.924
Pine needles	8.71×10^{-5}	3.63	6.52×10^{-1}	0.874
Sorghum	5.24	7.96×10^{-1}	4.55×10^{-1}	0.960
Soybeans	9.28×10^{-2}	2.84	1.02	0.919
Sunflower	1.66	8.87×10^{-1}	3.51×10^{-1}	0.916
Wheat	2.98×10^{-4}	3.27	6.28×10^{-1}	0.938
All residue types combined**	1.27×10^{-1}	1.55	3.88×10^{-1}	0.648

* Regression coefficients a, b and c are used in the equation

$$f_{cr} = \text{a (percentage cover)}^{\text{b}} / (Re)^{\text{c}}$$

where f_{cr} is the roughness coefficient for surface residue on croplands and Re is Reynolds number.

** For the "All residue types combined" analysis, Darcy-Weisbach roughness coefficients ranged from 0.17 to 18.7, while Reynolds number varied from approximately 500 to 16,000.

Each experimental block consisted of six tillage operations performed at random locations within the block. The tillage operations included an anhydrous applicator, chisel plough, disk, field cultivator, moldboard plough and planter. These implements were chosen to provide a wide range of random roughness conditions.

Existing wheat residue was first removed from the study area by burning and hand raking. Selected tillage operations were then performed parallel to the contour at the study site. Plots, of an area 1 m^2, were established within each tillage treatment using galvanized sheet metal borders for the top and both sides of the plots. A trough, located at the bottom of the plots, was used to collect runoff. When not in use, the plots were covered with plywood which was placed several centimetres above the plots. The plywood covering prevented

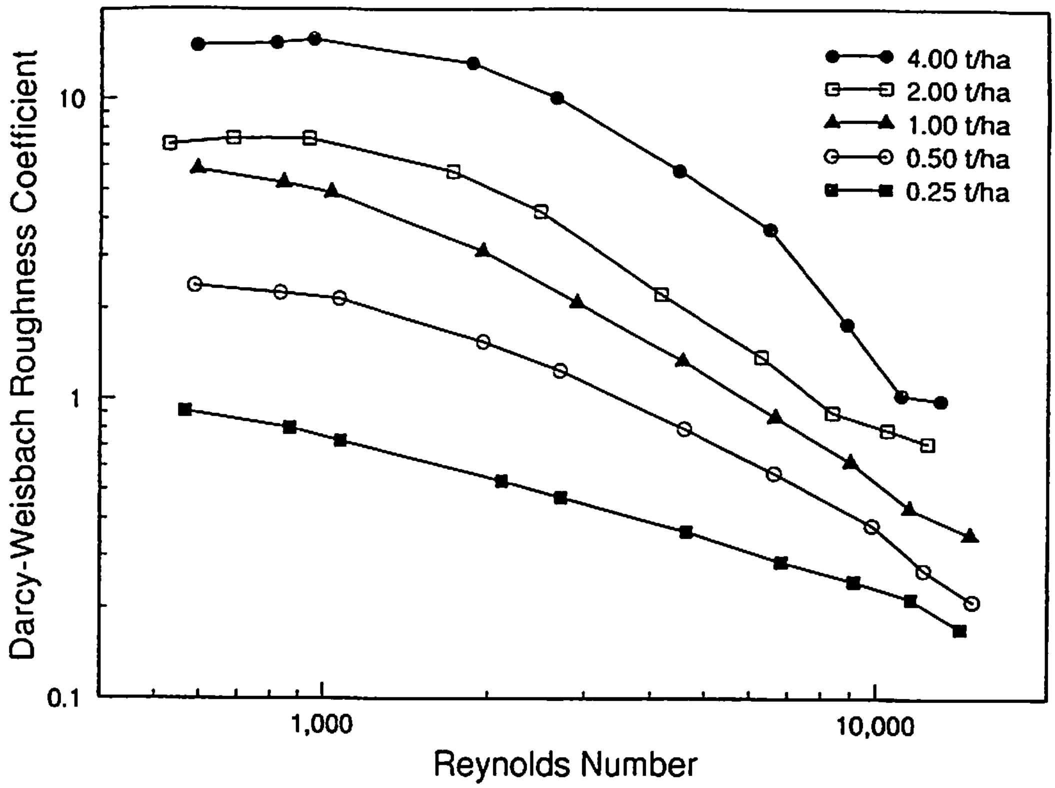

Figure 2.4 Darcy-Weisbach roughness coefficients vs. Reynolds number for selected rates of wheat residue.

disturbance of the soil surface by natural rainfall.

