Use of the Modified Universal Soil Loss Equation for average annual sediment yield estimates on small rangeland drainage basins

WILLIAM L. JACKSON
Hydrologist, USDI Bureau of Land Management
Service Center, Building 50, D-470, Lakewood, CO 80225

KARL GEBHARDT
Hydrologist, USDI Bureau of Land Management
Idaho State Office, 3380 Americana Terrace, Boise, ID 83705

BRUCE P. VAN HAVEREN
Hydrologist, USDI Bureau of Land Management
Service Center, Building 50, D-470, Lakewood, CO 80225

ABSTRACT The Modified Universal Soil Loss Equation (MUSLE) was related to average annual sediment yield on 14 small rangeland drainage basins by substituting average annual runoff and a calibrated design discharge for the runoff and peak flow terms respectively in MUSLE. The objective was to determine if a design discharge could be prescribed which would enable MUSLE, in this form, to be used for annual sediment yield estimates on small rangeland drainage basins. Calibrated peak flow terms far exceeded the one percent probability flow rate in seven of the fourteen basins. Those basins which experience the highest runoff rates in proportion to annual runoff volumes tend to have the highest calibrated peak flow terms. The analysis suggests that the exponent on the MUSLE runoff term may be too low for arid and semi-arid rangeland drainage basins, where runoff is mostly from thunderstorms, and needs to be recalibrated for these basins using storm period data before the procedure tested here for average annual sediment yield prediction has merit.

INTRODUCTION

Erosion involves the detachment, transport and deposition of soil particles and aggregates. Sediment yield is defined as the total amount of eroded material to be delivered from its source to a downstream control point (Gottschalk, 1964). Thus, sediment yield rates are directly dependent upon both soil loss rates and the transport efficiency of surface runoff and channel flow.

The Modified Universal Soil Loss Equation (MUSLE) was developed to relate empirically storm-period sediment yields to upland soil loss rates indexed by Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) erodibility factors and the transport efficiency of surface runoff indexed by a function of the product of total storm runoff volume and peak runoff rate (Williams, 1975). When applied to average annual sediment yield estimates, however, MUSLE becomes computationally cumbersome and generally requires daily (or hourly) hydrologic simulation. The purpose of this study is to adapt MUSLE to average annual sediment yield by substituting average annual runoff and a calibrated design discharge for the runoff and peak flow terms in MUSLE. Our objective is to determine if a design discharge could be prescribed which would allow MUSLE, in this form, to be used for annual sediment yield estimates on small rangeland drainage basins. The return period associated with the calibrated design discharge is examined in terms of basin runoff characteristics, and the importance of large runoff events to long-term sediment yields is discussed for small arid and semi-arid rangeland drainage basins.

BACKGROUND

Williams (1975) developed the MUSLE by replacing the rainfall-energy factor in the USLE with a runoff energy factor. The equation was developed using individual storm data from 18 basins in Texas and Nebraska and subsequently validated on 102 basins throughout the United States using runoff data generated by the hydrologic component of the SWRRB model (Williams, 1982).

The MUSLE is:

$$y = 11.8(Qq_p)^{0.56}\ KCSLP \qquad (1)$$

Where y = sediment yield (metric t)
Q = runoff volume (m^3)
q_p = peak runoff rate ($m^3\ sec^{-1}$)

and K, C, SL and P are the standard USLE factors for soil erodibility, crop management (cover), slope length-gradient, and erosion control practice.

The main advantages of MUSLE are its simplicity, the direct conceptual and physical relevance of its factors, the large data base upon which the empirical relationship was developed, and the capability to insert management considerations into factor selection. The main disadvantages are that the model is empirical and does not consider all physical factors affecting sediment yield, and generally there are fairly large errors associated with both soil loss (USLE) and runoff estimates. An additional disadvantage in rangeland applications of MUSLE is that USLE erodibility factors are not as well developed for rangelands as for croplands (Simonton et al., 1980; Renard, 1980).

