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WATERSHED SEDIMENT YIELD AND RANGELAND HEALTH

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ABSTRACT

Much of the western United States is considered to be rangeland. Rangeland areas produce a diverse mix of benefits and products, and their overall health, in an ecosystem context, is of national importance. Because sediment yield from a watershed is an integrated expression of all soil erosion and sedimentation processes occurring within it, it is logical that we seek to quantify and interpret sediment yield in the context of soil/site stability and watershed function as measures of rangeland health. Depth integrated suspended sediment samples were combined with runoff measured using flumes to calculate sediment discharge and yield from two experimental watersheds in the southwestern USA. Sediment yield estimates for individual runoff events were summed to produce estimates of annual sediment yield from these two rangeland watersheds. Estimated annual sediment yield data were then combined with the concepts of sediment delivery ratio and soil loss tolerance to assess soil/site stability at the watershed scale. Analyses suggest that using sediment yield estimates from distributed watershed processes with time-space averaged soil loss tolerance values is inconsistent. Thus, new distributed soil/site stability criteria are needed to replace the soil loss tolerance concept in assessing the health of rangeland watersheds. Sediment transport/yield models are used at interior points in a watershed to simulate distributed sedimentation processes. However, application of these models requires calibration and validation data and is thus dependent upon the availability of sediment concentration and yield databases. Therefore, additional efforts are required to build sediment yield databases through rescue of historical data along with continued measurement and monitoring at existing and new sampling sites.

Key Words: Sediment yield, Rangalang health, Ecosystem contex, Sedimentation processes, Sediment delivery ratio

1 INTRODUCTION

Differences in the prevailing land use and management of arid and semiarid areas are determined in large part by climate. Arid areas generally receive too little precipitation to support dryland agriculture or domestic livestock grazing although they are grazed by wildlife, and at times, by domestic livestock. In contrast, in semiarid areas adequate moisture is usually available at some time during the year to produce forage for livestock and wildlife, and there are some years when dryland crop production is successful. However, both climates are characterized by extreme variability in precipitation and both are subject to commonly occurring droughts and infrequent periods of above average rainfall and subsequent flooding.

From a land use and management perspective, arid and semiarid areas, meadows, and woodlands are generally considered to be rangelands. Worldwide, rangelands make up about 40% of all land areas (Branson et al., 1981), and in the United States rangelands and pastures make up over half the land areas. In the 17 western states of the U.S., rangelands comprise over 300 million hectares or some 80% of the land area.

These abundant Western rangelands produce a diverse mix of benefits and renewable products from aesthetics to forage for millions of domestic livestock, water, and wildlife habitat. They are host or home for much of the human population and numerous diverse species of animals and plants. Because of their climate, soils, topography, and location, rangelands in the U.S. are uniquely suited for these purposes.

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Note: The manucript of this paper was received in March 1999, Discussion open until March 2001

Thus, the many natural resources of rangelands, and therefore rangeland health, are critical to the well being of humans, wildlife, and ecosystems. When managed, used, and developed in sustainable ways, these rangelands will remain healthy, and will continue to provide these products and values indefinitely.

The terms "sustainable" and "rangeland health" represent concepts that are complex and difficult to quantify, however. Rangeland ecosystems are affected by many biotic and abiotic components, the interactions of which are generally poorly understood. Striking features of rangelands are the variations of their characteristics in time and space. For the purposes of this paper we adopt the following generalized definition of rangeland health as stated by the US National Academy of Science/National Research Council (NRC, 1994, p. 4): "Rangeland health should be defined as the degree to which the integrity of the soil and the ecological processes of rangeland ecosystems are sustained." A primary determination of rangeland health using this definition is based on the degree of watershed soil stability and an assessment of watershed function. In turn, the best criterion to assess soil stability and watershed function is the degree of soil movement by wind and water. Evaluation of soil movement is based on multiple indicators of the condition of the soil surface and evidence of soil erosion and sediment transport processes.

