Hydraulic Roughness Coefficients for Native Rangelands

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Abstract: A subfactor-based regression technique for estimating hydraulic roughness coefficients for shallow overland flow was developed from simulated rainfall/runoff plots originally collected for erosion studies. The data were collected from 14 different native rangeland areas in the western United States. Rainfall was applied at a constant intensity of 65 mm/hr from a rotating-boom rainfall simulator. Surfaces evaluated ranged from smooth bare soil to gravelly bare soil and sparsely to densely vegetated rangeland areas. A reference table of "effective roughness" coefficients for shallow overland flow is presented with a description of site characteristics. The derived roughness regression equations predict an "effective Darcy-Wiesbach roughness coefficient" for native rangeland ($r^2 = 0.70$) that incorporates the effect of raindrop impact, soil texture, random roughness, rocks, litter, and canopy and basal plant cover. The sites evaluated in the paper covered a wide range of vegetation types and included short-, mid-, and tallgrass prairies; desert shrubs and sagebrush; and oak and pinyon-juniper woodlands. No trend in effective roughness coefficient associated with type of vegetation (grass or shrub) or soil texture was apparent.

Introduction

In arid and semiarid rangelands, the characteristics of overland flow on hillslopes are difficult to observe and measure (Chow 1964). The generation of overland flow on rangeland hillslopes goes through several stages: (1) Soil surface becomes saturated; (2) depressional storage areas are filled; (3) concentrated flow begins through small preexisting flow paths; (4) the small flow paths overtop and converge to form shallow sheet flow; and (5) once precipitation ceases, sheet flow is reduced and overland flow is reconcentrated in the preexisting flow paths. After further drainage the water is left in the depressional storage areas to evaporate or infiltrate (Chow 1964).

On rangelands, overland flow is a combination of sheet flow and concentrated flow diverging and converging around surface microtopographic relief, vegetation, and rocks (Emmett 1970; Abrahams et al. 1986). Because of the converging and diverging flow paths, the characteristics of velocity and depth of overland flow are difficult to quantify. Accurately estimating overland flow hydraulic parameters is important for directly calculating overland flow velocities, calculating time of concentration, and routing of surface runoff hydrographs, and in calculating shear stress. The development of process-based erosion models also depends upon the ability to understand and model overland flow hydraulics.

Hydraulic roughness and overland flow velocities for rangelands are dif-

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ficult to measure and to generalize about because of the variability in ground surface cover, microtopography, soils, and the complex geometric shape of the concentrated-flow paths. Hydraulic roughness values change for similar vegetation and rock cover depending on rigidity of the vegetation and the degree of submergence by the flow (Foster et al. 1980; Roels 1984; Abrahams et al. 1986).

Barnes (1967) presented photographs, graphs, and tables for estimating roughness coefficients for channels and streams. Few researchers have estimated roughness coefficients for overland flow from grasslands, shrub-dominated lands, and woodlands (Woolhiser 1975; Foster et al. 1980; Roels 1984; Engman 1986). These researchers reported a variability in hydraulic roughness coefficients of greater than 10-fold for native rangeland vegetation types or land treatments. Roels (1984) reported that the resistance coefficient varied considerably, and that they were a function of bed slope, percent rock cover, and the type of rock cover (protruding stones or smooth flat stones). The hydraulic roughness coefficients Roels reported were a lumped-term coefficient, which did not separate the influence of microtopographic roughness, vegetation, or rocks. A further complication in the literature is that descriptions of the landscape and vegetation community are usually vague, leading to great difficulty in selecting the appropriate hydraulic roughness coefficient for new locations. None of the aforementioned researchers estimated the changes in hydraulic roughness as a function of management practice or seasonal changes in standing vegetation and litter for rangelands.

Abrahams et al. (1986) were unsuccessful in relating hydraulic roughness to the surface's morphological features, vegetation, and rock cover. They concluded that this does not mean that hydraulic roughness is not related to vegetative and morphological features, rather that it is a very complex interaction that needs further study.