No arid or semiarid drainage basin data from the intermountain western United States were used in the derivation of MUSLE and the equation has not yet been thoroughly validated for that region. Smith et al. (1984) found good correllations between measured and MUSLE-predicted sediment yields on grassland basins in Texas and Oklahoma. However, when applied to rangeland drainage basins at the Reynolds Creek Experimental Watershed in southwest Idaho, MUSLE over-predicted sediment yields for small events and under-predicted sediment yields for larger events (Johnson et al., 1986). Increasing the exponent from 0.56 to 0.75 on the MUSLE runoff terms improved the predictive capability of MUSLE at Reynolds Creek. Similarly, Renard & Stone (1981) found that MUSLE severely under-predicted sediment yields associated with larger events at the Walnut Gulch

Experimental Watershed in southeast Arizona. At that time, Renard & Stone concluded that the problem may have been more with the hydrologic model used to synthesize runoff than with MUSLE *per se*.

Williams (1982) demonstrated the applicability of hydrologic simulation as a substitute for measured runoff in MUSLE-sediment yield predictions. However, the vast majority of rangeland watersheds lack the long-term daily climate and precipitation data necessary for hydrologic simulation. One alternative is to use a synthetic climate generator. Yet, properly generated daily precipitation data should be represented by long-term precipi- tation depth-duration-frequency information currently available in NOAA climate atlases (U.S. Department of Commerce, 1973). The computational efficiency of MUSLE when applied to long-term sediment yield estimates is greatly simplified if the MUSLE runoff-energy factor can be synthesized from design rainfall data using common hydrologic methods.

METHODS

Long-term sediment yield data for small arid and semi-arid rangeland drainage basins were solicited from 23 watershed research projects in the western United States. Only three projects - the Reynolds Creek Experimental Watershed in southwest Idaho, the Badger Wash Watersheds in western Colorado, and the Walnut Gulch Experimental Watersheds in southeast Arizona - collected long-term (10-20 years) sediment yield data on small (< 6 km^2) basins (Fig. 1).* However, the data collection methods and the available corresponding runoff data varies greatly between the three areas.

Reynolds Creek is characteristic of sagebrush rangelands in the intermountain northwest United States. Summer thunderstorms, spring snowmelt, and rain-on-snow events all produce significant runoff. Runoff was recorded continuously in weirs and suspended sediment was sampled regularly over time to form the basis for storm-period and annual sediment yield determinations. Our primary source of sediment and hydrologic data for Reynolds Creek was Johnson et al. (1986) and USDA (1983). Although only the Reynolds Mountain basin meets the size criteria for this analysis, three other relatively small basins from the Reynolds Creek Watersheds with exceptionally good long-term records were included in the analysis.

Badger Wash is typical of the salt-desert shrub vegetation type in western Colorado and central and eastern Utah. Almost all runoff occurs as the result of high-intensity short-duration

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*Sediment yield data are also available for Boca Mountain, Colorado (9 yrs.) (Lusby, 1976), Stratton Study Area, Wyoming (10 yrs.) (Sturges, 1982), and Cornfield Wash, New Mexico (10 yrs.) (Burkham, 1966), but the dominance of snowmelt runoff and/or the fairly short periods of record made these sites poor selections for this study. In addition, Hidden Water Creek, Wyoming has sediment yield data (25 yrs.), but no corresponding runoff data (Ringen et al., 1979).

