Published online May 16, 2007

An Aggregation/Erodibility Index for Soils in a Semiarid Watershed, Southeastern Arizona

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Variations in soil profile thickness, surface soil properties, erosion rates, runoff, and sediment properties within similar soils and watersheds are controlled by slope factors such as steepness, length, and position through their influence on soil water regimes, and thus soil erodibility. This study was conducted to determine the effects of slope on the variation of soil erodibility at watershed scales using an aggregation index (AI) approach and soil attributes that influence erodibility and suspended sediment properties. Each major soil type in six subwatersheds (SWs) was sampled along transects positioned to represent the normal slope factors within a given mapping unit. At each sampling point, latitude–longitude, slope steepness, position, and aspect were recorded. Soil samples collected from the surface 5.0 cm were characterized for particle-size distribution, water dispersible clay (WDC), total and organic C, pH, and quantitative color. Suspended sediment samples collected from each SW were characterized for similar parameters. Clay contents of the soils and suspended sediments averaged 141.3 and 179.3 g kg^{-1}, respectively. An AI, was used as an indicator of soil erodibility. Enrichment ratios (ER) for clay contents in the sediment ranged from 1.03 to 1.67. The correlation coefficient (r) for AI versus ER was −0.946 ($p \leq 0.01$) indicating a strong relationship between watershed soil erodibility and suspended sediment properties. The data show that AI was greatest on the steeper slope classes, toeslope and backslope positions, and on the more northern aspects. These results suggest that AI can be used to determine the erodibility over a range of soil and slope conditions.

Abbreviations: AI, aggregation index; ER, enrichment ratio; MLRA, Major Land Resource Area; SWs, subwatersheds; WDC, water dispersible clay; WGEW, Walnut Gulch Experiment Watershed .

PEDOLOGY

Within a given mapping unit, the extent to which soils erode is largely determined by rainfall characteristics, topography, and vegetative cover. As soil phases change, differences in erosion losses can be attributed to changes in soil properties that determine soil erodibility (Bryan, 1969). Basically, soil erodibility is determined by aggregate stability, as poorly aggregated soils are dispersed at relatively low rainfall energies. This produces surface sealing and increased runoff that contains a high proportion of easily transported fine particles relative to better aggregated soils. Generally, the level of aggregate stability depends on the content of bonding agents in the soil such as clay, Fe and Al oxides, and organic C that bind soil materials into stable units. Within this context, the soil clay fraction serves as the building block for aggregate stability, and the degree to which clay particles in soil aggregates disperse in water can be taken as a measure of aggregate stability and soil erodibility.

The role of slope, in terms of soil erodibility and sediment characteristics, is related to its influence on those soil properties that determine aggregate stability since these properties vary as a function of surface morphometry factors (Schoeneberger et al., 2002) such as slope aspect, gradient, position, and shape. The relationship between soil properties that influence erodibility and slope has been addressed in several studies. Franzmeier et al. (1969) found 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 locations, and basic cations were concentrated on the lower slope positions. Hanna et al. (1982) reported 20% more available water on north-facing slopes relative to their south-facing counterparts, which should account for the greater organic C contents on the northern slopes. The east-facing slopes had the driest soils.

In a more recent study, Young and Hammer (2000) evaluated soil attribute variation with landscape position from a soil management and land-use perspective. They reported that backslope positions contained more argillic horizon clay, less organic C, lower pH and base saturation, and less silt on a clay-free basis, relative to summit and shoulder positions. These variations were attributed to differences in soil drainage patterns. Other researchers (Honeycutt et al., 1990) found organic C increases of 23% between the summit and footslope positions. Pierson and Mulla (1990) also recorded the highest organic C contents in the footslope and toeslope positions where they also recorded the greatest aggregate stability. Similar findings have been reported by Rhoton et al. (1998) in which WDC and soil erodibility were at a minimum on the lower, wetter slope positions due to high concentrations of ferrihydrite, an effective cementing agent of soil aggregates.