A major effort to develop a rangeland health evaluation procedure has been initiated by federal agencies in the U.S. including the Natural Resources Conservation Service (NRCS), the Bureau of Land Management (BLM), and the U.S. Forest Service (USFS). This procedure uses evaluations of soil, watershed, plant, and energy/mineral cycle indicators to determine if a rangeland site is healthy, at risk of degradation, or unhealthy. Most of the attributes and indicators used to assess rangeland health are qualitative and rely heavily on the expertise of the person performing the evaluation. As such, most attributes have not been sufficiently validated with field data and lack a sound scientific basis, although efforts are progressing to address these issues. Despite the limitations, the rangeland health assessment methodology is a significant advance in the evaluation, assessment, and planning for sustaining rangeland ecosystems.

Sediment yield from a watershed (in units of mass/time or mass/area/time) is an overall or integrated expression of all soil erosion and sedimentation processes occurring in the watershed areas contributing sediment at its outlet. Because sediment yield is an integrated expression of watershed function with respect to soil erosion and sediment delivery, it is logical that we seek to quantify and interpret sediment yield from rangeland watersheds in the context of rangeland health.

The assessment of soil stability and watershed function to address concerns for the health and viability of rangelands serves to renew the focus on long-term experimental watershed research. In the Southwestern United States, the US Department of Agriculture, Agricultural Research Service (USDA-ARS) has operated and maintained two long-term experimental watersheds on semiarid rangelands. These are the Walnut Gulch Experimental Watershed in southeastern Arizona (Renard et al., 1993; Goodrich and Simanton, 1995) and the Alamogordo Creek Experimental Watershed in eastern New Mexico (Renard et al., 1970). The location of these experimental areas is shown in Fig. 1.

The objectives of this paper are to: 1) describe aspects of sediment yield from the Walnut Gulch and Alamogordo Creek Watersheds, 2) discuss application of sediment transport and yield modeling at Walnut Gulch, 3) interpret sediment yield in the context of the rangeland health of these watersheds, and 4) identify key gaps in knowledge limiting our ability to assess rangeland health at the watershed scale. Analyses and interpretations are limited to the soil/site stability aspects of rangeland health and do not deal with issues of energy and nutrient cycling and plant recovery mechanisms.

2 EXPERIMENTAL WATERSHEDS

2.1 The Walnut Gulch Experimental Watershed

The 149 sq. km Walnut Gulch Experimental Watershed (or Walnut Gulch) is a brush and grass dominated rangeland watershed located in southeastern Arizona, USA at approximately 31 degrees 45 minutes north latitude and 110 degrees west longitude with elevations ranging from 1,250 to about 1,900 m above MSL (Fig. 1).