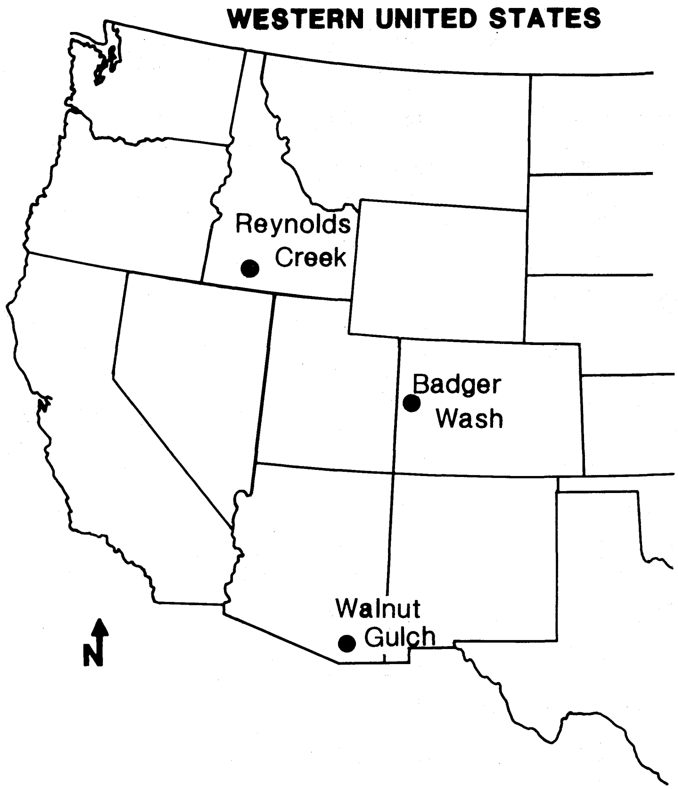

Figure 1. Locations of the study drainage basins

summer thunderstorms. Runoff volumes were recorded in retention reservoirs and sediment yields were calculated from annual reservoir surveys. Our primary source of sediment and hydrologic data for Badger Wash was Lusby (1979).

Walnut Gulch is a desert plains grassland at an altitude of 1400 m in southeast Arizona. Runoff is the result of high-intensity short-duration thunderstorms. Sediment yields were measured in runoff tanks on selected small watersheds. Discharge was not monitored regularly on those watersheds. Our primary source of sediment and hydrologic data for Walnut Gulch was Renard & Stone (1981).

In using MUSLE for average annual sediment yields we assumed that the event runoff volume, Q, could be replaced by the average annual runoff volume Q_a. Since a peak flow value for the MUSLE "q_p" term which would allow MUSLE to equate to average annual sediment yield is dependent both upon the long-term probability distribution of peak flows and the number of individual runoff events, we chose to solve arithmetically for a representative q_p, given measured values for annual sediment yield and either measured or derived values for the other variables in MUSLE. Q_a for the Walnut Gulch watersheds was derived from a generalized relationship (Renard & Stone, 1981), whereas Q_a was measured at the other two sites. Reported USLE factors were used for the Reynolds Creek and Walnut Gulch

TABLE 1 Runoff and sediment yield records

Watershed	Area (Km^2)	Record Length	Soil	Vegetation	Avg. Ann. Runoff, Q_a (m^3)	Avg. Ann. Sed. Yield (t)	Calibrated Peak, q_p (m^3/s)	Return Period for q_p, Yrs.*
Badger Wash								
1B	0.22	1954–1973	Shale, mixed	Saltbush, shrub	3317	221	3.3	1.3 X 100 yr.
2B	0.41	1954–1973	Sandy, mixed	Saltbush, shrub	4981	591	8.4	2.1 X 100 yr.
3B	0.12	1954–1973	Shale, mixed	Saltbush, shrub	2022	224	1.4	80 yr.
4B	0.05	1954–1973	Mixed	Saltbush, shrub	592	73	0.4	16 yr.
Walnut Gulch								
207	1.11	1962–1977	Rillito-Cave Tortugas	Brush	14302	93	111.0	7.3 X 100 yr.
212	3.41	1964–1977	Cave-Rillito-Laveen Tortugas	Brush	37236	286	46.0	1.7 X 100 yr.
213	1.60	1962–1979	Graham-House Mountain	Brush, Grass	19481	110	1.1	1 yr.
214	1.50	1957–1977	Hathaway-Bernardino	Grass	18741	425	249.0	12.3 X 100 yr.
216	0.84	1962–1977	Hathaway-Bernardino	Grass	11343	328	70.0	4.5 X 100 yr.
223	0.44	1962–1977	Rillito-Laveen	Brush	6411	100	45.0	5.2 X 100 yr.
Reynolds Creek								
Reynolds Outlet	233.7	1963–1985	Loamy	Sagebrush	18.7×10^6	15,169	71.7	18 yr.
Macks Creek	31.7	1965–1985	Loamy	Sagebrush	2.4×10^6	2,288	18.0	83 yr.
Reynolds Tollgate	54.4	1966–1985	Loamy	Sagebrush	13.7×10^6	4,728	6.9	2.4 yr.
Reynolds Mtn.	0.4	1963–1985	Loamy	Sagebrush	210,4000	10	0.08	1.3 yr.

