

IDENTIFICATION OF SEDIMENT SOURCES IN A SEMIARID WATERSHED USING MULTIPLE DIAGNOSTIC PROPERTIES

Fred Rhoton, Soil Scientist, USDA-ARS, Oxford, MS, frhoton@ars.usda.gov; William Emmerich, Soil Scientist, USDA-ARS, Tucson, AZ, bemmerich@tucson.ars.ag.gov; Mark Nearing, Agricultural Engineer, USDA-ARS, Tucson, AZ, mnearing@tucson.ars.ag.gov; Jerry Ritchie, Ecologist/Soil Scientist, USDA-ARS, Beltsville, MD, jritchie@hydrolab.usdaars.gov; Christopher Wilson, Research Geologist, USDA-ARS, Oxford, MS, cwilson@ars.usda.gov; David DiCarlo, Research Physical Scientist, USDA-ARS, Oxford, MS, ddicarlo@ars.usda.gov

Abstract: The identification of sediment source areas in watersheds is important for the development of sediment budgets and for the design of management practices to reduce sediment and chemical loadings in receiving streams. This study was conducted to determine the primary sources of sediment at a watershed scale using a weighted means soil geomorphology approach to the characterization of soil properties that influence erodibility and sediment transport. Each major soil mapping unit in six subwatersheds (SW) was sampled along transects positioned to include the normal soil geomorphological features associated with a given mapping unit. At each sampling point, latitude-longitude, slope class, topographic position, and aspect were recorded. Soil samples collected from the surface 5.0 cm were characterized for a range of physical and chemical properties used for fingerprinting purposes. Suspended sediment samples collected from supercritical flumes at the mouth of each SW were analyzed identically. An aggregation index (AI) calculated for the soils in each SW as follows: $100 \times (1 - \text{water dispersible clay} / \text{total clay})$, served as a measure of soil erodibility. The physical and chemical signatures of the suspended sediment collected at the six flumes were used in a multivariate mixing model to identify the primary contributing source. The results suggested that the SWs with the lowest soil AI were contributing the greatest amounts of sediment.

INTRODUCTION

Two primary approaches are used in sediment source identification research in which detailed comparisons are made between suspended sediments transported in stream channels and watershed soils using a range of physical and chemical properties. Direct monitoring of potential source areas may be the most widely used approach (Slattery et al., 1995). These methods use technology such as erosion pins, runoff troughs, automated suspended sediment samplers, and manually collected grab samples (Sutherland and Bryan, 1989). The other approach to sediment source identification, commonly referred to as fingerprinting, is based on the analysis of suspended sediment properties for which equivalent values exist in the watershed soils (Slattery et al., 1995). These physical, chemical, and mineralogical properties include: clay mineralogy, sediment color, sediment chemistry, radionuclide concentrations, and magnetic susceptibility.

Clay mineralogy of suspended sediment has been used to infer source areas (Neiheisel and Weaver, 1967; Klages and Hsieh, 1975; Wall and Wilding, 1976), but these measurements have limitations since some clay minerals are preferentially eroded from soil surfaces at the expense of other species (Rhoton, et al., 1979). Likewise, the use of sediment color to separate channel and non-channel sediment sources (Grimshaw and Lewin, 1980) without the benefit of companion analytical measurements can lead to erroneous interpretations in soils with contrasting colors between the surface and subsurface horizons. Magnetic susceptibility measurements of watershed soils and sediment have been used extensively to identify source areas (Dearing et al., 1986; Oldfield et al., 1979). This approach is considered relatively successful especially at separating topsoil from subsoil sources on a field or small watershed scale, but in large watersheds with a wide variety of parent materials and soil types, the effects of soil geomorphology on magnetic susceptibility must be carefully evaluated. Fallout radionuclides (i.e., ^7Be , ^{210}Pb , ^{137}Cs) have been used in monitoring and fingerprinting suspended sediments in rivers and coastal waters (Walling and Woodward, 1992; Wallbrink et al., 1999; Bonniwell et al., 1999). In such studies, radionuclides, and their ratios to one another, can be used to differentiate between freshly eroded soil from the landscape and collapsed bank material due to differences in half-lives and the different delivery mechanisms of sediment to the stream (Whiting et al., 2005). In terms of sediment chemistry, Peart and Walling (1988) proposed a method for determining the origin of suspended sediments using their chemical properties as natural tracers. The chemical data, derived from the selective dissolution analysis of soil, stream bank, and suspended sediment samples are evaluated with a mixing model.