International Journal of Sediment Research, Vol. 15, No. 1, 2000, pp. 51-59

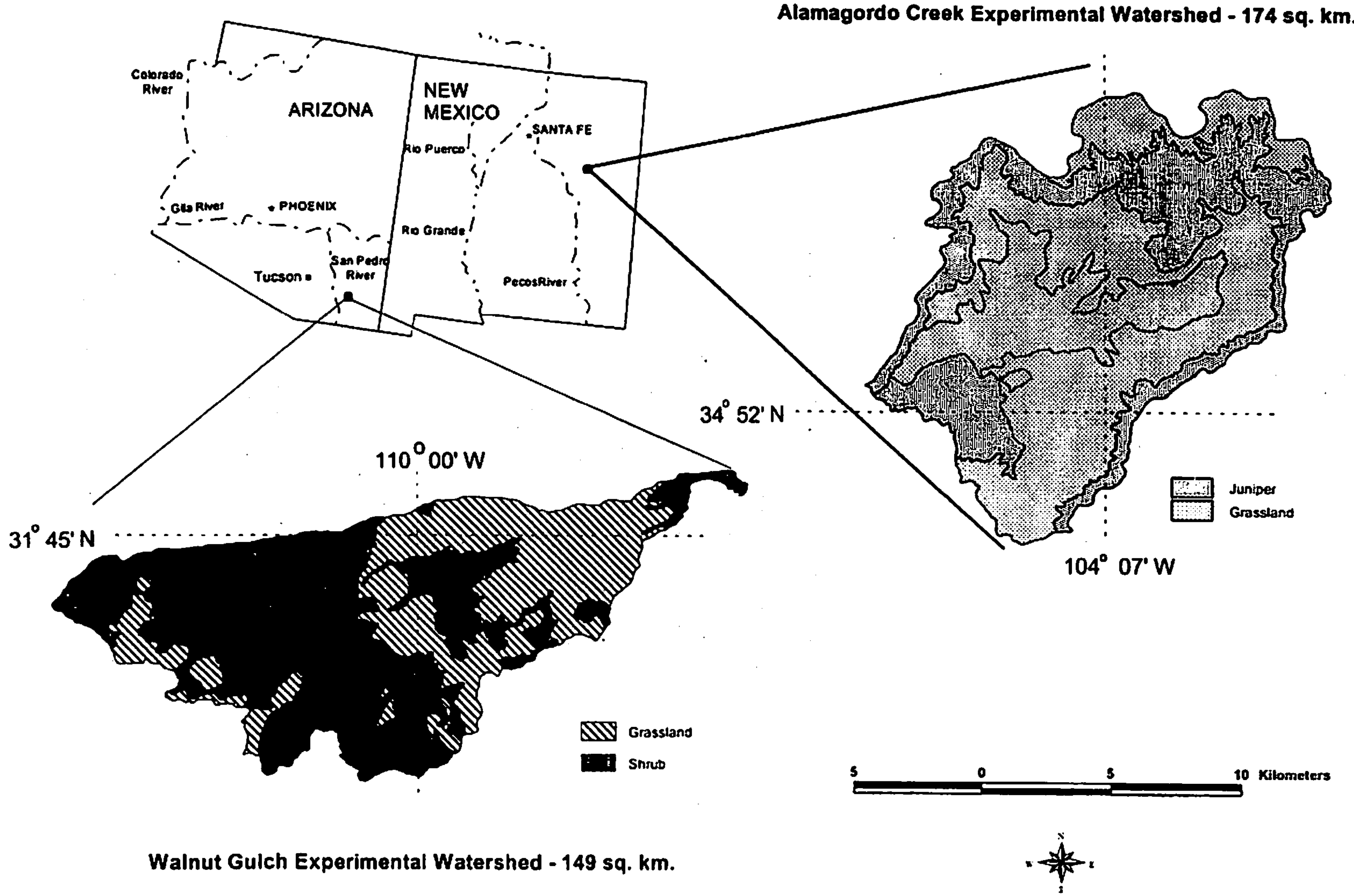

Fig. 1 Location map of the Walnut Gulch Experimental Watershed in southeastern m Arizona, USA and the Alamogordo Creek Experimental Watershed in eastern New Mexico, USA

The climate in the Walnut Gulch area is classified as semiarid or steppe, with about 70% of the annual precipitation occurring during the summer months, usually from convective thunderstorms of limited areal extent. The remainder of the precipitation is usually associated with winter frontal storms with more general rains and less convective activity. Climatic data from Tombstone, AZ, located within the Walnut Gulch watershed, for the period 1941-1970 were used to calculate mean annual precipitation as 324 mm and mean annual temperature as 17.6 degrees C.

Walnut Gulch is located in the Basin and Range Province of the Southwest and is bounded on the southwest, south, and east by mountain blocks separated by broad alluvium filled basins. Gilluly (1956) provided a detailed geologic description of Walnut Gulch, from which the following brief description is derived. The northern 50 to 70% of the total 149 sq. km drainage area consists of Quaternary and Tertiary alluvium, derived from the Dragoon Mountains. The remaining southern part of the watershed is composed of more complex geologic structures. Areas along the southeast watershed boundary are composed of volcanics of late Tertiary age. Areas along the southwestern and southern boundaries of the watershed comprise the Tombstone Hills. These are areas with complex structure and composition including limestone, quartzite, and granite.

Soils on Walnut Gulch are mostly well drained, calcareous, gravelly to cobbly loams and are closely associated with the geologic features described above. Shrub vegetation, such as creosote bush, acacia, tarbush, and small mesquite trees, dominates (30 to 40% canopy cover) the lower two thirds of the watershed. The major grass species (10 to 80% canopy cover) on the upper third of the watershed are the grama grasses, bush muhley, and lovegrass, with some invasion of the shrub species and mesquite (Renard et al., 1993). Land use consists primarily of grazing, recreation, mining, and some urbanization.