*Based upon 1-hr. design rainfall at Badger Wash and Walnut Gulch. Based upon Log Pearson III distribution of measured peaks at Reynolds Creek.

watersheds, and derived for Badger Wash using tables in Wischmeier & Smith (1978). Flood-frequency relationships at Reynolds Creek were derived from the measured data. Flood-frequency relationships were derived for the Badger Wash and Walnut Gulch basins using SCS runoff curve number and synthetic hydrograph procedures (USDA, 1972) and precipitation information from the NOAA II atlas (U.S. Department of Commerce, 1973). Curve numbers for Walnut Gulch are from Renard & Stone (1981); Curve numbers for Badger Wash are from Hawkins et al. (1983). Basin parameters are reported in Tables 1 and 2.

RESULTS AND DISCUSSION

Peak flows required to equate MUSLE to average annual sediment yields are presented in Table 2. Return periods associated with those flows are also listed in Table 2. The large number of calibrated peaks in excess of the 100-year return period flow made it unreasonable to try to correlate statistically the relative magnitude of calibrated flows to basin response characteristics. However, it can be noted that, in general, the largest calibrated return period flows occurred in the Walnut Gulch basins, followed by Badger Wash, then Reynolds Creek. Thus, the magnitude of the calibrated peaks correllates positively to the ratio of 100-year return period flow to average annual runoff volume. In other words, annual sediment yields seem to be more dominated by larger events in the more ephemeral basins. The fact that almost all calibrated peak flow magnitudes are higher than we expected is probably a direct result of the tendency of MUSLE to under-predict sediment yields for large events. This problem is exaggerated in highly ephemeral drainage basins where long-term sediment yields are dominated by large, infrequent runoff events.

To further support our notion that the representative peak flow term needed to equate MUSLE to annual sediment yields would be smaller if MUSLE did not tend to under-predict important sediment-yielding events, we rederived the MUSLE runoff factor for the Reynolds Creek basins in terms of peak flows only. Williams (1975) presented

$$B_1 \times Q\ B_2 \times q_p\ B_3 \qquad (2)$$

as another form of the runoff factor in (1), where Q and q_p are as defined previously and B_1, B_2 and B_3 are coefficients.

The arguments of (2) are redefined as

$$F \times V^a q^b = R_d \qquad (3)$$

where V is the event runoff volume and q the event runoff peak to assist in the following formulation.

If equation (3) is summed over a long period, the result should equal a runoff-delivery ratio that can be applied to the USLE portion of MUSLE.

$$F \times (V_1{}^a\ q_1{}^b + V_2{}^a\ q_2{}^b + V_3{}^a\ q_3{}^b \ldots + V_i{}^a\ q_i{}^b) = R_d \qquad (4)$$

TABLE 2 Summary of erosion and runoff variables used in MUSLE evaluations.