We propose that hydraulic roughness for rangelands be estimated as an "effective Darcy-Weisbach friction factor" (f_e). Development of (1) is an expansion of Graf's (1971) equation used to express drag due to grain resistance and form resistance in channel flow. The advantage of using f over the more commonly used Manning's n or Chezy's C is that it is dimensionless and applies to all states of flow (Abrahams et al. 1986). The f_e would include the effects of raindrop impact and the mixture of sheet and concentrated flow over obstructions such as rocks, litter, stems, and microtopographic features. We propose that f_e for a hillslope could be estimated by a subfactor approach [(1)]. A subfactor approach would allow for feedback mechanisms between land use and discharge to be incorporated into physically based continuous hydrologic simulation models, and improving estimation of runoff and soil loss. The Darcy-Weisbach effective friction factor, or coefficient, is defined as

$$f_e = f_{rs} + f_{rr} + f_{gc} + f_{pb} \qquad (1)$$

where f_{rs} = friction factor associated with grain roughness of the soil and is a function of soil texture; f_{rr} = friction factor associated with microtopographic features and can be expressed as a function of random roughness indices; f_{gc} = friction factor associated with ground surface cover (i.e., rocks, litter, and organic residue); and f_{pb} = friction factor attributed to standing vegetation.

For this study, runoff hydrographs from erosion plots with simple slope configurations, and uniform simulated rainfall rates applied at 65 mm/hr were analyzed. The data were selected from "wet" and "very wet" run equilibrium hydrographs where the infiltration rate on the rising limb of the hydrograph was considered nearly constant. The objective of the study was to develop a subfactor approach based on regression equations for predicting f_e for overland flow on rangelands. Criteria in the development of the regression equations were that they account for variability in f_e attributed to vegetation, soil surface conditions, and land use.

Materials and Methods

Data used in this paper were collected from 14 vegetation communities with differing soils properties (Table 1) from across the western United States (Fig. 1) as part of the USDA Water Erosion Prediction Project (WEPP). Detailed site description and sampling procedures are described by Simanton et al. (1987, 1991). Plot treatments consisted of natural vegetation, clipped (standing biomass clipped to 20 mm height and all clippings

TABLE 1. Hydraulic Roughness Field Site Location Codes and Average Surface Characteristics for Native Rangelands (Location of Field Sites Shown in Fig. 1)

Site (1)	Vegetation type (2)	Soil surface texture (3)	Canopy cover (%) (4)	Ground cover (%) (5)	Random roughness (mm) (6)	Slope (%) (7)
		(*a*) Shrublands				
1	Chihuahuan Desert	Gravelly sandy loam	32.2	82.7	20	10.3
2	Mohave Desert	Fine sandy loam	23.4	37.1	15	8.9
3	Salt Desert	Silty clay	10.6	42.1	—[a]	10.4
4	Sagebrush	Gravelly sandy loam	27.0	84.3	22	12.9
		(*b*) Grass Interspace within				
5	Oak savanna	Cobbly clay	31.6	84.5	—[a]	8.0
6	Pinyon-juniper	Fine sandy loam	27.4	71.1	16	6.5
		(*c*) Grasslands				
7	Chihuahuan Desert grassland	Sandy clay loam	30.5	39.3	15	4.2
8	Shortgrass prairie	Fine sandy loam	28.0	61.7	20	6.6
9	Shortgrass prairie	Silty clay	31.2	63.0	15	8.0
10	Mixed-grass prairie	Clay	36.5	78.6	12	12.1
11	Mixed-grass prairie	Sandy loam	33.8	56.5	9	4.5
12	Mixed-grass prairie	Loam	42.3	46.4	13	6.2
13	Mixed-grass prairie	Loam	23.1	81.3	—[a]	9.9
14	Tallgrass prairie	Loam	64.5	90.0	8	5.0

[a]Not applicable

FIG. 1. Location of Water Erosion Prediction Project (WEPP) Rangeland Field Experiments

removed), and bare (standing biomass clipped to ground surface and all rocks, litter, and root crowns removed with minimal soil disturbance).

Natural, or undisturbed, treatment data were used to develop runoff and infiltration relationships among types and degrees of vegetation and ground surface cover. The clipped treatment data were used to separate the effect of canopy cover from ground surface cover conditions. The bare plots were designed to be the standard treatment among sites to determine soil-property and microtopographic roughness relationships. The bare treatment formed the basic unit for intersite comparisons. The treatments were arranged in pairs so that two treatments were evaluated simultaneously.