Although some soil aggregate stability characterization work has been done on semiarid soils in New Mexico (Bird et al., 2002; Herrick et al., 2001), these studies did not necessarily address the issue of aggregate stability variations in the landscape. Also, considerable research has been conducted in southern Arizona on the influence of vegetation and stone cover on infiltration, runoff, sediment size distributions, and erosion losses (Abrahams

Soil Sci. Soc. Am. J. 71:984–992
doi:10.2136/sssaj2005.0238
Received 20 July 2005.
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and Parsons,1991; Parsons et al., 1991; Abrahams et al., 1995). However, this work was conducted either on small runoff or rainfall simulator plots. Again, there was no accounting for slope factors or watershed scale components, and the soil aggregate stability or erodibility parameters were not characterized in detail. Further, considerable work has been conducted on the genesis and formation of semiarid soils in this region (Gile et al., 1966; Gile, 1977), but basically no applied information is available for the parent material/soil formation influences on aggregate stability and erodibility. However, as indicated by Singer and Warrington (1992), the greatest contribution of soil formation in semiarid regions to this area of research may be through its influence on Ca accumulations and formation of petrocalcic horizons (Gile et al., 1966), and particle size distributions and organic C contents.

The objectives of this study were to assess the suitability of using an AI for quantifying soil erodibility at the watershed scale, on the basis of soil attributes that determine levels of soil aggregation and vary in the landscape as a function of slope.

MATERIALS AND METHODS

Site Characteristics

The research was conducted on six SWs (3, 7, 9, 10, 11, and 15) in the Walnut Gulch Experimental Watershed (WGEW), which includes the town of Tombstone in southeastern Arizona (Fig. 1). This 150 km^2 watershed is in a transition zone between the Sonoran and Chihuahuan Deserts (31° 43′ N, 110° 41′ W), and within Major Land Resource Area (MLRA) 41, Southeastern Arizona Basin and Range (Soil Conservation Service, 1981). Geomorphically, the WGEW is a high foothill alluvial fan component of the larger San Pedro River Watershed with elevations ranging from 220 to 1890 m. Climatically, the mean annual temperature is 17.6 °C, with an average annual precipitation of 324 mm (Renard et al., 1993), which occurs primarily as high intensity, short duration thunderstorms from July to mid-September (Osborn et al., 1979) that produce most of the surface runoff (Nichols et al., 2000).

Soil distribution in WGEW is largely determined by the composition of the parent material. The Walnut Gulch Basin is formed on Precambrian to Tertiary-age rocks consisting of sandstone and conglomerates, limestone, volcanics, granodiorite, and quartz monzonite. Limestone influenced, Quaternary alluvium parent material dominates the watershed, occupying ~80% of the basin surface (Alonso, 1997). The soils developed from this parent material are generally well-drained, calcareous, gravelly loams with rock and gravel contents at the soil surface ranging up to 70% on very steep slopes (Gelderman, 1970; Simanton et al., 1994). The other soils in the watershed were formed in alluvium and colluvium from basalt and andesite, and in residuum from coarser textured granodiorite. Generally, these soils are finer textured, shallow, and well-drained.

Major vegetation in SWs 3, 7, and 15 consists of the shrub species of creosote bush (*Larrea tridentata*), whitethorn (*Acacia constricta*), tarbush (*Flourensia cernua*), snakeweed (*Gutierrezia sarothrae*), and burroweed (*Aplopappus tenuisectus)*. The grass species of black grama (*Bouteloua eriopoda*), blue grama (*Bouteloua gracilis*), sideoats grama (*Bouteloua curtipendula*), curly mesquite (*Hilaria belangeri)* and bush muhly (*Muhlenbergia porteri*) are the dominant vegetation in SWs 9, 10, and 11 (Simanton et al., 1994). The entire watershed is used as rangeland.

Study Approach

Each SW used in the study was instrumented with a supercritical flume (Renard et al., 1993). Suspended sediments were collected at

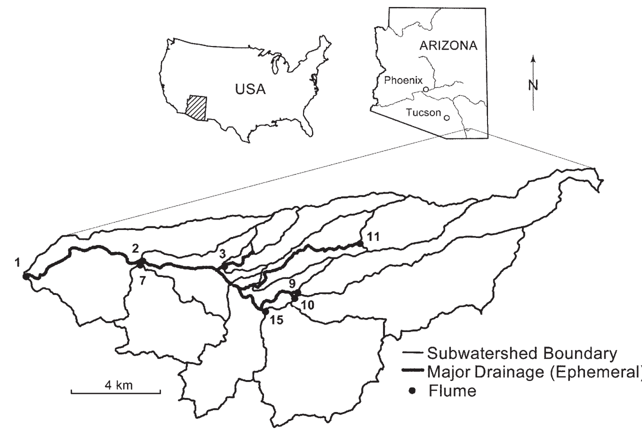

Fig. 1. Location of various subwatersheds in the Walnut Gulch Experimental Watershed, Arizona (from Simanton and Toy, 1994).