Soil geomorphology is critical to sediment source studies due to its influence on soil properties that determine soil erodibility and sediment characteristics. These soil properties, which include clay and organic matter contents and Fe and Al oxide contents, vary as a function of aspect, slope gradient, and topographic position (Schoenberger et al., 2002). The relationships between soil geomorphology and soil properties that influence erodibility have been addressed in previous studies. Franzmeier et al. (1969) reported greater organic C and darker soil colors on north-facing slopes that were attributed to lower temperatures and greater water contents. Particle size distributions were coarser on mid-slope positions, and basic cations were concentrated on the lower slope positions. In a similar study, Hanna et al. (1982) measured 20% more available water on north-facing slopes relative to south-facing slopes. East-facing slopes had the driest soils. Rhoton et al. (1998) indicated that water dispersible clay contents and soil erodibility were at a minimum on lower, wetter slope positions where the Fe oxide mineralogy was dominated by ferrihydrite, a poorly crystalline mineral that is most influential in aggregate stability.

The objective of this current research was to use fingerprinting techniques to identify primary sediment source areas in a large watershed by characterizing the distribution of several soil properties that determine the erodibility of watershed soils, and hence the characteristics of suspended sediments transported through the watershed.

MATERIALS AND METHODS

Site Characteristics: The research was conducted on the Walnut Gulch Experimental Watershed (WGEW) located at Tombstone, AZ (31 deg. 43 min. N. Lat., 110 deg. 41 min. W. Long.). The watershed covers approximately 150 km² with elevations ranging from 220 to 1890 m, a mean annual temperature of 17.6 ° C, and an average annual precipitation of 324 mm (Renard et al., 1993). The WGEW is situated primarily in a high foothill alluvial fan portion of the larger San Pedro River Watershed. The soil complexes mapped occur largely on alluvium composed of Cenozoic age clastic clays and silts. Smaller areas of limestone, granite, granodiorite, and andesite parent materials occur throughout the watershed. The soils are generally well-drained, calcareous, gravelly loams containing large percentages of rocks and gravels at the soil surface (Breckenfeld et al., 1995). Land-use over the entire watershed is rangeland.

Study Approach: The subwatersheds (SW) selected for study were numbers 3, 7, 9, 10, 11, and 15. Each SW was instrumented with a supercritical flume (Renard et al., 1993). Suspended sediments were collected at these flumes using vertical samplers mounted on the face of the flume. This sampler was designed to collect suspended samples in 30.5 cm increments above the floor of the flume for the total flow depth of 122 cm. The sediment was collected through 6.4 mm diameter ports drilled into a 10.2 cm diameter (i.d.) aluminum tube. Plastic tubing was used to connect the ports to 500 ml plastic sample bottles mounted inside the sealed sampler. Also, a 2 L sample bottle was mounted on the bottom of the sampler to collect additional sediment at the 30.5 cm flow depth to ensure adequate sample for low flow events. Once filled, float valves sealed the sample bottles to prevent continuous flow-through of suspended sediments. All samples were combined to give one composite sample per flow event.

Soil samples were collected from the SWs on the basis of relative acreage occupied by individual soil mapping units. Initially, digitized soil surveys were superimposed on digital elevation models of each SW. A sampling transect length of 1000 m was arbitrarily chosen for each 200 ha of a given soil mapping unit. These transects were positioned by GPS-derived coordinates such that a range of surface morphometry factors (Schoeneberger et al., 2002) were represented by the samples. Specifically, soil samples were collected as a function of topographic position, slope class, and aspect along the transects. At each selected location, the surface 5.0 cm were sampled at three points, approximately 10 m apart and perpendicular to the slope. The three soil samples were then composited to form a single bulk sample, and sealed in a plastic bag. Data were recorded at each sampling location for latitude - longitude, topographic position, aspect, and slope steepness.