The rainfall simulator used was a rotating boom type developed by Swanson (1965). The simulator is trailer mounted and has 10 7.6 m long booms radiating from a central stem. The nozzles spray downward from an average height of 3 m, move in a circular direction over the plots, and apply rainfall intensities of approximately 65mm/hr. Intermittent rainfall pulses are produced as the booms pass over the plots, with raindrop impact energies approximately 77% of natural rainfall.

Rainfall simulation plots were 3.05 m wide by 10.70 m long, with the long axis parallel to the slope. At the downslope end of the plot a 0.20 m deep sheet metal cutoff wall was installed, with the sill plate flush with the soil surface. Runoff was diverted into a measuring flume by troughs mounted below the sill plate. Runoff from each plot was measured with a precalibrated runoff measuring flume. Flow depths were continuously recorded using a pressure-transducer bubbler system. Continuous hydrographs were produced using the flume's depth/discharge rating tables.

The simulated rainfall sequence used was a "dry" run (60 min at 65 mm/

hr at ambient soil moisture conditions). Approximately 24 hr later a "wet" run was made (30 min at 65 mm/hr), and a "very wet" run (20 min at 65 mm/hr) was made. The very wet run was applied when no surface water was evident on the plot by visual inspection (approximately 30 min after the end of the wet run). Hydrographs from the wet and very wet rainfall simulation runs were used in this analysis.

Vegetation composition by life-form, canopy cover, and ground surface cover were characterized for each plot by using a vertical 49-pin point frame before and after treating each plot. Ten permanent transects were established on each plot, for a total of 490 points. Percent cover was calculated as the number of hits divided by total observations. Canopy cover was determined as the first aerial contact of vegetation as the pin was lowered to the soil surface. Ground surface cover characteristics included: bare ground, rocks, litter, and basal plant cover. During characterization, an elevated metal walkway was placed across the plot to prevent soil and plant disturbance.

Microtopography (random roughness) was determined for each plot before the dry run and after the very wet run. Random roughness was determined by using a vertical 21-pin point frame. A graduated scale attached to the back of the frame was used to determine variations in pin heights. Ten transects were taken horizontally across the plot along the same transects used for cover for a total of 210 topographic readings. The standard deviation of pin height (mm) was used as the index of random roughness (Kincaid and Williams 1966).

Overland flow is a combination of sheet and concentrated flow, and has been termed "mixed flow" by Horton (1945) and "composite flow" by Abrahams et al. (1986). Overland flow can be laminar, turbulent, or transitional over very short distances depending on bed slope, and type and density of surface cover (Roels 1984; Abrahams et al. 1986). The point of transition from laminar to turbulent flow on rangelands is not well defined. The relationship of flow state and depth is a complex interaction of several processes. The first is the progressive inundation of roughness elements and the increase in their wetted upstream projected area as flow rate increases. The second is the progressive increase in the depth of flow over already submerged roughness elements as flow rates increase. The actual relationship between friction factors and the type and depth of flow depends upon which process dominates (Abrahams et al. 1986). Roels (1984) found that flow was either transitional or turbulent at low Reynolds number (R 100) on rangelands. Engman (1986) determined that assuming overland flow was turbulent did not adversely affect the prediction of friction coefficients on natural terrain. Based on this work the type of flow was assumed to be turbulent flow for all times and places for this study.

An optimization technique utilizing the kinematic wave equations was used to fit the rising limb of the calculated hydrograph to the measured hydrograph and to estimate the friction coefficient (Engman 1986). For most field situations the kinematic wave formulation is a good approximation to describe overland flow conditions (Woolhiser and Liggett 1967; Morris and Woolhiser 1980). To use this approach, constant rainfall and steady-state infiltration rates were assumed. Other inputs required are the slope steepness (%), width (m), and length (m) of the overland flow plane, and an initial friction factor estimate.

Steady-state infiltration rates were calculated when runoff rate was constant as

$$F_c = Pt_i - Qt_i - D \quad (2)$$

where F_c = cummulative infiltration for a given time interval (m); Pt = cummulative rainfall applied to the plot for a given time interval; Qt_i = cummulative runoff volume for the time interval; and D = detention storage (amount of water retained on the surface without causing runoff).

