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Abstract

Random roughness parameters are used to characterize surface microrelief. In this study, random roughness was determined following six selected tillage operations. Random roughness measurements agreed closely with values reported in the literature.

Surface runoff on upland areas is analyzed using hydraulic roughness coefficients. Darcy-Weisbach and Manning hydraulic roughness coefficients were identified in this investigation on each soil surface where random roughness values were determined. Hydraulic roughness coefficients were obtained from measurements of discharge rate and flow velocity.

The experimental data were used to derive regression relationships which related Darcy-Weisbach and Manning hydraulic roughness coefficients to random roughness and Reynolds number. Random roughness values available in the literature can be substituted into the regression equations to estimate hydraulic roughness coefficients for a wide range of tillage implements. The accurate prediction of hydraulic roughness coefficients will improve our ability to understand and properly model upland flow hydraulics.

Keywords. Hydraulics, Flow, Roughness coefficients, Tillage.

Introduction

Hydraulic roughness coefficients are used to analyze surface runoff on upland areas. Calculation of time of concentration, determination of flow velocity and simulation of runoff hydrographs require the use of hydraulic roughness coefficients. The ability to understand and properly model upland flow hydraulics is also necessary for process-based erosion models.

Frictional drag over the soil surface, standing vegetative material, residue cover and rocks lying on the surface, raindrop impact, and other factors may influence resistance to flow on upland areas. Roughness coefficients caused by each of these factors contribute to total hydraulic resistance. In this study, hydraulic roughness coefficients resulting from tillage-induced surface micro-relief were identified.

Random roughness is used to characterize surface micro-relief. Height measurements were employed in a procedure developed by Allmaras et al. (1967) for calculating random roughness. To reduce the variation among measurements, the effects of slope and oriented tillage tool marks were mathematically removed. The upper and lower 10% of the readings were also eliminated to minimize the effect of erratic height measurements on the final result.

Several other techniques have also been introduced to characterize surface roughness (Luttrell, 1963; Currence and Lovely, 1970; Podmore and Huggins, 1980; Linden and Van Doren, 1986; and Potter et al., 1990). Several of these methods have considerable potential for use in describing surface micro-relief. However, to date, these other techniques have not received wide acceptance.

A description of previous studies involving hydraulic roughness coefficients on agricultural areas was provided by Engman (1986). Hydraulic roughness coefficients were developed from runoff plot data originally collected for erosion studies. Friction factors were presented in a tabular format with a description of various surfaces and land uses.

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

Overland flow resistance for selected types of surface roughness induced by tillage operations was investigated by Sadeghian and Mitchell (1990). Darcy-Weisbach and Manning hydraulic roughness coefficients for both rill and interrill areas were identified. Gilley et al. (1990) measured hydraulic characteristics of rills on several sites located throughout the eastern United States. Regression equations were developed which related Darcy-Weisbach and Manning hydraulic roughness coefficients to Reynolds number.

Laboratory measurements of hydraulic roughness coefficients of surfaces covered with sand or gravel were made by Woo and Brater (1961), Emmett (1970), Phelps (1975), and Savat (1980). Similar tests were conducted under field conditions on natural landscapes by Dunne and Dietrich (1980), Roels (1984), and Abrahams et al. (1986). In most of these studies, hydraulic roughness coefficients decreased with increasing Reynolds number. Once roughness elements are submerged, their influence on

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overland flow is less pronounced as the depth of overland flow becomes greater.

The objective of this investigation was to develop regression equations for estimating hydraulic roughness coefficients using random roughness and Reynolds number as independent variables. Relationships were identified for predicting both Darcy-Weisbach and Manning hydraulic roughness coefficients. The equations were derived using random roughness values varying from 6 to 32 mm, and Reynolds numbers ranging from 20 to 6000.

HYDRAULIC EQUATIONS

The Darcy-Weisbach and Manning equations have been widely used to describe flow characteristics. Both relations contain a hydraulic roughness coefficient. Under uniform flow conditions, the Darcy-Weisbach hydraulic roughness coefficient, f, is given as (Chow, 1959):

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

where
- g = acceleration due to gravity,
- S = average slope,
- V = flow velocity, and
- R = hydraulic radius defined as:

$$R = \frac{A}{P} \qquad (2)$$

where A is cross-sectional flow area and P is wetted perimeter.