Differences in soil surface height were recorded using a mechanical profile meter. The surface profile meter, similar to the device described by Allmaras et al. (1967), could be easily rolled above the entire plot surface on a rectangular support frame. The support frame was of variable height and was levelled in the horizontal plane. The rectangular frame was supported by four 250 mm steel stakes which were securely anchored into the soil to provide a horizontal reference. The upper left corner of each plot border as viewed from the bottom of the plots was used as a vertical bench mark, creating a three-dimensional referencing system.

The profile meter consisted of a single row of equal length, 3.2 mm diameter steel pins positioned at a spacing of 6.4 mm. When lowered onto the soil surface, the top of the pins formed a nearly continuous line which was traced onto a strip of paper located behind the pins. The profile meter and frame were oriented so that surface elevations were measured parallel to the contour of the study area. Transects were spaced every 50 mm along the slope and transect traces were later digitized at 25 mm spacings. A total of 629 surface elevations were used for determination of random roughness for each plot.

Darcy-Weisbach roughness coefficients

Several tests were to be performed on each plot under identical soil conditions. Thus, soil-surface stabilization was required to prevent destruction of soil-form roughness during test procedures. After measurements for random roughness were obtained, the plot surfaces were stabilized using a biodegradable, latex-based soil stabilizer. The stabilizer was sprayed over the entire soil surface using a hand sprayer. The stabilizing material penetrated the soil approximately 5 mm, effectively binding the soil particles together in a water-permeable layer.

Following application and drying of the latex-base soil stabilizer, flow was added uniformly across the top of each plot at 12 selected rates. Flow inlet energy was dissipated at the top of the plots using an artificial turf carpet. Runoff was diverted into an HS flume with a stage recorder for measurement of flow rate.

Flow velocity was determined using dye tracing techniques. Approximately 0.2 l of fluorescent dye was uniformly injected across the width of the plot, 0.76 m upslope from the lower boundary. A peristaltic pump was used to continuously withdraw flow at four points spaced equally along the collection trough. Discharge was then circulated through a fluorometer which provided a visual display of dye concentration. Average time of travel was calculated as the length of time required for the dye concentration peak to reach the lower boundary. Five measurements of travel time were obtained at each of 12 inflow rates. The mean of the five readings was used to calculate flow velocity at a particular inflow rate.

Random roughness values

Random roughness was calculated using the procedure outlined by Allmaras et al. (1967). Table 2.8 presents random roughness measurements obtained in the present study, and values reported by Zobeck & Onstad (1987) in a review of available literature. Random roughness values in the present investigation ranged from 6 mm for the planter to 32 mm for the moldboard plough treatment.

The anhydrous applicator and planter caused little disturbance to the relatively smooth surface which existed at the study site. Random roughness values for these two operations were less than those reported previously. For the other tillage operations, random roughness measurements obtained in the present study were in close agreement with values reported by Zobeck & Onstad (1987).

The addition of rainfall may serve to reduce random roughness. To quantify this reduction, a relative random roughness term, *RRR*, was defined by Zobeck & Onstad (1987) as

Table 2.8 Random roughness values for selected tillage operations used to measure roughness coefficients on interrill areas.

Tillage operation	Random roughness* mm	Random roughness (present study) mm
Large offset disk	50	
Moldboard plough	32	32
Lister	25	
Chisel plough	23	21
Disk	18	16
Field cultivator	15	14
Row cultivator	15	
Rotary tillage	15	
Harrow	15	
Anhydrous applicator	13	8
Rod weeder	10	
Planter	10	6
No-till	7	
Smooth surface	6	

*Zobeck & Onstad (1987).

$$RRR = \frac{RR}{RR_o} \tag{2.16}$$

where RR is random roughness of a surface following rainfall, and RR_o is random roughness immediately after tillage. From published data on relative random roughness, Zobeck & Onstad (1987) developed the following equation

$$RRR = 0.89\,e^{-0.026\,cumulative\,rainfall} \tag{2.17}$$

where cumulative rainfall is given in cm. Equations 2.16 & 2.17 can be used to estimate random roughness of a surface following rainfall using information on cumulative rainfall since the last tillage operation.

Roughness coefficient equations

Darcy-Weisbach hydraulic roughness coefficients at varying Reynolds numbers for the moldboard plough and planter treatments are presented in Figure 2.5. The trends presented for the moldboard plough and planter operations are also characteristic of the other experimental treatments. In general, hydraulic roughness coefficients can be seen to decrease with greater Reynolds number.