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 watershed on the basis of relative acreage occupied by individual 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 (Fig. 2). 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 slope position, steepness, and aspect along the transects. At each selected location, the surface 5.0 cm was sampled at three points, approximately 10 m apart and perpendicular to the slope. The three soil samples were composited to form a single bulk sample, sieved to <4 mm, and sealed in a plastic bag. Data were recorded at each sampling location for latitude–longitude, slope position, slope aspect, and steepness.

Laboratory Analyses

In the laboratory, soil and sediment samples were either air- or oven-dried at 60°C, and sieved to <2 mm. Particle-size distribution was determined by standard pipette analysis following overnight dispersion in sodium hexametaphosphate (Soil Survey Staff, 1984). The WDC 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 was 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 C was quantified by treating a separate 1-g sample with 5*M* HC1 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

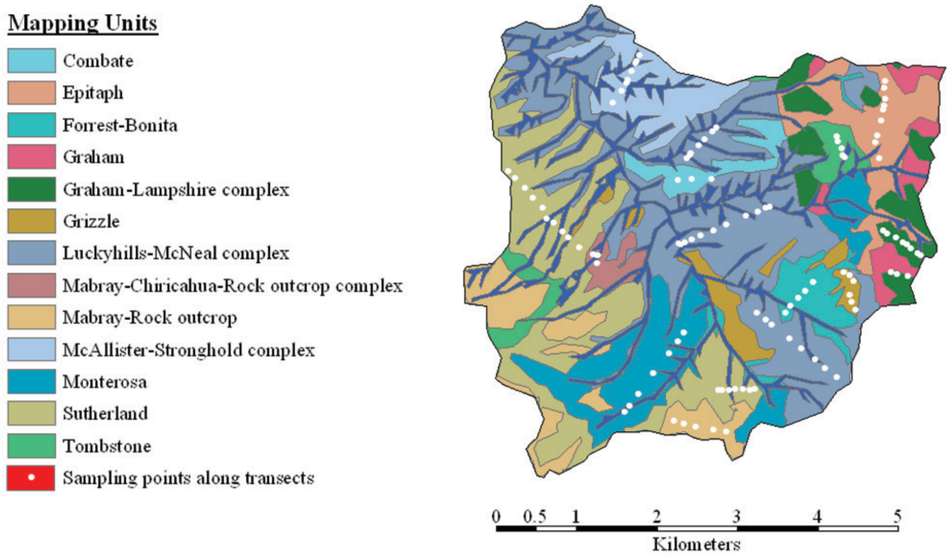

Fig. 2. Watershed sampling approach based on relative area of the mapping units, showing sampling points along transects in subwatershed 15.

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 content. 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:

$$AI = 100\left(1 - \frac{\text{WDC}}{\text{total clay}}\right)$$

All statistical analysis utilized the GLM procedure of SAS version 8 (SAS Institute, 1999).

RESULTS AND DISCUSSION

Soil Characteristics

The soils mapped in WGEW (Breckenfeld et al., 1995) with associated landforms, according to the terminology of Peterson (1981), appear in Table 1. The majority of the soils are mapped either on fan remnants or hills. Fan remnants are the oldest and most stable landform developed from the early Pleistocene to early Holocene. According to Breckenfeld et al. (1995), hills are not associated with any specific age, and are thus not considered a geomorphic surface. The alluvial fans and flood plains are being developed on recent Holocene alluvium. The basin floor landform developed in the late to mid-Pleistocene. In terms of soil distribution, the Luckyhills–McNeal complex, which contains 4300 ha, was by far the most extensive mapping unit in the overall watershed (Table 2). Three other mapping units (Elgin-Stronghold, McAllister-Stronghold, Tombstone) ranged from 1280 to 1510 ha. Most of the other mapping units had considerably smaller acreage.

The watershed soil properties (Table 3) were averaged across individual soil mapping units within a given SW. The fine earth fractions (<2 mm) of the soils fell within the loamy sand or sandy

Table 1. Soil taxonomy and landforms of mapping units in Walnut Gulch Experimental Watershed.