2.2 The Alamogordo Creek Experimental Watershed

The 174 sq. km Alamogordo Creek Watershed is located in east central New Mexico (Fig. 1). The watershed is a relatively flat, recessed basin with a steep escarpment surrounding most of the basin. Elevations range from 1420 at the outlet to over 1680 m MSL at the upper end of the watershed. Sandstone formations underlie the basin and isolated outcrops in the main stream channels control local grades and gradients. Small areas of the watershed located on the mesa above the escarpment have shallow limestone layers overlying the sandstone formations.

The mean slope of the main stream channel on Alamorgodo Creek is about 0.58% compared with 1.2% for Walnut Gulch. Stream channels on both watersheds are classified as ephemeral. However, the steeper channels on Walnut Gulch are characterized by coarser material (sands and gravels with up to a few percent silt and clay) in comparison to the finer material (mostly sands with a few percent up to as much as 30% silt and clay) at Alamogordo Creek. As a result, transmission losses (infiltration of streamflow to stream channel beds and banks) are less significant and transported sediment is much finer at Alamogordo Creek than at Walnut Gulch.

The climate at Alamogordo Creek, as at Walnut Gulch, is classified as semiarid with mean annual precipitation of just over 350 mm. Soils are generally heavy in clay: clay to clay loams, to loamy soils, and are less well drained and cobbly than on Walnut Gulch. The central, relatively flat basin areas of Alamogordo Creek are grasslands dominated by grama grasses while juniper trees dominate the steeper escarpment area. Land use is primarily domestic livestock grazing. Additional information on the Alamogordo Creek Watershed is given in Drissel and Osborn (1968) and Renard et al. (1970).

3 ANALYSES AND DISCUSSIONS

3.1 Analysis of Observed Data

Depth integrated suspended sediment samples were taken in the streamflow above the runoff measuring flumes at Walnut Gulch and Alamogordo Creek using wading (USDH48 sampler) and cableway (USP61 sampler) sampling during 8 runoff events in 1964 and 1996 (Walnut Gulch) and during 23 runoff events in 1965-1973 (Alamogordo Creek).

During 1957-1978 and 1980-1992 there were 428 runoff events recorded at Walnut Gulch Flume 1 representing an average of about 12 events per year over the 35 years of record. During 1955-1973 there were 141 runoff events recorded at Alamogordo Creek Flume 1 representing an average of about 7 1/2 events per year over the 19 years of record.

The 8 events sampled for sediment concentrations at Walnut Gulch represent 2% of the total number of events that could have been sampled and the 23 events sampled at Alamogordo Creek represent 16% of those that could have been sampled. The reason for using only 2% of the events sampled at Walnut Gulch in the analysis is that to date no other sampled events have been verified and converted to electronic form. Data rescue activities will greatly expand the Walnut Gulch database, but monitoring at Alamogordo Creek was terminated in 1978 limiting the existing database to 23 sampled events.

Total sediment yield for each of the sampled events was calculated by integrating the product of sediment concentration and instantaneous water discharge over the duration of each runoff hydrograph. This resulted in a database of runoff volumes, Q (mm), and sediment yields, Qs (tons), which were then related by non-linear regression to develop runoff volume-sediment yield relationships for the two watersheds. The derived relationships were then applied to all of the unsampled runoff events for the periods of record to estimate sediment yield for each runoff event. Finally, runoff and sediment yield were summed to obtain annual values and these in turn were related by regression analyses to derive annual sediment yield estimation equations as functions of measured annual runoff volumes. These analyses are summarized in Table 1.

Table 1 Summary of relationships between measured runoff and sediment yield at Walnut Gulch and Alamogordo Creek Watersheds and the resulting derived equations for annual sediment yield.

Watershed	No. of Events	Runoff (mm) Mean	Standard Deviation	Sediment Yield (tons) Mean	Standard Deviation
Measured Runoff Event Relationships					
Walnut Gulch	8	1.07	1.59	4640 (2.91%)*	6940
$Qs = 4290*Q^{1.07}$			R^2=0.99		
Alamogordo Creek	23	0.61	1.11	2310 (2.18%)	6000
$Qs = 2750*Q^{1.20}$			R^2=0.93		
Estimated Annual Relationships					
Walnut Gulch	35**	3.48	3.25	15140 (2.92%)	14930
$Qs = 3900*Q^{1.07}$			R^2=0.99		
Alamogordo Creek	19	8	10.24	29300 (2.10%)	45400
$Qs = 2140*Q^{1.19}$			R^2=0.99		

* Mean sediment concentration in percent by weight represented by the indicated mean runoff and sediment yield.
** Represents number of years, not events, for the annual relationships.