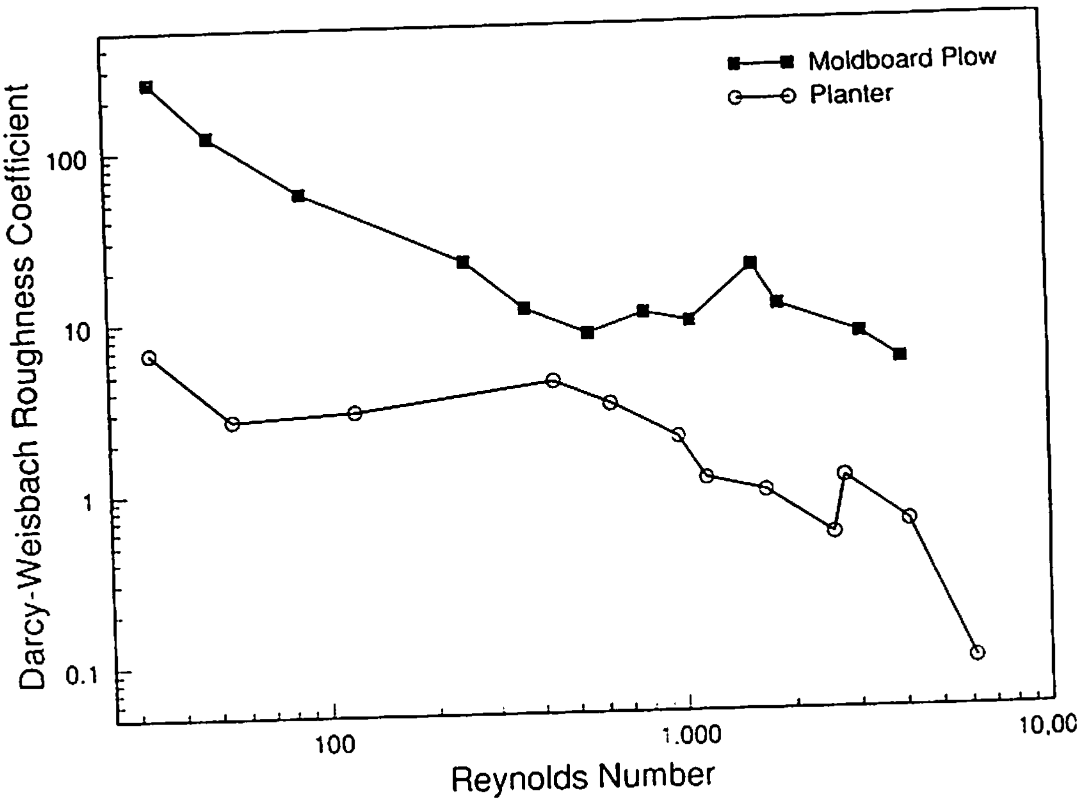

Figure 2.5 Darcy-Weisbach roughness coefficients vs. Reynolds number for selected tillage operations.

The moldboard plough and planter treatments produced the largest and smallest random roughness values, respectively. The largest hydraulic roughness coefficients usually occurred on those plots with the greatest random roughness. The planter treatments with relatively low random roughness values produced the smallest hydraulic roughness coefficients.

Within the same tillage operation, substantial variations in hydraulic roughness coefficients were found. These variations may have been caused by several factors. The range of selected flow rates produced conditions where the heights of the roughness elements were initially greater than and then less than flow depth. Also, as Reynolds number increased, differences in flow patterns sometimes occurred. Finally, transition from laminar to turbulent flow conditions may have resulted during a given test series.

Information from the six tillage treatments was used to derive the following regression equation for estimating roughness coefficients for interrill areas

$$f_{si} = \frac{6.30(RR_o)^{1.75}}{Re^{0.661}} \tag{2.18}$$

where RR_o is given in mm. In deriving Equation 2.18, RR_o values varied from 6 to 32 mm while Reynolds number ranged from 20 to 6000. If rainfall has occurred since the last tillage operation, RR should be substituted for RR_o in Equation 2.18 to obtain the new roughness coefficient. Roughness coefficient values varying from 0.10 to 254 were used in the derivation of Equation 2.18. The relatively large roughness coefficients correspond with small Reynolds numbers. Reynolds number values used in this study were substantially less than those found in some of the other investigations.

Roughness coefficients for plants on cropland areas

Experimental procedures

Cox & Palmer (1948) conducted tests to measure roughness coefficients for alfalfa planted in test channels 0.61 m wide and 30.5 m long. Roughness coefficients for cotton, sorghum and wheat were determined by Ree & Crow (1977) using test channels with a bottom width of 6.1 m and a length of 183 m. In both studies, hydraulic measurements were collected under steady-state conditions. In addition, selected measurements were made to identify plant characteristics.