Soil phase	Taxonomic classification	Landform
Baboquivari gravelly coarse sandy loam	fine-loamy, mixed, thermic Ustic Haplargids	fan remnant
Bernardino gravelly clay loam	fine, mixed, superactive, thermic Ustic Calciargids	fan remnant
Blacktail gravelly sandy loam	fine, mixed, superactive, Calcidic Agriustolls	fan remnant
Bodecker extremely gravelly sandy loam	sandy-skeletal, mixed, thermic Ustic Torriorthents	flood plains
Bonita cobbly silty clay	fine, smectitic, thermic Typic Haplotorrerts	flood plains
Budlamp very gravelly fine sandy loam	loamy-skeletal, mixed, thermic Lithic Haplustolls	mountains
Chiricahua very cobbly loam	clayey, mixed, superactive, thermic, shallow Ustic Haplargids	hills
Combate gravelly loamy coarse sand	coarse-loamy, mixed, non-acid, thermic Ustic Torrifluvents	alluvial fans
Elgin very gravelly fine sandy loam	fine, mixed, thermic Calcic Paleargids	fan remnant
Epitaph very cobbly clay loam	fine, smectitic, thermic Petrocalcic Calcitorrerts	hills
Forrest loam	fine, mixed, superactive, thermic Ustic Calciargids	basin floor
Graham cobbly clay loam	clayey, smectitic, thermic Lithic Ustic Haplargids	hills
Grizzle coarse sandy loam	fine loamy, mixed, superactive, thermic Ustic Calciargids	hills
Lampshire very cobbly loam	loamy-skeletal, mixed, superactive, non-acid, thermic Lithic Ustic Torriorthents	hills
Luckyhills very gravelly sandy loam	coarse-loamy, mixed, thermic Ustic Haplocalcids	fan remnant
McAllister loam	fine-loamy, mixed, thermic Ustic Calciargids	fan remnant
McNeal gravelly sandy loam	fine-loamy, mixed, thermic Ustic Calciargids	fan remnant
Mabray very gravelly loam	loamy-skeletal, carbonatic, thermic Lithic Ustic Torriorthents	hills
Monterosa very gravelly sandy loam	loamy-skeletal, mixed, superactive, thermic, shallow Ustic Petrocalcids	fan remnant
Mule very gravelly fine sandy loam	loamy-skeletal, carbonatic, thermic Ustic Haplocalcids	fan remnant
Schiefflin very stony loamy sand	mixed, thermic Lithic Torripsamments	hills
Stronghold gravelly fine sandy loam	coarse-loamy, mixed, thermic Ustic Haplocalcids	fan remnant
Sutherland gravelly fine sandy loam	loamy-skeletal, carbonatic, thermic, shallow Calcic Petrocalcids	fan remnant
Tombstone extremely gravelly fine sandy loam	loamy-skeletal, mixed, thermic Ustic Haplocalcids	fan remnant
Woodcutter very gravelly fine sandy loam	loamy-skeletal, mixed, thermic Lithic Agriustolls	hills and mountains

loam textural classes, with sand and silt contents ranging from 608 to 731 g kg^{-1} and 136 to 251 g kg^{-1}, respectively. Clay contents were between 118 and 163 g kg^{-1}. Total C contents ranged from 16.4 to 29.2 g kg^{-1}, with the organic fraction averaging 53%. The AI data, which ranged from 18 to 31.9, indicated a large difference in aggregate stability over the watershed. Soil hues in individual SWs ranged from 6.4 to 8.2 YR.

The variability in these soil properties between individual SWs reflect the influence of various parent materials. The greatest difference in this regard is between SW 7 and the other SWs in terms of clay content, organic C, and AI. Many of the soils in SW 7 were formed from igneous residuum (i.e., granite, granodiorite). These parent materials are more resistant to weathering than the limestone found in other watersheds. Consequently, soils formed on the more resistant parent materials have less clay and organic C, and thus lower AI values. The higher Munsell color notations for these soils are likely the result of the lighter colored granitic rocks and lower organic C contents. By contrast, a high percentage of the acreage in SW 9 consisted of soils formed by the weathering of fine grained, igneous rocks (i.e., andesite, basalt) that are composed of more weatherable minerals (i.e., hornblende, olivine). These parent materials weather to soils with finer particle sizes, which is consistent with the highest total clay and organic C contents, AI, and the darker soil color (hue, value). This suggests that AI/soil erodibility in WGEW is influenced by the parent material composition.