3.2 Example of Sediment Transport Modeling

Recently, the Walnut Gulch Hydrologic Method (WGHM) was used to calculate sediment transport and yield on Walnut Gulch (Lane and Nichols, 1997). The hydrologic portion of the method includes a watershed model and a piecewise hydrograph approximation method (Lane, 1982a, Lane, 1982b). The sediment transport component includes a modified Duboys procedure for bed sediments and a modified Bagnold method (Bagnold, 1966) for suspended sediment.

Testing and evaluation studies by Lane and Nichols (1997) resulted in application of the sediment transport equations at 3 sites: 1) Muddy Creek, Wyoming, 2) Rio Grande near Bernalillo, New Mexico, and 3) Walnut Gulch, Arizona. Descriptive characteristics of the data sets are presented in Table 2.

For additional information, please see:

1 Sampling, measurements, and transport rates given by Andrews (1981)

2 Site descriptions and procedures given by Nordin (1964)

3 Details given by Renard and Laursen (1975)

4 As calculated using modified Einstein method for 2 events (Nordin, 1964)

Table 2 Summary of descriptive characteristics for the evaluation data sets used by Lane and Nichols (1997).

Site	Sampling Dates	No. of Events	Discharge (cm/s)	Sediment Transport Suspended (kg/s)	Sediment Transport Bed Load (kg/s)	Sampler
Muddy Creek[1]	4/6/75 - 8/31/75	35	0.15 - 1.57	--	0.0039 - 0.82	Helly-Smith bedload sampler
Rio Grande[2]	4/25/52 - 5/19/61	21	35 - 286	42 – 870	45 - 840[4]	US D-49
Walnut Gulch[3]	8/19/63 - 9/12/64	10	0 – 187	0 – 5930	--	US P61 and US DH48

In applying the WGHM, normal flow assumptions approximated flow conditions very well at Muddy Creek and Rio Grande and values for Manning's n were computed to match mean depths, velocities and discharges. The WGHM was applied to both data sets and discrepancy ratios (defined as the ratio of simulated to measured sediment discharge rates) were calculated. With respect to the 35 bedload measurements at Muddy Creek, 74% of the discrepancy ratios were within the range 0.5 to 2.0. As a comparison, Andrews (1981) reported that the percentage of discrepancy ratios in the range 0.5 to 2.0 for several sediment transport formulae were: Engelund and Hansen (1967) 77% without including samples for ripple bedforms; Yang (1973) 60% for all data; Shen and Hung (1972) 71% for all data; and Ackers and White (1973) 66% for all data.

The sediment transport procedure was also applied to the Rio Grande data where the simulated bed material discharges for material coarser than 0.062 mm were compared to measured values of suspended sediment coarser than 0.062 mm. Discrepancy ratios ranged from 0.56 to 2.18 with only one of 21 values outside of the 0.5 to 2.0 range. From these analyses, as well as those at Muddy Creek, Lane and Nichols (1997) concluded that their sediment transport calculation procedure produces reasonable results.

Runoff and measured and simulated suspended sediment yield data for 7 unsteady, non-uniform flow events in 1964 at the outlet of Walnut Gulch (Flume 1) are summarized in Table 3. The sediment transport procedure was applied using values for Manning's n from 0.020 to 0.022.

Table 3 Total runoff, measured and simulated suspended sediment yield data for 7 events on Walnut Gulch, Flume 1.

Event date	Runoff (mm)	Measured Sediment Yield (mg)	Simulated Sediment Yield (mg)	Discrepancy Ratio
7/31/64	0.28	1100	890	0.81
8/2/64	0.28	1410	910	0.65
8/8-9/64	0.08	270	150	0.56
9/8/64	0.91	3440	3260	0.95
9/9/64	0.38	1710	1310	0.77
9/10/64	4.68	20310	20760	1.02
9/11/64	1.98	8840	8780	0.99

Application of the WGHM resulted in an excellent degree of correspondence (discrepancy ratios varied from 0.56 to 1.02). Simulated sediment yields explained about 99% of the variance in observed sediment yields. However, calibration of the hydraulic resistance coefficient, Manning's n, was required to accurately simulate observed sediment yield. The WGHM shows potential for accurately computing sediment yield from Walnut Gulch although accurate simulations were based on calibration, and thus, the presence of observed sediment concentration data. This further supports the need for additional sediment concentration and yield data at Walnut Gulch.