Watershed	KLSCP[1]	CN_I [2]	TC[3]	Slope	q_{100}/Q_a
Badger Wash			(hours)	(%)	(cfs/ac.ft.)
1B	0.12	90	.16	14.3	33.0
2B	0.14	90	.21	15.7	34.1
3B	0.21	90	.13	20.3	34.8
4B	0.31	90	.07	27.8	64.6
					($\bar{x}$ = 41.6)
Walnut Gulch					
207	0.0026	87	.42	6.9	45.9
212	0.0077	84	.53	5.8	30.9
213	0.034	87	.45	11.0	50.5
214	0.0065	87	.45	8.6	46.9
216	0.0136	88	.34	12.0	59.7
223	0.0073	88	.35	9.4	59.2
					($\bar{x}$ = 48.8)
Reynolds Creek					
Reynolds Outlet	0.0166	N/A	N/A	20.0	0.38
Macks Creek	0.0183	N/A	N/A	22.0	0.34
Reynolds Tollgate	0.0171	N/A	N/A	22.0	0.03
Reynolds Mountain	0.0221	N/A	N/A	15.0	0.07
					($\bar{x}$ = 0.21)

1. Universal Soil Loss Equation Parameter Valves
2. SCS Curve Number for Antecedent Soil Moisture Condition I
3. Time of Concentration for SCS Curve Number Runoff Model

By substituting an expression for Q in terms of q_p we can express the R_d term wholly in terms of individual peak flows. The general form of the regression relationship is

$$\text{Runoff Volume} = H_q I \tag{5}$$

where the coefficients for the Reynolds Creek basins are presented in Table 3.

Table 3. Regression results for Reynolds Creek Basins

Watershed	H	I	r^2
Reynolds Mtn.	0.00074	0.895	0.89
Macks	0.00059	1.02	0.87
Tollgate	0.00067	1.05	0.83
Reynolds Outlet	0.00096	0.965	0.77
	$\bar{x}$= 0.00074	$\bar{x}$= 0.98	
	S= 0.00016	S= 0.07	

Substituting Equation (5) into Equation (3) yields,

$$R_d = F \times (Hg^I)^a g^b \tag{6}$$

Lumping parameters into a constant, J, a general form of Rd becomes

$$Jq^{aI+b} = Rd \tag{7}$$

Substituting this into a general form for MUSLE yields

$$y = Jq^{aI+b}\ KLSCP \tag{8}$$

The reduced form of equation (8) for the Reynolds Creek basins using average values of H as.0074 and F as 11.8, a and b as 0.56, and I as 0.98 is

$$y = 0.09q_p^{1.11}\ KLSCP \tag{9}$$

With the coefficient on q_p so close to 1.0 we can deduce that if summed and averaged over long periods of time, we would expect a representative peak flow term for average annual sediment yields to be only somewhat larger than the average event peak flow. Since this was not the case and a much larger peak flow term was required, we believe that, in its commonly presented form, MUSLE would tend to significantly under-predict long term sediment yields, which may be why our calibrated peak flow terms were larger than expected.

CONCLUSIONS

Our effort to calibrate MUSLE to average annual sediment yields on small arid and semiarid rangeland drainage basins resulted in calculated peak flows well in excess of the one percent probability flow for 7 of the 14 basins tested. Thus, using the generally reported form of MUSLE for estimating average annual sediment yields by substituting annual runoff and an easily determined design discharge is not practical at this time.

While our results could have been caused by improper selection of USLE parameters, we believe that the documented attribute of MUSLE to under-predict sediment yields for large events makes it an improper model, in its commonly reported form, for estimating long-term sediment yields from small arid and semiarid rangeland watersheds. This is because in watersheds of this type, long-term sediment yields tend to be dominated by large, infrequent events. The larger the ratio of the 100-year return period flow to average annual runoff volume, the greater will be the tendency of MUSLE to under-predict long-term sediment yields.

Williams (1975) indicated that it may be necessary to recalibrate the runoff term in MUSLE to the site of interest. Johnson et al. (1986) have recently done this for Reynolds Creek, resulting in a larger exponent on the runoff term. To be applicable for long-term sediment yield estimates on small ephemeral rangeland basins - either using an approach such as the one reported here, or by applying MUSLE on an event basis using a climate generator and hydrology model - we believe it will be necessary to adjust upward the exponent on the MUSLE runoff term. While that presently may have to be done by calibration to the site of interest, ideally, the coefficients on the runoff term would be able to be estimated from climate and hydrologic characteristics of basins.

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