Roughness coefficient equations

Most of the hydraulic tests were performed at relatively large discharge rates which caused the vegetative materials to become submerged. Few of the tests were run at Reynolds number values which could be considered representative of overland flow conditions. From the available data, a maximum roughness coefficient value of 0.3 was assigned for cotton and sorghum. A maximum roughness coefficient of 3 was estimated for wheat, while alfalfa was assigned a maximum roughness coefficient value of 12. The following equation can be used to estimate the roughness coefficient for plants on cropland areas:

Darcy-Weisbach roughness coefficients

$$f_{st} = \frac{canopy\,height}{maximum\,canopy\,height} f_{stm} \qquad (2.19)$$

where f_{stm} is the maximum value of the roughness coefficient for selected plants on cropland areas. It should be noted that Reynolds number is not included as an independent variable in Equation 2.19.

Equation 2.19 was derived from limited experimental data. Thus, calculated roughness coefficient values should be considered as best estimates. If roughness coefficients are required for other plants on cropland areas, data for the crop reported above that is most like the material under consideration should be used.

Roughness coefficients for rangeland areas

Experimental procedures

A rotating boom rainfall simulator was used to supply rainfall to selected rangeland sites located throughout the western United States (Laflen et al. 1991). Rainfall was applied simultaneously to two plots having dimensions of 3.1 by 10.7 m. During the initial run, rainfall was applied for a 60 min duration at an intensity of approximately 65 mm h^{-1}. A wet run having a 30 min duration occurred approximately 24 h later. A very wet run with varying rainfall intensity and added inflow began about 30 min after completion of the wet run.

An optimization procedure similar to that used by Engman (1986) was employed by Weltz et al. (1992) to identify roughness coefficients for rangeland areas. The requirements for use of this procedure are that: (a) an equilibrium hydrograph must be achieved; (b) the infiltration rate is approximately uniform; and (c) the rainfall rate must be constant until the runoff hydrograph reaches an equilibrium condition.

Roughness coefficient equations

Weltz et al. (1992) used optimization procedures to develop an equation for estimating the roughness coefficient for litter and organic residue on rangelands

$$f_{lt} = 114 r_l^{3.0} \qquad (2.20)$$

where r_l is the fraction of the surface covered with litter and organic residue. Optimization procedures were also used by Weltz et al. (1992) to develop an equation for estimating the friction coefficient for plants on rangeland areas

$$f_{pb} = 39.0C_c^{0.8} + 126B_a^{0.8} \tag{2.21}$$

where C_c and B_a are the fraction of canopy cover and basal plant cover, respectively. Reynolds number is not included as an independent variable in either Equation 2.20 or 2.21.

Future needs for estimating roughness coefficients

Roughness coefficients for plants on croplands are not as well defined as some of the other factors contributing to hydraulic resistance. Additional experimental data for a wide variety of crops are needed. The data should include information on the effects of Reynolds number on roughness coefficients. The prediction equations should also include selected plant characteristics. Generalized equations should be developed which allow roughness coefficients to be estimated for plants not included in the experimental data sets. Many of these concepts are presently incorporated into procedures used in the design of grassed waterways (Temple et al. 1987).

Computer optimization techniques were employed to identify roughness coefficients for rangeland areas. Iteration procedures were used to achieve a best fit to the rising side of the hydrograph, resulting in a single roughness coefficient being identified for a particular site. Consequently, Reynolds number was not included in the regression equations obtained for estimating roughness coefficients for rangeland areas. Field experimental tests should be performed to determine the effects of Reynolds number on roughness coefficients. Again, generalized equations should be developed which relate roughness coefficients to selected characteristics of rangeland plants. Kao & Barfield (1978) related flow resistance parameters to Reynolds number and selected vegetation factors.

The additive property of roughness coefficients has been successfully demonstrated for the components of Equations 2.1 & 2.2. Equations 2.9–2.12 each contain four factors which may contribute to total hydraulic resistance. Procedures used to identify roughness coefficients for each of these components have been developed and tested. However, the ability to add these individual factors to obtain total hydraulic resistance for a particular site has not been verified. Field and laboratory tests should be conducted to determine whether individual roughness coefficients are additive. Measured and calculated roughness coefficients should be compared for a wide variety of surfaces.