Overland flow can be described as one-dimensional flow in which the flux is proportional to some power of the storage per unit area (Woolhiser et al. 1990). The uniform flow conditions were solved by using the single-parameter Darcy-Weisbach, Manning, or Chezy equations (Table 2). The Darcy-Weisbach equation is

$$q = \left(\frac{8g}{f}\right)^{1/2} S^{1/2} h^{1/2} \quad (3)$$

where q = rate of runoff; S = slope of the overland flow plane; h = depth of flow; f = Darcy-Weisbach friction coefficient; and g = acceleration due to gravity (Chow 1959).

The Manning and Chezy hydraulic roughness equations were also evaluated to identify flow characteristics. The Manning and Chezy hydraulic roughness coefficients, n and C, respectively, are related to Darcy-Weisbach friction coefficient (Chow 1959) as

$$n = \left(\frac{f}{8g}\right)^{1/2} h^{1/6} \quad (4)$$

TABLE 2. Mean Optimized Effective Manning's n (s/m$^{1/3}$), Chezy C (m$^{1/2}$/s), Darcy-Weisbach f_e Friction Factors, and Flow Depths (mm) for Native Rangelands

Site (1)	Vegetation type (2)	Manning's n (3)	Chezy C (4)	Darcy-Weisbach f_e (5)	Flow depth (6)
	(*a*) Shrublands				
1	Chihuahuan Desert	0.15	3.99	16.17	1.3
2	Mohave Desert	0.09	6.66	5.80	1.6
3	Salt Desert	0.47	1.55	107.62	4.1
4	Sagebrush	0.2	1.16	58.41	1.1
	(*b*) Grass Interspace within				
5	Oak savanna	0.40	1.86	74.21	4.7
6	Pinyon-juniper	0.44	0.93	91.31	4.9
	(*c*) Grasslands				
7	Chihuahuan Desert	0.53	0.83	114.16	7.5
8	Shortgrass prairie	0.56	0.76	135.91	5.9
9	Shortgrass prairie	0.40	1.00	78.59	3.9
10	Mixed-grass prairie	0.22	1.79	24.44	3.9
11	Mixed-grass prairie	0.29	1.27	48.65	2.5
12	Mixed-grass prairie	0.52	0.76	135.28	4.0
13	Mixed-grass prairie	0.56	0.75	141.26	5.3
14	Tallgrass prairie	0.54	0.76	136.53	4.6

$$C = \left(\frac{8g}{f}\right)^{1/2} \quad \text{(5)}$$

The second governing equation for overland flow is the continuity equation, which can be expressed as

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i \quad \text{(6)}$$

where i = applied precipitation minus infiltration. The Darcy-Weisbach and the continuity equations were rewritten in their finite-difference form using the kinematic wave equation for a single plane and solved for q, by the Newton-Raphson technique. The kinematic equation for a single plane can be expressed as

$$Q = \frac{\partial h}{\partial t} + \frac{\partial Q}{\partial y} = q \quad \text{(7)}$$

for Manning's hydraulic resistances $Q = \alpha h^m$; and $\alpha = (1.49\ S^{1/2})/n$; and $m = 5/3$ (Woolhiser et al. 1990).

An optimization program developed by Engman (1986) was used to calculate a hydrograph with an assumed f under turbulent flow conditions for all times and places over the overland flow plane. The initial friction coefficients were estimated from Engman's (1986) Manning's n coefficients and converted to f with (4) for rangelands. The program optimized for f by minimizing the difference between corresponding runoff rates on the measured and the calculated hydrograph. The objective function chosen was the least-square difference U between the measured and calculated hydrograph; U is defined as

$$U = \min \Sigma\ (q_o - q_c)^2 \quad \text{(8)}$$

where q_o = observed flow rate; and q_c = simulated flow rate. The optimization program was run in an iterative process in which f was systematically altered until the minimum value of U was found. The best-fit f-value was taken as the friction coefficient for the runoff plot. This effective friction coefficient is a lumped term, and it implicitly encompasses random roughness, oriented roughness, raindrop impact, standing biomass, and grain roughness for differing soils, rocks, and other ground surface components.