Laboratory Analyses: In the laboratory, all soil and sediment samples were air-dried or oven-dried at 60°C, and sieved to < 2 mm. Particle size distribution was determined by standard pipette analysis following overnight dispersion in Na hexametaphosphate (USDA-NRCS, 1996). The water dispersible clay component of the total clay fraction was also estimated by this methodology using only distilled water as the dispersant. Soil pH was measured in a 1:1 soil/distilled water (v-v) suspension (McLean, 1982). Total C and N were determined by combusting 0.5 g samples in a Leco CN-2000 carbon-nitrogen analyzer (Leco Corp., St. Joseph, MI). The inorganic fraction of the total carbon was quantified by treating a separate 1 g sample with 5 N HCl in a sealed decomposition vessel (200 mL) fitted with a rubber septum. Carbon dioxide pressure generated by the acid-decomposition of the sample was

measured with a Tensimeter (Soil Measurement Systems, Tucson, AZ) probe inserted through the septum. Pressure readings were converted to C contents using a standard curve, and subtracted from total C to give the organic C (OC) content. The Na pyrophosphate (p), acid ammonium oxalate (o), and Na citrate-bicarbonate-dithionite (d) extractable Fe and Mn contents of the soils and sediment were determined by the procedures of the USDA-NRCS (1996). Exchangeable cation contents were determined following extraction with ammonium acetate (USDA-NRCS, 1996). All extracts were analyzed by atomic absorption spectrophotometry. Radionuclide activities were measured using Gamma Spectroscopy similar to the methods of Whiting et al. (2005). Quantitative soil color was measured with a Minolta Chroma Meter (Minolta Corp., Ramsey, NJ). The total clay and WDC content data were used to calculate an aggregation index (AI) for the watershed soils based on the method of Harris (1971) as follows: $AI = 100 (1 - WDC/\text{total clay})$.

The relative contribution of each SW to the sediment load leaving the WGEW at flume 1 was estimated using the multivariate mixing model methods of Walling and Woodward (1995), and the physical and chemical signatures for Fe_p , Fe_o , Fe_d , Mn_p , Mn_o , Mn_d , clay content, OC, and total N in the suspended sediment. This was done using the following linear optimization procedure. Each suspended sediment property was normalized by its standard deviation for each flume (SW). Thus, calling the vector of sediment properties obtained at flume i d_i , the linear optimization problem becomes finding the vector containing the proportion of sediment from each SW ($\mathbf{x}$) which minimizes the function $(\mathbf{Cx} - \mathbf{d})^* (\mathbf{Cx} - \mathbf{d})$, where $\mathbf{C}$ is the matrix consisting of the possible contributing SWs, and $\mathbf{d}$ is from the flume where the sediment is measured. This function is minimized with the constraints that the sum ($\mathbf{x}$) = 1, (i.e., the total sediment signature is from the contributing SWs) and $\mathbf{x} > 0$ (i.e., a SW cannot contribute negative sediment). This routine was run in which the signature of sediment at flume 1 was expressed in terms of possible contributions from flumes 3, 7, 9, 10, 11, and 15.

All statistical analysis related to soil and sediment properties utilized the GLM and CORR procedures of SAS version 8 (SAS Institute, 1999).

RESULTS AND DISCUSSION

Watershed Soil Characteristics: The distribution of soil mapping units within WGEW (Breckenfeld et al., 1995) is shown in Table 1. The most extensive mapping unit in the watershed is the Luckyhills-McNeal complex, very gravelly sandy loam, which occupies approximately 4300 ha on a whole watershed basis. Other mapping units comprising substantial acreages are the Elgin-Stronghold complex, very gravelly fine sandy loam (1509 ha), McAllister-Stronghold complex, gravelly fine sandy loam (1363 ha), and Tombstone extremely gravelly sandy loam (1280 ha).

Selected physical and chemical properties of the soils are shown in Table 2. Again, the soil samples were collected from the surface 5 cm at each sampling point, irrespective of surface horizon thickness. In most cases, A-horizon thickness in these soils corresponds to our sampling depth according to the field descriptions of Breckenfeld et al. (1995). This sampling depth was considered representative of the portion of the profile most affected by erosion processes involving rill formation and infilling. These data, being from a composited depth sample include contributions from both A- and upper B-horizons in various proportions. Based on these data, some soil properties reflect differences in parent material composition between SWs. The most obvious differences exist between SWs 3 and 7, and the other SWs in terms of total clay, OC, AI, magnetic susceptibility, and hue. A large portion of the soils in SW 7 were formed on igneous residuum (i.e., granite, granodiorite) compared to limestone, andesite, and basalt parent materials in the other SWs. Consequently, SW 7 soils should have less clay and OC, and a lower AI. Similarly, the soils in SW 7 had the highest magnetic susceptibility readings, reflecting the higher magnetite contents of the igneous parent rocks. The higher Munsell color readings in SW 7 may be explained by the lighter colored, high quartz content granitic rocks, and lower OC contents. The calcareous alluvium parent materials in SW 3 contributed to somewhat similar soil conditions in terms of higher hue, value and chroma readings, a high pH, and low values for OC and AI. By contrast, SW 9 contained substantial acreages of soils formed from fine-grained igneous parent materials (i.e., andesite, basalt) which should weather to form soils with finer particle sizes. In fact, the soils in SW 9 had the highest total clay contents and AI, and relatively low average hue and value readings. Obviously, parent material has an important role in the physical and chemical behavior of soils in the WGEW.