The correlations between AI and other soil properties are shown in Table 4. Of these soil properties, silt and organic C contents were most highly correlated with AI. Although total C was also significantly correlated with AI in four of the six watersheds, its importance may simply be a function of an interaction between the organic and total C fractions. This suggests that the silt and organic C fractions are better determinants of AI for these semiarid soils than clay contents, with the exception of SW 15. The lowest *r* values for silt contents vs. AI were in SWs 7 and 11. However, no other soil property was significantly correlated with AI in these SWs other than total C in SW 11. In terms of soil color, the only significant *r* values were recorded for hue, value, and chroma for SW 9, and in SW 15 for value and chroma. The practical significance of the relationship between the soil color components and AI is unclear. The generally positive correlations between hue and AI suggests a lack of involvement of Fe oxides in the stabilization of these soils, assuming higher Fe oxide concentrations would have resulted in lower hues. The significant negative correlations between value and chroma, and AI are more or less expected since the organic C fraction is also highly

Table 2. Mapping unit acreages for the subwatersheds studied in Walnut Gulch Experimental Watershed.

Soil phase	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	1	41.2				403.9
Tombstone very gravelly fine sandy loam			486.3	252.0	223.6	73.4
Woodcutter gravelly sandy loam				61.9		
Totals	947.2	1368.1	2398.9	1579.4	788.2	2375.6

Table 3. Selected soil physical and chemical properties averaged for individual watersheds.

Subwatershed	*n*	Particle-size distribution			Water dispersible clay	Total carbon	Organic carbon	Aggregation index	pH	Munsell color		
		Sand	Silt	Clay						Hue	Value	Chroma
		g kg^{-1}										
3	59	720	148	133	108	23.2	10.7	18.0	8.6	7.1†	3.1	2.0
7	49	719	162	118	91	18.6	8.5	22.8	7.9	8.2	3.3	2.0
9	114	653	184	163	111	19.3	12.1	31.9	7.4	6.5	2.9	1.7
10	74	698	142	160	116	16.4	11.5	28.1	6.9	6.4	3.0	1.8
11	47	731	136	134	102	26.8	11.8	23.9	8.5	6.8	3.1	1.5
15	92	608	251	140	98	29.2	14.2	28.2	7.9	6.9	3.1	1.8

†All Munsell colors are from wet samples. The hues are YR (yellow red).

Table 4. Correlation coefficients for aggregation index (AI) versus selected physical and chemical properties by subwatershed.

Comparison		Correlation coefficients (*r*)					
		SW3	SW 7	SW 9	SW 10	SW 11	SW 15
AI vs	Sand	–0.312*	–0.049	–0.388**	–0.046	0.214	–0.455**
	Silt	0.293*	0.037	0.520**	0.366**	–0.253	0.372**
	Clay	0.258*	0.051	0.026	–0.181	-0.030	0.466**
	Organic C	0.489**	0.254	0.643**	–0.214	0.270	0.618**
	Total C	0.453**	0.128	0.362**	–0.254	0.341*	–0.023
	Hue	0.229	–0.186	0.339**	0.131	0.144	–0.044
	Value	0.066	–0.102	–0.445**	0.071	0.132	–0.459**
	Chroma	–0.210	–0.033	–0.433**	0.243*	–0.255	–0.389**
	pH	0.132	–0.122	–0.111	–0.408**	0.002	–0.733**

*Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

correlated, assuming at increasing C levels, value and chroma will be lowered. Soil pH and AI were significantly correlated in SWs 10 and 15. These two SWs had a weighted pH average of 6.9 and 8.0, respectively, suggesting that the existence of acid soil pH conditions is more favorable for enhanced AI values perhaps due to greater exchange capacities.

Sediment Characteristics

The characteristics of the suspended sediments from each SW (Table 5) indicate a considerable difference relative to the watershed soils. Particle-size distributions of the suspended sediment is finer due to size selectivity associated with erosion and sediment transport processes. Relative to textural class, the sediments were generally loam or clay loam. Both total and organic C contents of the suspended sediments were higher than their source soils, ranging from 28.0 to 50.3 g kg^{-1} for total, and 19.3 to 32.1 g kg^{-1} for the organic fraction. Suspended sediment pH did not show much variation as a function of SW as all average values were between 7.5 and 7.8. Sediment hues varied from 6.6 at SW 10 to 8.6 at SW 7, which is indicative of the differences in parent material. Value and chroma were relatively constant among watersheds, at 3.5 and 2.0, respectively.