4 INTERPRETATIONS

The sediment yield data presented in Table 1 are subject to a great deal of uncertainty. With only 2 to 16% of the runoff events sampled for sediment concentration, the subsequent annual sediment yield data as estimated from measured runoff are approximate and should be seen as relative, rather than quantitative, values. Nonetheless, they can be useful in interpreting relative soil and site stability at the watershed scale provided the interpretations remain qualitative and approximate.

The concept of a soil loss tolerance, T (t/ha/yr), is based on the Universal Soil Loss Equation (USLE) as described by Wischmeier and Smith (1978). In summary, one considers the long-term average annual soil loss rate (t/ha) from eroding portions of the landscape where the USLE is applicable (i.e. on uniform slopes in the absence of sediment deposition or soil erosion and transportation by concentrated flow). This average soil loss rate is then compared to a soil loss rate which can be "tolerated indefinitely" without reducing the productivity of the soil. Obviously, this restricts consideration to uniform portions of hillslopes and ignores all sediment deposition and channel erosion, transport, and deposition process occurring on a watershed. Moreover, "tolerated indefinitely" is an ill-defined term that depends upon a variety of soil properties. Regardless of these severe shortcomings, soil loss tolerance is the most widely accepted concept used to classify erosion rates according to a site's sustainability. For most soils, the accepted T values are 1, 3, or 5 t/ac/yr or 2.24, 6.73, or 11.2 t/ha/y respectively. Depending on soil depth and properties, each soil is assigned a single T value, usually within the range of 2.24 and 11.2 t/h/yr. A conservative approach would be to adopt the lower T value of 1 ton/acre/yr = 2.24 t/ha/yr as the criterion for rangeland soils.

A related concept is that of sediment yield delivery ratio or simply delivery ratio. If gross erosion, E (t/ha), is the soil erosion over the entire watershed and sy is the watershed sediment yield (t/ha), then a delivery ratio, DR (unitless), is DR = sy/E or in more conventional form

$$sy = DR*E \quad (1)$$

In its usual application, the delivery ratio approach to sediment yield estimation uses the USLE to estimate gross erosion and so suffers all the restrictions and limitations of the USLE. Alternatively, one can estimate gross erosion on a watershed using sediment yield from one or more small interior subwatersheds. The delivery ratio is then the ratio of sediment yield at the watershed outlet to that of the smaller interior watersheds.

Lane et al. (1997) compiled sediment yield data from 14 subwatersheds on Walnut Gulch. The estimates of gross erosion from the 7 subwatersheds in this group with drainage areas under 500 ha ranged from 0.5 to 4.4 t/ha/y with an average of 2.46 t/ha/y over the entire period of record. From Table 1 the mean annual sediment yield from the 14,900 ha Walnut Gulch Watershed computed over the entire period of record is 15,140 t/y or 1.02 t/ha/y. Thus, a rough estimate of the delivery ratio based on the average subwatershed sediment yield is DR = 1.02/2.46 = 0.41.

The only interior sediment yield estimate available on Alamogordo Creek is from 8 years of reservoir sedimentation data on a small stockpond with a drainage area of 16.2 ha. The mean annual sediment yield is 11.8 t/ha/y. With this value and a watershed sediment yield value from Table 1 of sy = 29300/19 = 1.68 t/ha/y, a rough estimate of delivery ratio for Alamogordo Creek is DR = 1.68/11.8 = 0.14.

If the delivery ratios derived above are approximately correct, and if gross erosion estimated from watershed sediment yield and a delivery ratio can be compared with soil loss tolerance, T, on a watershed-wide basis as a measure of watershed stability with respect to soil erosion, then it is possible to make a first-order assessment of rangeland health based on watershed sediment yield.

Using this first-order rangeland health assessment technique, the average gross erosion for Walnut Gulch is on the order of 2.5 t/ha/y. It can be inferred that all sites on soils with T values of 2.24 t/ha/y or less (1.0 ton/acre/yr or less) are unstable with regard to soil erosion and thus unhealthy. Similarly, the estimated gross erosion for Alamogordo Creek is 11.8 t/ha/yr and this is in excess of the highest commonly used T value of 11.2 t/ha/y. By this criterion, all of Alamogordo Creek would be unstable with respect to soil erosion and thus unhealthy.