The OC distributions varied significantly ($p \neq 0.05$) between SWs, with SW 15 containing nearly twice the concentrations of SW 7. Total N distributions were closely related to OC contents, again, with SW 15 having

Table 1 Mapping unit acreages for the subwatersheds studied in Walnut Gulch Experimental Watershed.

Soil Mapping Unit	Subwatershed					
	WS 3	WS 7	WS 9	WS 10	WS 11	WS 15
	ha					
Baboquivari-Combate complex		19.5	188.7	190.1	6.7	
Blacktail gravelly sandy loam				245.5		
Budlamp-Woodcutter complex				64.6		
Chiricahua very gravelly clay loam		101.3				
Combate loamy sand	3.0	8.2				60.0
Elgin-Stronghold complex	120.2		881.7	283.7	75.3	
Epitaph very cobbly loam			71.9	18.1		152.7
Forrest-Bonita complex			12.6	18.7		103.2
Graham cobbly clay loam			175.7	13.8		66.8
Graham-Lampshire complex			122.1	9.1		113.4
Grizzle coarse sandy loam						81.6
Lampshire-Rock outcrop complex		28.4	52.5			
Luckyhills loamy sand		14.0	7.0			
Luckyhills-McNeal complex	443.4	286.8	44.6	1.1		740.1
Mabray-Chiricahua-Rock outcrop complex		295.8				36.3
Mabray-Rock outcrop complex		193.4				150.7
McAllister-Stronghold complex	273.0		317.4	229.3	61.4	144.8
Monterosa very gravelly fine sandy loam	12.7	15.6				248.6
Riverwash-Bodecker complex		8.1		12.6		
Schiefflin very stony loamy sand		190.2				
Stronghold-Bernadino complex	94.9		38.6	178.8	421.1	
Sutherland-Mule complex		65.7				
Sutherland very gravelly fine sandy loam		141.2				403.9
Tombstone very gravelly fine sandy loam			486.3	252.0	223.6	73.4
Woodcutter gravelly sandy loam				61.9		
	947.2	1368.1	2398.9	1579.4	788.2	2375.6

significantly ($p \# 0.05$) greater amounts than the other SWs. The C/N ratios exhibited more mean separation between SWs than the OC and N components taken individually. There were also significant differences identified in the pH values between SWs that ranged from 8.6 to 6.9. Again, these greater pH values are attributed to higher CaCO_3 contents in SWs 3 and 11, whereas, the lower readings in SWs 9 and 10 are probably related to higher acid clay contents in some of these soils. In terms of exchangeable cations, Ca was the dominant element, but there were few statistically significant differences in the concentrations between SWs. Extractable Fe and Mn contents were generally low and not significantly different between SWs with the exception of Fe_d which was significantly greater in SWs 7 and 10. The distribution of ^{137}Cs in the watershed soils appeared to be controlled by soil clay contents. The highest concentrations were found in SWs 9 and 10, which also had the greatest amounts of clay.

Sediment Characteristics: The physical and chemical properties of the suspended sediments (Table 3) indicate that the particle size distributions of suspended sediments were much finer than the watershed soils within SWs due to particle size selectivity created by soil erosion and sediment transport processes. However, there were basically no significant differences between SWs regardless of size fraction. Relative to color, the hue, value, and chroma of the suspended sediment were generally higher than the watershed soils, perhaps reflecting the differences in particle size distributions between the soils and sediment. Magnetic susceptibility of the sediments ranged from 103 (SW 3) to $226 \cdot 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (SW 7). Organic C contents of the suspended sediments averaged 24.0 g kg^{-1} compared to 11.4 g kg^{-1} for the watershed soils. Total N content of the sediment was statistically similar between SWs, and was approximately 6% of the OC contents. The C/N ratios were generally slightly higher in the sediments. The pH of the

Table 2 Selected physical and chemical properties of soils for individual subwatersheds.