Results and Comment

The results of the analysis for total f from the optimized kinematic procedure are listed in Table 2. Direct comparisons with Manning's n coefficients reported by others could not be made until f was transformed to Manning's n. The transformation required estimated flow depths. Estimated flow depths for the different sites evaluated ranged from 1 mm to 12 mm. The mean flow depth across all sites was 4 mm. To compare results reported here to those reported by others, the mean flow depth for each site was used to transform f to Manning's n. The various sites were classified by type and density of vegetation, and the results are listed in Table 3.

Manning's n-values reported here are slightly higher than reported by others for the Chihuahuan Desert and shortgrass prairie vegetation types (Table 3). No specific reason for the higher estimated roughness coefficients was apparent. The reason for the higher roughness coefficients is probably

TABLE 3. Estimated Manning's *n* Roughness Coefficients for Shallow Overland Flow on Native Rangelands and Pastures

Soil texture/vegetation type (1)	Residue/ litter (kg/ha) (2)	Standing biomass (kg/ha) (3)	Value recom- mended (4)	Range (5)
Bare Soil				
Sand[a,b]	—	—	0.01	0.01–0.016
Loam	—	—	0.037	—
Clay-loam	—	—	0.041	—
Clay-loam[a] (eroded)	—	—	0.02	0.012–0.033
Silt	—	—	0.043	—
Clay	—	—	0.048	—
Gravel surface[a]	—	—	0.02	0.012–0.03
Shrublands				
Chihuahuan Desert[h]	—	—	—	0.03–0.20
Chihuahuan Desert	10	770	0.25	0.11–0.29
Chihuahuan Desert[c]	—	—	0.13	0.01–0.32
Mohave Desert	0	490	0.15	0.14–0.16
Salt Desert	2,000	1,580	0.62	0.52–1.00
Sagebrush	2,850	3,950	0.48	—
Sagebrush[d]	—	—	0.51	0.01–2.60
Oak savanna	2,460	1,450	0.40	0.30–0.52
Pinyon-juniper	1,380	420	0.44	0.31–0.56
Native Grasslands				
Desert	460	750	0.64	—
Shortgrass prairie	280	620	0.42	0.15–0.73
Shortgrass prairie[a]	—	—	0.15	0.10–0.20
Mixed-grass prairie	1,041	1,620	0.52	0.31–0.78
Tallgrass prairie	2,800	3,080	0.79	0.16–0.97
Tallgrass prairie[f] (burned)	—	—	0.23	0.19–0.29
Pasture				
Bermuda grass[g]	—	—	0.41	0.30–0.48
Bluegrass sod[c]	—	—	0.45	0.39–0.65
Grassed wasterways				
Tallgrasses[e]	—	—	0.60	0.45–0.75

[a]From Woolhiser (1975).
[b]From Foster et al. (1980).
[c]From Engman (1986).
[d]From Emmett (1970).
[e]From Ree (1977).
[f]From Duell (1990).
[g]From Palmer (1946).
[h]From Abrahams et al. (1986).

the result of differences in flow depths, standing biomass, and ground cover. The friction coefficients reported here were within the range reported for other rangeland vegetation communities.

Hydraulic roughness for overland flow can be partitioned into two parts, one part that is the result of exposed bare soil and another part that is the result of litter, rocks, and other ground surface cover. A subfactor method is proposed here to estimate the portion hydraulic friction (f_e) associated with bare soil and the portion associated with random roughness, rocks, litter, and standing vegetation. This method is appropriate for use in physically based, distributed hydrologic models that reflect physical features of the plots. The equations presented here should improve surface runoff routing over flow planes and calculations of shear stress for erosion models on rangelands.

To reduce the uncertainties of selecting appropriate hydrologic roughness values, a subfactor regression equation was developed. Three plot treatments (bare soil, clipped vegetation, and natural vegetation) were used to disaggregate the effect of soil texture and the other components of friction from the total f_e found with the optimization program. All the plots in which canopy cover and ground cover were less than 0.05% were used to determine the portion of f_e associated with soil texture and the portion associated with random roughness (mm). The f_e for the bare soils was calculated as

$$f_e = f_{rs} + f_{rr} \qquad (9)$$

where f_{rs} = friction coefficient for bare soil; and f_{rr} = friction attributed to random roughness.