The Manning hydraulic roughness coefficient, n, is given as (Chow, 1959):

$$n = \frac{R^{2/3}\,S^{1/2}}{V} \qquad (3)$$

Manning and Darcy-Weisbach hydraulic roughness coefficients can be related using the following equation:

$$n = \left[\frac{f\,R^{1/3}}{8g}\right]^{1/2} \qquad (4)$$

Flow characteristics can also be described using Reynolds number, Rn, which is given as (Chow, 1959):

$$Rn = \frac{V\,R}{\nu} \qquad (5)$$

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

For broad sheet flow conditions where flow width, b, is much greater than flow depth, y, hydraulic radius can be assumed to be approximately equal to flow depth. For these situations:

$$Rn \cong \frac{q}{\nu} \qquad (6)$$

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

$$q = \frac{Q}{b} \qquad (7)$$

The continuity equation for flow is defined as:

$$Q = V\,A \qquad (8)$$

where Q is flow rate. For broad sheet flow, water depth is given as:

$$y = \frac{Q}{V\,b} \qquad (9)$$

In this study, water depth was determined indirectly using equation 9, and measurements of Q, V, and b.

The Chezy equation may also be used to characterize flow. The Chezy hydraulic roughness coefficient, c, is given as:

$$c = \frac{V}{[R\,S]^{1/2}} \qquad (10)$$

The Chezy hydraulic roughness coefficient can be determined directly from the Darcy-Weisbach hydraulic roughness coefficient using the relationship:

$$c = \left[\frac{8\,g}{f}\right]^{1/2} \qquad (11)$$

Information on existing flow characteristics is needed to relate the Manning hydraulic roughness coefficient to either Chezy or Darcy-Weisbach hydraulic roughness coefficients, since:

$$n = \frac{R^{1/6}}{c} \qquad (12)$$

In this study, information is presented to allow expanded use of either the Darcy-Weisbach, Manning or Chezy flow equations on upland areas.

EXPERIMENTAL PROCEDURES

Field tests were conducted at the University of Nebraska Rogers Memorial Farm located in Lancaster County, approximately 18 km east of Lincoln, NE. 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 consisted of two randomized complete blocks, with the first block being located immediately upslope from the second. Each experimental block consisted of six tillage operations performed at random locations within the block. The tillage operations included an anhydrous applicator, chisel plow, disk, field cultivator, moldboard plow, and planter. These implements were chosen to provide a wide range of random roughness conditions.

SITE PREPARATION

Existing wheat residue was first removed from the study area by burning and hand raking. Selected tillage operations were then performed along the contour at the study site. One-meter-square plots were established within each tillage treatment using galvanized sheet metal borders for the top and both sides of the plots. A collection 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 centimeters above the soil surface. The plywood covering prevented weathering of the soil surface.

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-base 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 with a water permeable layer.

RANDOM ROUGHNESS

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 leveled 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 one meter square plot.

FLOW VELOCITY

Following surface stabilization with the latex-base soil stabilizer, flow was added to the top of each plot at twelve rates ranging from approximately 2 to 300 L/min. 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 flourometer and a scale on the instrument 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 inflow rate. The mean of the five readings was used to calculate flow velocity at a particular inflow rate. Calculated flow velocities were used to determined flow depths and corresponding hydraulic roughness coefficients. Additional details concerning experimental procedures are given by Finkner (1988).

RESULTS AND DISCUSSION

Random roughness values were first identified for each of six selected tillage operations. Darcy-Weisbach and Manning hydraulic roughness coefficients were then measured on each of the soil surfaces where random roughness values were obtained. Independent variables influencing hydraulic roughness coefficients were determined. Finally, regression equations were developed for estimating Darcy-Weisbach and Manning hydraulic roughness coefficients from values of random roughness and Reynolds number.