Property	Units	Subwatershed					
		3	7	9	10	11	15
Sand	g kg ⁻¹	720a [†]	719a	653b	698a	731a	608c
Silt	g kg ⁻¹	148c	162bc	184b	142c	136c	251a
Clay	g kg ⁻¹	133bc	118c	163a	160a	133bc	141b
WDC	g kg ⁻¹	108ab	91c	111ab	116a	102bc	98bc
AI		18.0c	22.8c	31.9a	28.1b	23.9c	28.2b
MS	10 ⁻⁸ m ³ kg ⁻¹	198b	800a	294b	189b	264b	217b
Hue [‡]		7.1b	8.2a	6.5d	6.4d	6.8c	6.9bc
Value		3.1ab	3.3a	2.9c	3.0c	3.1b	3.1b
Chroma		2.0ab	2.0a	1.7c	1.8c	1.5d	1.8bc
Organic C	g kg ⁻¹	10.2bc	8.5c	12.1ab	11.5b	11.8b	14.2a
Total N	g kg ⁻¹	0.62b	0.62b	0.76b	0.74b	0.64b	0.99a
C/N		17.4b	13.7c	16.8b	17.6b	19.1a	15.4c
pH		8.6a	7.9b	7.4c	6.9d	8.5a	7.9b
Exch. Ca	cmol kg ⁻¹	32.2a	30.4a	27.2a	17.4b	32.4a	31.9a
Exch. Mg	cmol kg ⁻¹	1.0b	1.3ab	1.7a	1.7a	1.0b	1.2ab
Exch. K	cmol kg ⁻¹	0.7a	0.7a	1.0a	0.9a	0.6a	1.0a
Exch. Na	cmol kg ⁻¹	0.02a	0.02a	0.03a	0.02a	0.01a	0.02a
Fe _p	g kg ⁻¹	0.02b	0.03b	0.08ab	0.14a	0.01b	0.05b
Fe _o	g kg ⁻¹	0.20a	0.71a	0.27a	0.40a	0.15a	0.28a
Fe _d	g kg ⁻¹	3.76c	5.46ab	4.42bc	5.34a	3.43c	3.91c
Mn _p	g kg ⁻¹	0.03b	0.03b	0.06ab	0.10a	0.03b	0.04ab
Mn _o	g kg ⁻¹	0.16b	0.32a	0.23ab	0.24ab	0.20b	0.16b
Mn _d	g kg ⁻¹	0.19b	0.40a	0.26ab	0.26ab	0.23b	0.24b
Cs	Bq kg ⁻¹	11.2c	12.8bc	14.2b	16.5a	11.1c	12.8bc

[†]Values followed by the same letter are not statistically different at $p \leq 0.05$ based on Duncan's multiple range test.

[‡]All hues are yellow red (YR).

suspended sediments averaged slightly lower than the soils which may be the result of higher clay contents in the sediment. The activities of ¹³⁷Cs in the suspended sediments were low relative to the activities of the soils. This was unexpected considering the high clay enrichment in the sediment and the strong relationship between ¹³⁷Cs and soil clays. This may indicate clays are preferentially eroded from areas depleted in ¹³⁷Cs such as rills and gullies. The suspended sediment was so uniform relative to exchangeable cation concentrations that no significant differences occurred between SWs. The extractable Fe data show that the suspended sediment was substantially higher than the soils for all three extractants in all SWs. These higher Fe_p values for the sediment are explained by the higher OC contents in the sediment, and the increases in Fe_o and Fe_d can be largely attributed to the enhanced silt and clay contents of the sediment. The Fe_o component is primarily transported as a clay coating. The Fe_d is also transported as

clay coatings, but also as clay and silt-size discrete particles. The extractable Mn component only showed consistent increases in the suspended sediment phase for the Mn_d phase, and there were basically no differences between SWs.

Table 3 Selected physical and chemical properties of suspended sediments for individual subwatersheds.