The portion of f_e for bare, smooth soil was based on the work of Gilley et al. (1989). There was a positive relationship between f_e and clay content. The corresponding increase in f_e with an increase in clay content was attributed to differences in aggregate size. Soils with higher clay content were more cloddy and had larger aggregates than sandy soils. The friction coefficient for grain roughness of the soil texture was calculated as

$$f_{rs} = \left(\frac{3.42^{\text{clay}}}{12.42^{\text{sand}}}\right)^{1/2} \qquad (10)$$

where clay and sand = fractions of these components.

The equation used to estimate the friction coefficient associated with random roughness (f_{rr}) was based on the work by Foster et al. (1980), and is given as

$$f_{rr} = \beta(1.0 - e^{-0.773Rr}) \qquad (11)$$

where Rr = random roughness of the overland flow plane; and β = a fitting coefficient. The portion of f_e associated with random roughness for bare soil was found by subtraction after rearrangement of (9). This residual friction was then used to determine the β-coefficient with linear regression analysis (β = 22.76). A significant correlation was found between predicted f_e and optimized f coefficient (r^2 = 0.55) for the bare soil (Fig. 2). The poor correlation in predicting f_e for the bare soil was attributed to the exposure of roots and rocks during the rainfall-simulation event. No method was found that accounted for the change in hydraulic roughness during the rainfall-simulation event associated with changes in percent roots and rocks on the soil surface.

Once the friction coefficients associated with soil texture and random roughness were determined for each site, the influence of ground surface cover was estimated from the clipped plots. Total f_e for the clipped plots can be expressed as

$$f_e = f_{rs} + f_{rr} + f_{gc} \qquad (12)$$

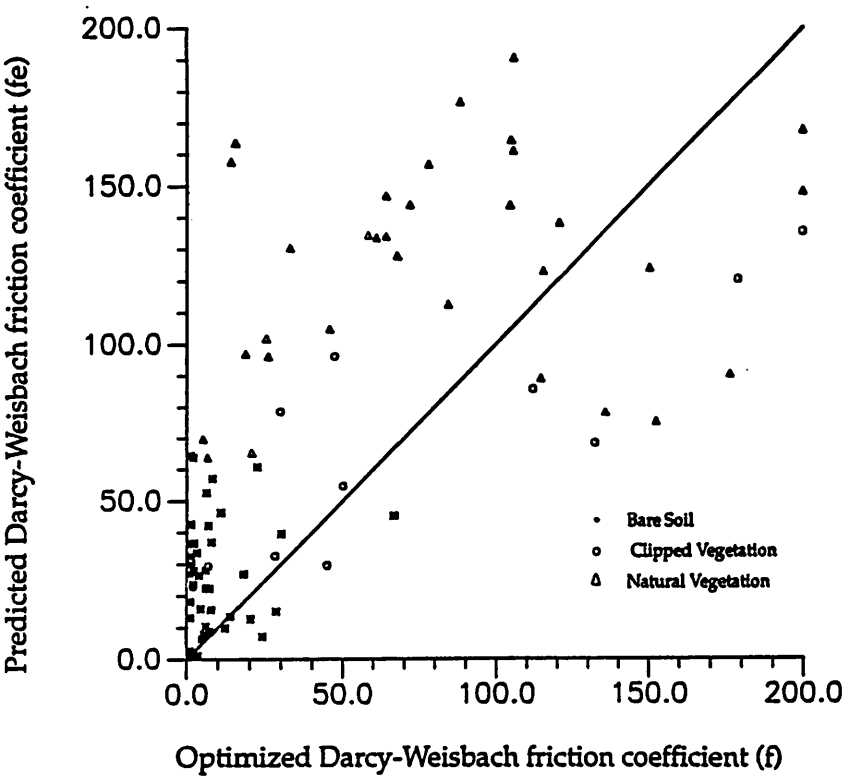

FIG. 2. Optimized versus Predicted Darcy-Weisbach Friction Coefficient for Native Rangelands

where f_{rs} and f_{rr} are as described earlier. The roughness coefficient for rocks, litter, and organic residue on the soil surface is f_{gc}.