The sediment and soil properties were compared in their respective SW (Table 6). The watershed soil data represent a weighted average calculated by multiplying the relative acreage of a given soil type in a SW times the value for a given soil property. These values were then summed for all soil types for a weighted average by SW. Since particle-size distributions and organic C contents strongly influence aggregate stability and AI (Table 3), the discussion will be primarily concerned with relationships involving these two soil properties and their impact on suspended sediment properties.

Relative to the soils, the clay contents of the suspended sediments 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 3). This indicates that, overall, SW 3 had the most highly erodible soils in 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 SW. The resulting correlation coefficient (*r*) was −0.946 ($p \leq 0.01$). The only apparent discrepancy in this strong relationship is the relatively high ER for SW 15 considering its high AI. However, SW 15 soils had the highest C contents, suggesting that this sediment is transported in an organic C stabilized, clay aggregate form as opposed to dispersed clay size particles elsewhere.

The organic C contents of the suspended sediment were enriched relative to the SW soils. The average ER was 2.13, or C contents were more than twice those of the soils. The highest C concentrations in the suspended sediments were associated with the lower AI soils, again with the exception of SW 15. The *r* value for the ER of suspended sediment/soil organic C versus AI was −0.866 ($p \leq 0.05$).

Slope Effects on Soil Properties

Based on the strong correlations between AI and suspended clay concentrations in WGEW, AI is taken as an index of soil erodibility. Using this approach, the distribution of AI and other associated soil properties were evaluated as a function of slope factors. The distribution of these properties (Table 7) indicate that AI was responsive to changes in slope class in some SWs. More specifically, the AI values recorded for the E (13–20%) and F (>20%) slope classes were significantly ($p \leq 0.20$) greater than most others in SWs 3, 9, 11, and 15. These higher AI values coincide, in most instances, with maximums for clay and total/organic C contents. The Graham, Graham–Lampshire, and Epitaph soils occur on these steeper slopes, and have higher clay and nutrient contents (data not shown). Both of these factors contribute to greater water holding capacity and fertility, and thus favors a higher AI and organic C content since a wide variety of grasses dominate these three mapping units. This may be substantiated in SWs 7, 9, 11, and 15 by the minimum Munsell value and chroma readings on the F slopes. Soil pH was also lowest on F slopes in SWs 7, 9, 10, and 15, which may be due to the loss of basic cations in runoff on these steep slopes. Conversely, the higher AI values for soils on the steeper slopes may simply be the result of more acid parent materials occurring on those slopes. For example, the two lowest pH readings of 6.2 and 6.4 were recorded on the F slopes in SW 10 and 15, respectively. Both of

Table 5. Chemical and physical properties of suspended sediments.

Subwatershed	Particle-size distribution			Carbon content		pH	Munsell color		
	Sand	Silt	Clay	Total	Organic		Hue	Value	Chroma
	g kg^{-1}								
3	374	410	216	50.3	32.1	7.8	6.7†	3.5	2.1
7	499	326	175	43.1	24.9	7.5	8.6	3.6	2.0
9	506	337	157	30.8	19.9	7.7	6.8	3.5	1.8
10	419	410	171	28.0	19.3	7.6	6.6	3.4	1.9
11	512	321	168	44.8	21.6	7.8	7.0	3.6	1.8
15	423	395	189	47.8	26.0	7.8	6.8	3.5	1.9

†All Munsell colors are from wet samples. The hues are YR (yellow red)

these SWs had a substantial acreage of soils (Graham, Graham–Lampshire complex) formed on slopes exceeding 20% with a pH range of 6 to 6.5.

The distribution of AI by slope position (Table 8) indicated that the greatest values occurred on the TS position in SWs 3, 7, 9, and 10. In SW 11 and 15, AI was at a maximum on the backslope (BS) and summit (SUM) positions, respectively. Although few significant differences ($p \leq 0.20$) were identified between slope positions within a watershed, the data suggest an increasing trend for AI at the lower slope positions for those soils with the lower AI readings on

Table 6. Ratio of suspended sediment to watershed soil properties.