Given the major uncertainties involved in estimating gross erosion and sediment delivery ratios, it is instructive to compare watershed sediment yield directly to T values using a probabilistic or frequency approach. Frequency analyses of the annual sediment yield data summarized in Table 1 produced the following results:

Table 4 Summary of frequency analyses for annual sediment yield from Walnut Gulch and Alamogordo Creek.

Watershed	Sediment Yield (t/ha/yr)			
	2-yr	5-yr	10-yr	25-yr
Walnut Gulch	1.22	3.89	7.15	13.6
Alamagordo Creek	1.34	5.24	10.7	23.0

From the data in Table 4, both watersheds yield sediment less than the lower T value for the mean annual sediment yield, both exceed the lower T value for return periods between 2 and 5 years, both exceed the middle T value for return periods between 5 and 10 years, and both exceed the highest T value for return periods between 10 and 25 years. Using the mean annual sediment yield both watersheds are stable with respect to T. Both watersheds are at risk or unhealthy for return periods longer than 2-5 years.

The major disadvantage with both the frequency approach and the rangeland health assessment approach is that given sediment yield from a complex watershed, parts of the watershed will always be producing sediment at less than the watershed average rate represented by the sediment yield. In addition, other parts of the watershed will be producing sediment at rates higher than the average rate of delivery to the watershed outlet. Clearly, there is a logical inconsistency in using a spatially averaged criterion, T, to evaluate the rangeland health consequences of distributed erosion and sedimentation processes. This inconsistency can only be corrected by using distributed criterion for soil/site stability and sustainability. One approach to accomplish this objective is through the use of sediment transport/yield model such as the WGHM, which has been demonstrated to successfully simulate the distributed features of watershed sediment yield on rangeland watersheds.

5 SUMMARY COMMENTS

Sediment yield data and the concepts of sediment delivery ratio and gross erosion allow estimates of soil erosion within a watershed to be compared with soil loss tolerance, T. Comparisons of estimated watershed wide gross erosion and soil loss tolerance on the Walnut Gulch and Alamogordo Creek Watersheds suggest that these watersheds are unstable with respect to T values of 2.24 t/ha/y (1 ton/acre/yr). Similar analyses based on a frequency analysis of estimated annual sediment yield suggest that both watersheds are stable for the mean annual (2 yr) sediment yield but unstable for longer return periods.

While it is logical to use watershed sediment yield as an overall measure of rangeland health, erosion and sediment yield processes are distributed with time and space within a watershed and should be compared with attributes or criteria that are also distributed. Comparison of sediment yield resulting from distributed watershed processes with a time-space average criterion such as soil loss tolerance presents a logical inconsistency. A major gap in our understanding of soil/site stability at the watershed scale involves the lack of distributed criteria or attributes to replace the soil loss tolerance concept.

Application of sediment transport/yield models at interior points within a watershed offers a potential to simulate the distributed features of watershed sediment yield. However, application of sediment transport/yield models such as the WGHM (see Tables 2 and 3) has been limited on Walnut Gulch. Additional applications will require calibration and validation at interior subwatersheds and this requires databases such as those summarized in Table 1. There is a critical need for further model calibration and validation on Walnut Gulch. Inasmuch as the calibration and validation efforts require extensive sediment transport and yield databases, this leads to a third critical need, an organized data rescue effort to capture and archive historical sediment concentration and yield data from watersheds with historic data collection programs such as Walnut Gulch. More data are needed to improve estimates of sediment yield, and so emphasis should be put on assembling, upgrading, and analyzing existing data in a comparable priority to the emphasis placed on new data collection efforts.

ACKNOWLEDGMENTS

We gratefully acknowledge the USDA-ARS employees who have operated and maintained the Walnut Gulch and Alamogordo Creek Experimental Watersheds over the years, making this research possible.

We also acknowledge funding and support provided by the USDA-ARS Southwest Watershed Research Center, Tucson, AZ. Finally, we thank the reviewers of this manuscript who have helped to improve it significantly.

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