Summary and conclusions

Darcy–Weisbach roughness coefficients are used to analyse overland flow. Total hydraulic resistance on a site may be caused by several factors. Equations were identified to estimate roughness coefficients for: (a) rills; (b) gravel and cobble materials; (c) surface residue on croplands; (d) interrill areas; (e) plants on cropland areas; and (f) rangeland areas.

A rainfall simulation study was conducted at 11 sites located throughout the eastern United States to measure rill hydraulic characteristics. Roughness coefficients were calculated from experimental measurements of flow rate, flow velocity and flow width. Regression equations were developed which related roughness coefficients for rills to Reynolds number.

Roughness coefficients for gravel and cobble materials were identified in a laboratory investigation. Selected rates of flow were introduced into a flume in which a given size class of gravel or cobble material had been securely attached. The laboratory data were used to develop regression equations which related roughness coefficients for gravel and cobble materials to surface cover and Reynolds number. The regression relations were tested using hydraulic data collected on surfaces containing a distribution of size classes. Close agreement between predicted and measured roughness coefficients was obtained by adding the roughness contributions of individual size classes.

A laboratory study was also performed to determine roughness coefficients for surface residue on croplands. Roughness coefficients were determined for corn, cotton, peanut, pine needles, sorghum, soybeans, sunflower and wheat residue. Regression equations were developed which related roughness coefficients for residue on croplands to surface cover and Reynolds number.

Roughness coefficients on interrill areas were identified in a field investigation. A random roughness parameter is frequently used to characterize surface microrelief. Six selected tillage operations were performed which produced a range of random roughness parameters. Hydraulic roughness coefficients corresponding with the random roughness parameters were then determined. The experimental data were used to derive regression relationships which related hydraulic roughness coefficients on interrill areas to a random roughness parameter and Reynolds number.

Field studies have been performed to determine roughness coefficients for plants on croplands (Cox & Palmer 1948, Ree & Crow 1977). Roughness coefficient measurements were made for alfalfa, cotton, sorghum and wheat. An equation was presented to relate roughness coefficients for plants on cropland to canopy height.

Roughness coefficients for rangeland areas were identified using data collected during rainfall simulation tests. Optimization techniques were used

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by Weltz et al. (1992) to determine roughness coefficients using the rising side of runoff hydrographs. Regression equations were then identified which related roughness coefficients on rangeland areas to surface cover, canopy cover and basal plant cover.

Roughness coefficients for plants on croplands and rangelands are not as well defined as some of the other factors contributing to hydraulic resistance. Additional experimental data for a wide variety of cropland and rangeland plants are needed. Generalized equations should be developed which relate roughness coefficients to selected plant characteristics and Reynolds number. Our ability to understand and accurately model upland flow hydraulics will improve as additional information on roughness coefficients becomes available.

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Notation

Symbol	Definition	Units
A	cross-sectional flow area	m^2
b	flow width	m
B_a	fraction of basal plant cover on rangeland areas	
C_c	fraction of canopy cover on rangeland areas	
f	Darcy–Weisbach roughness coefficient	
f_b	roughness coefficient associated with bed-form roughness	
f_{cr}	roughness coefficient for surface residue on croplands	
f_g	roughness coefficient associated with grain roughness	
f_i	total roughness coefficient for interrill cropland areas	
f_{ir}	total roughness coefficient for	

	interrill rangeland areas	
f_{lt}	roughness coefficient for litter and organic residue on rangelands	
f_{pb}	roughness coefficient for plants on rangeland areas	
f_r	total roughness coefficient for rills on croplands	
f_{ra}	roughness coefficient associated with rainfall	
f_{rk}	roughness coefficient for gravel and cobble materials	
f_{rr}	total roughness coefficient for rills on rangelands	
f_{si}	roughness coefficient for interrill areas	
f_{sr}	roughness coefficient for rills	
f_{st}	roughness coefficient for plants on cropland areas	
f_{stm}	maximum value of the roughness coefficient for selected plants on cropland areas	
f_{wo}	roughness coefficient without rainfall	
g	acceleration due to gravity	$m\ s^{-2}$
P	wetted perimeter	m
Q	flow rate	$m^3\ s^{-1}$
r_l	fraction of the rill surface covered with litter and organic residue on rangelands	
R	hydraulic radius	m
Re	Reynolds number	
RR	random roughness of a surface following rainfall	m
RR_o	random roughness immediately after tillage	m
RRR	relative random roughness	
s	average slope	
SF	shape factor	
V	mean flow velocity	$m\ s^{-1}$
y	flow depth	m
ν	kinematic viscosity	$m^2\ s^{-1}$

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