RANDOM ROUGHNESS

Random roughness was calculated using the procedure outlined by Allmaras et al. (1967). Table 1 presents random roughness measurements obtained in the present study, and values reported by Zobeck and 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 plow treatment.

TABLE 1. Random roughness values for selected tillage operations

Tillage Operation	Random Roughness* mm	Random Roughness (Present Study) mm
Large offset disk	50	
Moldboard plow	32	32
Lister	25	
Chisel plow	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, T. M. and C. A. Onstad (1987).

The random roughness values shown in Table 1 represent best estimates for a particular tillage operation. Differences in soil texture, water content at time of tillage, or tillage depth may affect surface conditions. In addition, variations in the physical characteristics of the tillage implements may result in different random roughness values.

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 previously reported. For the other tillage operations, random roughness measurements obtained in the present study were in close agreement with values reported by Zobeck and 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 and Onstad (1987) as:

$$RRR = \frac{RR}{RR_o} \tag{13}$$

where RR is the random roughness of a surface following rainfall, and RR_0 is random roughness immediately after tillage. From published data on relative random roughness, Zobeck and Onstad (1987) developed the following equation:

$$RRR = 0.89\, e^{-0.026 \text{ cumulative rainfall}} \tag{14}$$

where cumulative rainfall is given in centimeters. Equations 13 and 14 can be used to estimate random roughness of a surface following rainfall from information on cumulative rainfall since the last tillage operation.

Independent Variables Influencing Hydraulic Roughness Coefficients

Three criteria were established for the model equations used to predict hydraulic roughness coefficients. The equations should be simple and easily solved using the fewest number of independent variables necessary to obtain reasonable results. The independent variables should be generalized, and applicable to conditions beyond those found in the present study. Finally, the independent variables used in the relationships should be easily identified at other locations.

Variables which could significantly affect hydraulic roughness coefficients included random roughness, Reynolds number, slope, type of implement operation, and hydraulic radius. However, not all of these variables would serve as useful, generalized predictors. No common basis existed for relating the six tillage implements to other machinery. Therefore, the type of implement operation would not serve as a desirable generalized independent variable.

Including hydraulic radius in the model equation would require an iterative procedure to solve the prediction equations. An iterative solution would be more time consuming and difficult to solve, and could introduce difficulties with convergence. Thus, hydraulic radius was also eliminated from the analysis.

Random roughness, Reynolds number, and slope were retained as possible predictors. In an analogy to pipe flow, random roughness provided a measure of the physical roughness of the flow boundary and Reynolds number furnished a flow property. Bed slope was included because it has previously been found to influence hydraulic roughness coefficients (Issard, 1944; Emmett, 1970; and Yoon, 1970).

A simple multiplicative relationship which included random roughness, Reynolds number, and slope as independent variables was tested. The effect of adding each of these three variables into the prediction equations was evaluated using multiple linear regression analysis. Only random roughness and Reynolds number were found to be significant at the 0.10 probability level. Therefore, only these two variables were considered in subsequent analyses.

Darcy-Weisbach Hydraulic Roughness Coefficients

Darcy-Weisbach hydraulic roughness coefficients at varying Reynolds numbers for the moldboard plow and planter treatments are presented in figure 1. The trends presented for the moldboard plow 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.

The moldboard plow 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. Roughness elements were sometimes larger than water depth. As Reynolds number increased, variations in flow patterns sometimes occurred. In addition, 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 Darcy-Weisbach hydraulic roughness coefficients:

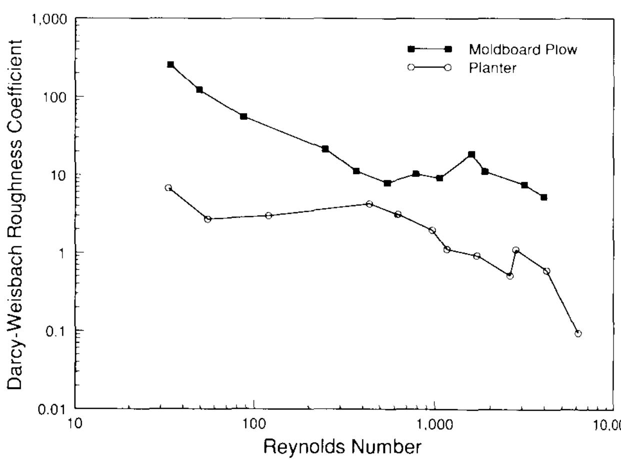

Figure 1–Darcy-Weisbach roughness coefficients vs. Reynolds number for selected tillage operations.