$$f_{gc} = f_{rk} + f_{lt} \quad \text{(13)}$$

where f_{rk} = friction coefficient associated with gravel, rocks, and stones; and f_{lt} = friction associated with litter and organic residue on the overland plane. Several of the sites used for this study were devoid of surface rocks. We stratified the clipped plots based on presence or absence of rocks to estimate the friction associated with litter and root crowns and friction associated with rocks. We first estimated friction associated with grain roughness and random roughness with (10) and (11), respectively, for all sites. We then subtracted the friction associated with grain and random roughness from total f (estimated from the optimization technique) on the runoff plots without rocks. The residual friction was used to estimate friction associated with litter and root crowns. Linear, multiple, and nonlinear regression equations utilizing litter, basal, and canopy cover (expressed as a fraction), leaf area index, and standing, root, and litter biomass (g/m^2) to predict hydraulic friction were evaluated. The best predictive equation (based on highest r^2) for the friction associated with litter and root crowns was

$$f_{lt} = 113.73Rl^3 \qquad (14)$$

where Rl = fraction (0 to 1.0) of the overland flow plane surface covered by nonmoveable litter and other organic debris ($r^2 = 0.85$). We were unable to directly calculate a separate friction coefficient for root crowns left after clipping the vegetation. Friction associated with root crowns was lumped with other organic residue on the soil surface. The model does not account for the fraction of litter that is detached and transported by overland flow. The approach used here assumed that litter was immoveable, and we did not try to estimate the formation or destruction of litter debris dams.

Friction associated with rocks was estimated in a manner similar to that used for litter. We first estimated the friction associated with grain and random roughness and litter on the clipped plots and subtracted that from total f. The regression equation for the friction coefficient for rocks and erosion pavement on the soil surface was estimated as

$$f_{rk} = 1.85Rk \qquad (15)$$

where Rk = fraction (0 to 1.0) of the soil surface covered by gravel, rocks, and stones ($r^2 = 0.85$).

The estimated friction attributed to rock is lower than that attributed to other subfactors. The relationship between the subfactors and total f_e is a complex interaction of several processes. The disaggregation approach utilized here assumes that the subfactors are independent of each other. This is not the case. The relatively small friction associated with rocks is partially the results of interactions with f_{rr}. A portion of the friction from rocks is accounted for in the random roughness term. The method of measuring random roughness lumps variation in heights associated with coppice dunes and soil aggregates with that associated with protruding rocks. A second factor is that there is a critical density of rocks with a maximum friction. A further increase in rocks creates interference of the wakes, which tends to decrease the friction (Roels 1984). Because of the complex interactions and interdependence of the subfactor, caution should be exercised in trying to substitute equations developed from other studies for a particular factor into these equations.

The natural plots were used to estimate the friction coefficient associated with standing vegetation using the residual approach employed for the clipped plots. We first estimated the friction associated with grain and random roughness and litter and rocks using the previously defined equations [(10), (11), (14), and (15)] and subtracting that from total f. Predicted f_e and optimized f were significantly correlated ($r^2 = 0.70$) for natural plots. For the natural plots, total f_e was estimated as

$$f_e = f_{rs} + f_{rr} + f_{gc} + f_{pb} \qquad (16)$$

where f_{pb} = friction attributed to standing biomass, and the other terms were defined previously. The regression equation to estimate the fraction of hydraulic friction attributed to standing vegetation is

$$f_{pb} = 38.95C_c0.8 + 125.91B_a0.8 \qquad (17)$$

where C_c and B_a = fraction (0 to 1.0) of the canopy cover and basal plant cover, respectively, of the overland flow plane. Basal plant cover should include estimates for all plant life-forms (e.g., trees, shrubs, grasses, club moss) greater than 10 mm.