	Particle-size distribution			Carbon content			Munsell color		
Subwatershed	Sand	Silt	Clay	Total	Organic	pH	Hue	Value	Chroma
3	0.50	2.72	1.67	2.07	2.89	0.91	0.94†	1.13	1.11
7	0.72	1.83	1.40	2.05	2.59	0.96	1.06	1.13	0.99
9	0.74	2.02	1.03	1.56	1.72	1.04	1.05	1.19	0.99
10	0.58	3.08	1.17	1.74	1.76	1.10	1.03	1.13	1.12
11	0.70	2.36	1.25	1.64	1.81	0.92	1.01	1.16	1.21
15	0.70	1.53	1.36	1.59	2.01	0.98	0.99	1.08	1.00

†All Munsell colors are from wet samples. The hues are YR (yellow red).

Table 7. Distribution of a watershed soil properties as a function of slope class.

Slope class	Particle-size distribution: Sand	Silt	Clay	WDC	Carbon: Total	Organic	Aggreg. index	pH	Soil color: Hue	Value	Chroma
	g kg^{-1}										
					Subwatershed 3						
A†	621b‡	240a	139b	109b	32.1a	14.3a	21.0a	8.7a	7.6a§	3.2a	1.9b
B	722a	148b	129b	107b	18.1c	9.3b	16.9b	8.6a	6.7b	3.1a	2.2a
C	743a	132b	124b	103b	23.6bc	9.5b	17.1b	8.6a	7.3a	3.2a	1.9b
D	744a	127b	129b	106b	22.5bc	10.1b	17.6b	8.5a	7.2a	3.1a	1.8b
E	692a	144b	165a	131a	27.5ab	14.7a	20.9a	8.8a	6.9b	3.2a	2.1a
F											
					Subwatershed 7						
A	763a	149bc	89c	69d	17.5bc	3.8a	23.3a	8.1a	7.5c	3.7a	2.3a
B	724ab	166abc	110abc	86bcd	14.8bc	5.9cd	22.0a	8.0ab	7.9bc	3.4bc	2.2a
C	769a	128c	103c	79cd	10.2c	4.0d	22.3a	7.7b	8.7ab	3.2cd	2.1ab
D	733ab	141c	126c	100ab	21.5ab	8.9c	20.4a	7.9ab	8.9a	3.4b	2.0bc
E	689bc	183ab	128ab	98abc	26.5a	12.8b	23.7a	7.9ab	8.4abc	3.1d	1.8cd
F	644c	199a	157a	114a	21.5ab	17.3a	27.1a	7.3c	7.9bc	2.7e	1.7d
					Subwatershed 9						
A	629a	215b	156ab	104a	13.7c	9.4c	32.0b	7.1bc	6.4b	2.9b	1.7ab
B	698a	158c	144b	102a	20.3ab	10.8c	29.9b	7.7a	6.6ab	3.1a	1.8a
C	642a	175bc	183a	124a	15.7bc	11.0c	31.3b	7.3abc	6.3b	2.9b	1.8a
D	666a	168bc	166ab	118a	22.0a	12.3c	30.2b	7.5ab	6.6ab	3.0ab	1.7ab
E	659a	167bc	174ab	115a	23.0a	16.5b	34.0b	7.2bc	6.8a	2.7c	1.6b
F	488b	323a	189a	99a	25.4a	21.8a	46.6a	7.0c	6.8a	2.5d	1.3c
					Subwatershed 10						
A	678a	155ab	167ab	120ab	10.4c	8.6b	30.2a	6.7bc	6.2c	3.0a	1.8ab
B	695a	168a	137b	91b	16.1bc	9.7b	30.0a	7.1ab	6.3bc	3.1a	1.8ab
C	748a	120c	132b	98b	15.2bc	10.9ab	25.9a	6.5bc	6.1c	2.9a	1.9ab
D	708a	136bc	156ab	116ab	25.4a	13.8a	26.2a	7.6a	6.7ab	3.0a	1.6b
E	680a	134bc	187a	142a	18.4b	13.5a	26.0a	6.9bc	6.4bc	2.9a	1.7b
F	746a	121c	132b	92b	13.9bc	13.2a	32.0a	6.2c	7.0a	3.1a	2.1a
					Subwatershed 11						
A	701c	165a	134ab	110ab	18.5d	8.1c	18.4c	8.3b	6.7a	3.1ab	1.7ab
B	707bc	150a	143a	115a	20.3cd	8.8c	20.2bc	8.5ab	6.7a	3.1ab	1.7a
C	718bc	163a	119b	90b	32.0ab	13.2ab	24.1ab	8.3b	7.0a	3.3a	1.6ab
D	723abc	150a	126ab	94ab	37.4a	15.1a	26.0a	8.5a	7.0a	3.1ab	1.5bc
E	757a	111b	132ab	99ab	26.2bc	12.1b	24.7ab	8.5a	6.8a	3.1b	1.4c
F	745ab	111b	143a	101a	28.2b	13.3ab	28.9a	8.5a	6.9a	3.0b	1.3c
					Subwatershed 15						
A	561bc	285ab	154c	105bc	25.5a	14.5bc	28.7bc	7.8ab	6.8b	3.1ab	1.9a
B	648bc	230b	121c	91c	30.6a	11.4c	25.2c	8.2a	6.8b	3.3a	2.0a
C	660a	209b	131c	99bc	30.8a	10.9c	24.3c	8.2a	6.8b	3.2a	1.9a
D	600ab	256ab	143c	91c	29.0a	17.2b	34.1ab	7.4b	7.4a	3.0b	1.5b
E	491c	318a	191b	118ab	29.5a	25.5a	38.7a	6.8c	7.1ab	2.7c	1.5b
F	496c	276ab	229a	136a	23.6a	23.1a	36.5a	6.4c	7.1ab	2.6c	1.4b