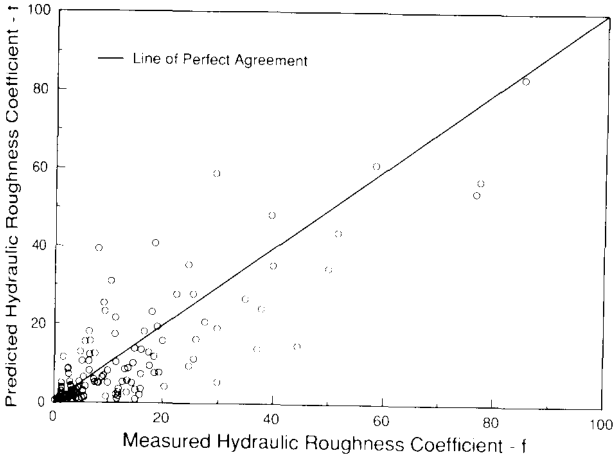

Figure 2–Predicted vs. measured Darcy-Weisbach hydraulic roughness coefficients.

$$f = \frac{6.30\ RR_0^{1.75}}{Rn^{0.661}} \qquad (15)$$

for RR_0 given in mm. In deriving equation 15, RR_0 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 after rainfall should be substituted for RR_0 in equation 15 to obtain the new Darcy-Weisbach roughness coefficient.

The experimental data was used to test the reliability of equation 15 for use in estimating hydraulic roughness coefficients. Predicted versus measured Darcy-Weisbach hydraulic roughness coefficients for roughness coefficient values less than 100 are shown in figure 2. Linear regression analysis of predicted versus measured hydraulic roughness coefficients yielded a coefficient of determination, r^2, value of 0.898.

Many of the hydraulic roughness coefficients shown in figure 2 are relatively small. It can be seen from figure 1 and equation 15 that hydraulic roughness coefficients vary inversely with Reynolds number. Thus, as flow rate increases, hydraulic roughness coefficients rapidly decrease, even for those tillage treatments with relatively large random roughness values.

Manning Hydraulic Roughness Coefficients

Figure 3 presents Manning hydraulic roughness coefficients as a function of Reynolds number for the moldboard plow and planter treatments. The shape of the curves shown in figures 1 and 3 are similar. Hydraulic roughness coefficients can again be seen to generally decrease with greater Reynolds number. Surfaces with the largest random roughness values usually had the greatest hydraulic roughness coefficients.

The following regression equation for predicting Manning hydraulic roughness coefficients was obtained using data from the six tillage treatments:

$$n = \frac{0.172\ RR_0^{\ 0.742}}{Rn^{0.282}} \qquad (16)$$

where RR_0 is given in mm. In deriving equation 16, RR_0 values ranged from 6 to 32 mm while Reynolds number varied from 20 to 6000. When estimating Manning hydraulic roughness coefficients, the random roughness after rainfall term, RR, should be substituted for RR_0 in equation 16 if rainfall has occurred since the last tillage operation. It is important to remember that equations 15 and 16 should only be used within the range of values for which they were derived.

The reliability of equation 16 for use in estimating hydraulic roughness coefficients was evaluated. Figure 4 shows predicted versus measured Manning hydraulic roughness coefficients. A coefficient of determination, r^2, value of 0.727 resulted from linear regression analysis of predicted versus measured hydraulic roughness coefficients.

Summary and Conclusions

Analysis of surface runoff on upland areas requires identification of hydraulic roughness coefficients. Total hydraulic roughness on a site is usually a composite of roughness coefficients caused by several factors. In this investigation, hydraulic roughness coefficients induced by surface microrelief were examined.