Property [†]	Units	Subwatershed						
		1	3	7	9	10	11	15
Sand	g kg ⁻¹	380ab [‡]	374ab	498ab	506ab	419ab	512a	423ab
Silt	g kg ⁻¹	143a	409a	326a	337a	410a	320a	395a
Clay	g kg ⁻¹	207ab	216ab	176ab	157b	171ab	168b	182ab
MS	10 ⁻⁸ m ³ kg ⁻¹	164b	103d	226a	176b	122cd	166b	116b
Hue		7.3b	6.7c	8.6a	6.8c	6.6c	7.0bc	6.8c
Value		3.6a	3.5ab	3.6ab	3.5ab	3.4b	3.6a	3.5ab
Chroma		2.0b	2.1a	1.9b	1.8c	1.9bc	1.8c	1.9bc
Organic C	g kg ⁻¹	23.1ab	32.1a	24.9ab	19.9b	19.3b	21.6b	26.0ab
Total N	g kg ⁻¹	1.44ab	1.90a	1.60ab	1.16b	1.21ab	1.24ab	1.58ab
C/N		16.0b	16.9ab	15.6b	17.2a	16.0b	17.4a	16.5ab
pH		7.6ab	7.8ab	7.5ab	7.7ab	7.6ab	7.8ab	7.8ab
Exch. Ca	cmol kg ⁻¹	36.7a	37.3a	36.4a	37.7a	34.9a	39.1a	38.6a
Exch. Mg	cmol kg ⁻¹	2.2a	2.1a	2.0a	2.1a	1.9a	1.8a	1.7a
Exch. K	cmol kg ⁻¹	1.2a	1.2a	1.0a	1.5a	1.1a	1.0a	1.4a
Exch. Na	cmol kg ⁻¹	0.05a	0.03a	0.04a	0.05a	0.04a	0.03a	0.05a
Fe _p	g kg ⁻¹	0.11ab	0.11ab	0.10ab	0.09bc	0.14a	0.04d	0.06cd
Fe _o	g kg ⁻¹	0.91b	0.71b	1.89a	0.48b	0.72b	0.34b	0.51b
Fe _d	g kg ⁻¹	5.38abcd	5.60abc	6.47a	4.77cd	6.11ab	4.14d	4.99bcd
Mn _p	g kg ⁻¹	0.04c	0.03c	0.04c	0.08b	0.13a	0.03c	0.03c
Mn _o	g kg ⁻¹	0.18b	0.16b	0.30a	0.22ab	0.27a	0.15b	0.16b
Mn _d	g kg ⁻¹	0.35b	0.32b	0.52a	0.33b	0.41ab	0.41b	0.34b
Cs	Bq kg ⁻¹	8.9	8.1	11.9	7.6	8.0	6.7	12.1

[†]p, o, and d denote pyrophosphate, oxalate and dithionite extractable, respectively.

[‡]Values followed by the same letter are not significantly different at $p \leq 0.05$ based on Duncan's multiple range test.

The ratios determined for suspended sediment versus watershed soil properties indicate that, relative to the watershed soils, clay contents of the sediment were enriched by an average factor of 1.38. The greatest enrichment (1.67) occurred in SW 3, and the least (1.02) was recorded for SW 9. These two SWs had the lowest and highest AI, respectively (Table 2). This indicates that, overall, SW 3 had the most highly erodible soils in the WGEW, and SW 9 had the least erodible. These enrichment ratios (ER) of suspended sediment clays to soil clays were correlated against the SW soil AI for the six individual SWs. The resulting correlation coefficient (r) was -0.946 ($p \neq 0.01$). The only apparent discrepancy in the indicated strong relationship is the relatively high ER for SW 15 considering its high AI. However, SW 15 soils had the highest OC contents, suggesting that this sediment is transported in an OC stabilized, clay aggregate form as opposed to dispersed clay-size particles elsewhere. Further, suspended

sediments were more enriched in silt-size material, relative to the clay fractions, in most SWs by a factor of 2 to 3 times. Likewise, the OC contents of the suspended sediment were enriched by an average ratio of 2.13, relative to the watershed soils. The highest OC concentrations in the suspended sediments were associated with the lower AI soils, with the exception of SW 15. The magnetic susceptibility ratios for suspended sediments versus SW soils averaged 0.56 indicating the suspended sediments were depleted relative to the soils. This suggests that the soil magnetic fraction, primarily magnetite, is concentrated in the sand-size fraction which is also depleted in the suspended sediment. Since magnetic susceptibility is so particle size dependent, an accurate assessment of this soil property as a fingerprinting tool requires that similar particle size distributions be used when measuring soil and sediment samples.