The hydraulic roughness for a given density and canopy cover of vegetation changes as a function of the rigidity and depth of submergence of the vegetation (Foster 1980). Standing biomass was not significant in predicting friction from the natural plots in this study. We propose that canopy cover be used as a surrogate for standing biomass in predicting hydraulic friction on rangelands. As canopy cover increased there was a corresponding increase in plant density, a decrease in number and size of concentrated-flow paths, and a corresponding increase in tortuosity of the concentrated-flow paths; and all of these factors act to increase hydraulic friction. The 14 sites evaluated here covered a wide range of vegetation types and included short-, mid-, and tallgrass prairies, and desert shrub, great basin shrub-steeps, and pinyon-juniper woodlands. There were no apparent trends in f_e associated with type of vegetation (grass or shrub). One reason for this may be that depth of flow never exceeded the height of standing vegetation. A second reason was that velocities were too low to deform or alter the standing vegetation.

The impact of raindrops appears to have an affect on f_e resistance. Although there is no general basis for quantifying this effect, the literature suggests that significant increase in f_e can occur with increasing rainfall intensity on smooth surfaces (Bell et al. 1989; Emmett 1970; Shen and Li 1973; Yu and McNown 1964). The increase in f_e from raindrop impact is of less importance as surface roughness increases (Chen 1976; Emmett 1970; Shen and Li 1973). Velocity of raindrop impact was not found to significantly alter hydrologic roughness coefficients within a physically realistic range (Wenzel 1970). With the nonsteady-state rainfall rates of natural storms and the variability in the geometric shape of channels and other physical ground surface characteristics, the effect of raindrop impact was not estimated separately but was lumped with canopy cover effect.

It should be noted that the regression equations were developed from overland flow planes of limited slope lengths and with limited developed concentrated-flow paths. For situations with highly developed concentrated-flow paths and planes greater than 0.8 ha, the predicted f_e may need to be adjusted (n downward and C upward) based on the work by Lane and Woolhiser (1977), Goodrich et al. (1988), and Woolhiser et al. (1990). Here, the influence of raindrop impact was lumped with the canopy-cover friction coefficient. The f_e predicted from these regression equations may need to be corrected when modeling overland flow with rainfall intensities greater than the 65 mm/hr used in this study.

Summary

The subfactor approach allows us to predict hydraulic roughness values for overland flow planes for most rangelands. By utilizing predictive equations like those developed here instead of tabular estimates, the values of f_e can be updated on a daily basis in a continuous simulation model or within overland flow planes as the vegetation and soil surface is changed according to seasonal or management influences. This should reduce the amount of time required to optimize and/or fit observed to simulated hydrographs. The subfactor approach proposed here allows us to estimate the lumped hydraulic roughness of both concentrated and interrill flow paths, and to improve our ability to simulate surface runoff on rangeland watersheds.

A subfactor-based regression equation was developed to estimate the effective friction coefficients for rangeland overland flow areas. The results from this research are summarized in Table 3; they should be suitable for most circumstances in which shallow overland flow on rangelands needs to be analyzed. An effective friction coefficient for rangelands is predicted by (16). This subfactor-based regression equation permits the estimation of hydraulic roughness values for areas where little hydraulic information is available.

Appendix I. References

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APPENDIX II. NOTATION

The following symbols are used in this paper:

B_a = fraction of soil surface occupied by basal plant cover;
C = Chezy roughness coefficient;
C_c = fraction of soil surface covered by plants;
D = detention storage volume;
F = total infiltration volume;
F_c = cummulative infiltration rate;
f = Darcy-Weisbach friction factor;
f_e = estimated Darcy-Weisbach effective friction coefficient;
f_{gc} = friction coefficient for ground cover;
f_{lt} = friction coefficient for litter;
f_{pb} = friction coefficient for standing biomass;
f_{rk} = friction coefficient for rocks;
f_{rr} = friction coefficient for random roughness;
f_{rs} = friction coefficient for bare soil;
g = acceleration due to gravity;
h = depth of flow;
m = coefficient;
n = Manning's roughness coefficient;
P = cummulative volume of rainfall;
Q = cummulative volume of runoff;
q = volume rate of runoff;

q_c = simulated flow rate;
q_o = observed flow rate;
R = Reynolds number;
Rk = fraction of soil surface occupied by rocks;
Rl = fraction of soil surface occupied by litter;
Rr = random roughness of overland flow plane;
S = slope of overland flow plane;
t = time;
t_i = time interval;
U = least-square difference objective function;
x = distance downslope;
α = slope roughness coefficient; and
β = fitting coefficient for random roughness.