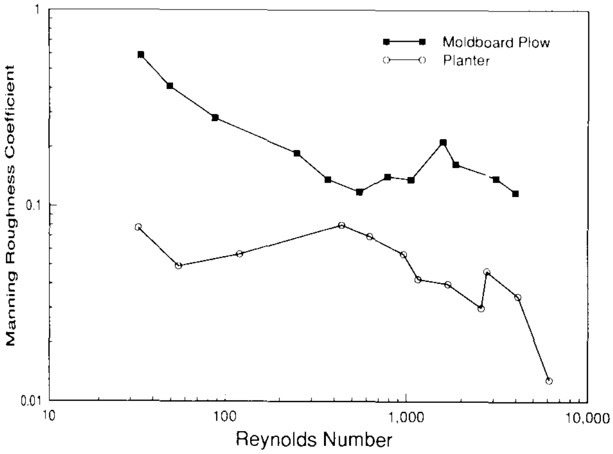

Figure 3–Manning roughness coefficients vs. Reynolds number for selected tillage operations.

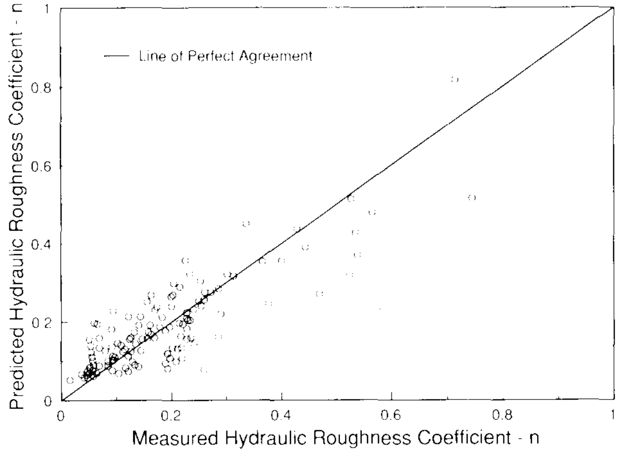

Figure 4–Predicted vs. measured Manning hydraulic roughness coefficients.

Random roughness is calculated from surface elevation measurements. Information exists in the literature for relating random roughness values to single and multiple tillage operations. If cumulative rainfall since the last tillage operation is known, the reduction in random roughness caused by precipitation can also be estimated.

A field study was conducted to identify random roughness and corresponding hydraulic roughness coefficients over a wide range of conditions. Random roughness measurements were made following six tillage operations performed on initially smooth soil surfaces. Random roughness measurements were found to be similar to previously reported values.

Following measurement of random roughness, plot surfaces were stabilized using a biodegradable, latex-base material. Steady uniform flow conditions were then established for a wide variety of discharge rates. From measurements of discharge rate and flow velocity, Darcy-Weisbach and Manning hydraulic roughness coefficients were calculated.

Multiple linear regression analysis was used to identify the independent variables influencing hydraulic roughness coefficients. Hydraulic roughness coefficients were found to be significantly affected by random roughness and Reynolds number. The field data were used to obtain regression relationships which related Darcy-Weisbach and Manning hydraulic roughness coefficients to random roughness and Reynolds number. The regression relationships can be used for random roughness values varying from 6 to 32 mm, and Reynolds numbers ranging from 20 to 6000.

Several factors may contribute to total hydraulic resistance on a given upland site. Information is needed on hydraulic roughness coefficients provided by each of these factors, their contribution to total hydraulic roughness, and the effect of flow rate on hydraulic roughness coefficients. The accurate prediction of hydraulic roughness coefficients will improve our ability to understand and properly model upland flow hydraulics.

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Symbols

A = cross-sectional flow area
b = flow width
c = Chezy roughness coefficient
f = Darcy-Weisbach roughness coefficient
g = acceleration due to gravity
n = Manning roughness coefficient
P = wetted perimeter
q = flow rate / unit width
Q = flow rate
R = hydraulic radius
Rn = Reynolds number

RR = random roughness of a surface following rainfall
RR_o = random roughness immediately after tillage
RRR = relative random roughness
S = average slope
V = flow velocity
y = flow depth
ν = kinematic viscosity