Based on the highest ER for clay and the lowest soil AI (Table 2), both indicators of low aggregate stability/high erodibility, SW 3 would be expected to produce the greatest amounts of sediment in the runoff on a per unit area basis for a given rainfall event. Following SW 3, the order for ER is: $7 > 15 > 11 > 10 > 9$. The order for AI by SW is: $9 > 15 \geq 10 > 11 > 7 > 3$. These results may be substantiated by the average suspended sediment concentrations measured at each of the flumes which are reasonably close to expected results based on ER and AI. Specifically, the order of suspended sediment concentrations were: SW 7 (0.040 g ml^{-1}) $>$ 3 (0.028 g ml^{-1}) $>$ 11 (0.23 g ml^{-1}) $>$ 9 (0.015 g ml^{-1}) $>$ 10 (0.013 g ml^{-1}) $>$ 15 (0.009 g ml^{-1}). Obviously, the relative land areas associated with the various slope factor components in each SW also have a strong influence on sediment yields measured at each flume, but the use of soil-sediment factors such as ER and AI appears to be a reasonable approach to estimating potential sediment yields in the SWs.

Sediment Source Estimations: Based on the results obtained from the multivariate mixing model as previously described, the percentage contributions of each SW to the sediment load monitored at flume 1 are as follows: SW 3, 54.2%; SW 7, 20.3%; SW 9, 12.6%; SW 10, 0%; SW 11, 12.9%; and SW 15, 0%. Obviously, these data present a number of questions. Specifically, how can we realistically assume no contributions from SWs 10 and 15 considering their size (Table 1)? Further, how realistic is the estimated 54.2 and 20.3% contributions of SW 3 and 7? Presently, such questions cannot be adequately addressed; however, there are some factors which make some of these source contributions seem reasonable. For example, SWs 10 and 15 had the two highest AI values after SW 9, which means that on the average, the soils in these SWs were relatively unerodible. Within this context, the 12.6% contribution by SW 9 is hard to explain since it had the third lowest average sediment concentration behind 10 and 15, and the lowest ER for clay content of all SWs. Of perhaps greater importance in this regard is the fact that 40.4 and 38.4% of the soils in SWs 9 and 11, respectively, occurred on E class (13-20%) slopes or steeper, compared to 35.5 and 17.4% for the soils in SWs 10 and 15, respectively.

In the case of SWs 3 and 7, the estimated greatest contributors of sediment leaving the watershed, the soils in these two SW had the lowest AI while the percent clay ER and sediment concentrations measured at these two flumes were the highest in the WGEW. All of these results correspond well with data expected from highly erodible watersheds. Additionally, these two SWs are closest to flume 1, thus the sediment contributed by these SWs to the main channel does not undergo as much sorting prior to its delivery at flume 1, relative to the other SWs. Also, the soils in the SW surrounding flume 1 are most similar to those in SW 3. This is a problem that could lead to an overestimation of the contribution from SW 3 which requires additional attention.

CONCLUSIONS

This preliminary study demonstrated that an approach of characterizing watersheds on the basis of soil geomorphology in conjunction with the use of a range of fingerprinting properties, digital elevation models, and digitized soil surveys has the potential to provide a reasonably accurate means of estimating which portions of a watershed are producing the greatest amounts of sediment. Additional research is necessary, however, to resolve questions related to the accuracy of multivariate mixing models used to calculate the relative contributions of sub-components of the watershed, and to determine which soil mapping units are the greatest sediment sources in individual SWs. Eventually, this ability to identify primary sediment sources in watersheds will contribute to a more efficient design of best management practices to affect maximum reductions in sediment and chemical contaminant loads in watersheds.

REFERENCES

- Bonniwell, E.G., Matisoff, G., and Whiting, P. J. (1999). "Determining the times and distances of particle transit in a mountain stream using fallout radionuclides", *Geomorph.* 27: 75-92.
- Breckenfeld, D. J., Svetlik, W. A., and McGuire, C. E. (1995). *Soil Survey of Walnut Gulch Experimental Watershed*. U. S. Dept. of Agric., Soil Conservation Service, Washington, DC.
- Dearing, J. A., Morton, R. A., Price, T. W., and Foster, I. D. L. (1986). "Tracing movements of topsoil by magnetic measurements: Two case studies", *Phys. Earth Planet. Inter.* 42: 93-104.
- Franzmeier, D.P., Pedersen, E. J., Longwell, T. J., Byrne, J. G., and Losche, C. K. (1969). "Properties of some soils in the Cumberland Plateau as related to slope aspect and position", *Soil Sci. Soc. Am. Proc.* 33: 755-761.
- Grimshaw, D.L., and Lewin, J. (1980). "Source identification for suspended sediments", *J. Hydrol.* 47: 151-162.
- Hanna, A. Y., Harlan, P. W., and Lewis, D. T. 1982. "Soil available water as influenced by landscape position and aspect", *Agron. J.* 74: 999-1004.
- Harris, S. (1971). "Index of structure: Evaluation of a modified method of determining aggregate stability", *Geoderma* 6: 155-162.
- Klages, M. G., and Hsieh, Y. P. (1975). "Suspended solids carried by the Gallatin River of southwestern Montana: II. Using mineralogy for inferring sources", *J. Environ. Qual.* 1: 68-73.
- McLean, E. O. (1982). "Soil pH and lime requirement", p. 199-204. *In* A. L. Page et al. (ed.) *Methods of soil analysis*. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
- Neiheisel, J. and Weaver, C. E. (1967). "Transport and deposition of clay minerals, southeastern United States", *J. Sediment Petrol.* 37: 1084-1116.
- Oldfield, F., Rummery, T. A., Thompson, R., and Walling, D. E. (1979). "Identification of suspended sediment sources by means of magnetic measurements: Some preliminary results", *Water Resour. Res.* 15: 211-218.
- Peart, M. R., and Walling, D. E. 1988. "Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK; A comparative assessment", *In*, *Sediment Budgets*, Intl. Assoc. Hydrol. Sci. Publ. 174, pp. 269-279.
- Renard, K. G., Lane, L. J., Simanton, J. R., Emmerich, W. E., Stone, J. J., Wertz, M. A., Goodrich, D. C., and Yakowitz, D. S. (1993). "Agricultural impacts in an arid environment: Walnut Gulch studies", *Hydrol. Sci. Technol.* 9: 145-190.
- Rhoton, F. E., Smeck, N. E., and Wilding, L. P. (1979). "Preferential clay mineral erosion from watersheds in the Maumee River Basin", *J. Environ. Qual.* 8: 547-550.
- Rhoton, F. E., Lindbo, D. L., and Römken, M. J. M. (1998). "Iron oxides – erodibility interactions for soils for the Memphis Catena", *Soil Sci. Soc. Am. J.* 62: 1693-1703.
- SAS Institute. (1999). *The SAS system for windows*. SAS Inst., Cary, NC.
- Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., and Broderson, W. D. (2002). *Field book for describing and sampling soils*, Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
- Slattery, M.C., Hurt, T. P., and Walden, J. (1995). "The application of mineral magnetic measurements to quantify within-storm variations in suspended sediment sources", *IAHS Publ. No.* 229: 143-151.
- Sutherland, R.A., and Bryan, R. B. (1989). "Variability of particle size characteristic of sheetwash sediments and fluvial suspended sediment in a small semiarid catchment, Kenya", *Catena* 16: 189-204.
- USDA-Natural Resources Conservation Service. (1996). *Soil Survey Laboratory Methods Manual*, Soil Survey Investigations Report No.42. U. S. Govt. Print. Office, Washington, DC.
- Wall, G. J., and Wilding, L. P. (1976). "Mineralogy and related parameters of fluvial suspended sediments in Northwestern Ohio", *J. Environ. Qual.* 5: 168-173.
- Wallbrink, P. J., Murray, A. S., and Olley, J. M. (1999). "Relating suspended sediment to its original soil depth using fallout radionuclides", *Soil Sci. Soc. Am. J.* 63: 369-378.
- Walling, D. E., and Woodward, J. C. (1992). "Use of radiometric fingerprints to derive information on suspended sediment source", *IAHS Publ. No.* 215: 153-164.
- Walling, D. E., and Woodward, J. C. (1995). "Tracing sources of suspended sediment in river Basins: A case study of the River Culm, Devon, UK", *Mar. Freshwater Res.* 46: 327-336.
- Whiting, P. J., Matisoff, G., Fornes, W. F., and Soster, F. M. (2005). *Suspended sediment sources and transport distances in the Yellowstone basin*. GSA Bulletin, 117, pp 515-529.