†A, 0–2%; B, 3–5%; C, 6–8%; D, 9–12%, E, 13–20%; F, >20%.

‡Values followed by the same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

§ All hues are YR (yellow red).

the summit and shoulder positions. Again, AI appeared to be dependent on organic C and clay contents, reaching a maximum in a number of instances, when either of these soil properties were also at a maximum. However, it should be noted that as in the case of AI, few statistically significant differences existed in soil properties as a function of slope position. A partial explanation for the lack of a better relationship between AI and slope position in this watershed may be the fact that, in many cases, the data being compared between slope positions were not collected from the same slope since the samples were collected along a transect, and not from cross-sections across stream channels.

The trends for higher clay contents in the lower slope positions agrees with the findings of Franzmeier et al. (1969) that soils on the mid-slope positions were coarser than those above or below, and with those of Honeycutt et al. (1990) and Pierson and Mulla (1990) who found the highest organic C concentrations in the footslope and toeslope positions along with the greater aggregate stability. Both the clay and organic fractions would be expected to be preferentially transported to the lower slope positions in time. This is supported by the suspended sediment data. The silt contents, in most cases, are also greatest toward the bottom of the slopes. Thus, it appears that the accumulation of finer particle sizes and organic C in the lower slope positions contributes to an enhanced AI. In terms of soil color, hue and value are generally lowest on the toeslope or footslope. Again, an indication accumulations of clay and organic C, assuming the redder hues are related to Fe oxides associated with the clay fractions.

The effect of slope aspect on these soil properties (Table 9) indicate that the distribution of AI was not consistent between watersheds, and in two SWs (3 and10) there was no mean separation as a function of aspect. Even though the statistically significant differences between aspects are limited, there are logical trends in the data. As AI approaches a maximum in the more northern aspects in SWs 7, 9, 10, and 11 so do clay contents and organic C although neither property coincides directly with AI for a given SW. The higher concentrations of organic C on these aspects, which contribute to enhanced AI values, are attributed to cooler temperatures and higher soil water contents which supports greater plant production (Hanna et al., 1982; Franzmeier et al., 1969). The existence of higher clay contents on the more northern aspects may be attributed to slightly wetter soil environments that has enhanced the rate of the weathering process, relative to the

Table 8. Distribution of watershed soil properties as a function of slope position.

Slope position	Particle-size distribution: Sand	Silt	Clay	WDC	Carbon: Total	Organic	Aggreg. index	pH	Soil color: Hue	Value	Chroma
	g kg^{-1}										
					Subwatershed 3						
SU†	710a‡	165b	125b	101b	25.7ab	11.8b	19.0ab	8.7b	7.6a§	3.1a	1.8b
SH	773a	116b	111b	89b	12.7ab	5.2b	19.6ab	9.7a	6.8b	3.1a	2.1b
BS	738a	131b	131b	108b	22.6ab	10.0b	17.5ab	8.6b	7.1ab	3.2a	2.0b
FS	742a	122b	136b	113ab	16.8b	10.8b	15.8b	8.5b	6.1c	3.3a	2.7a
TS	453b	370a	177a	135a	32.8a	18.2a	23.0a	8.6b	6.8b	3.0a	2.2b
					Subwatershed 7						
SU	721b	186a	93abc	78a	15.1a	1.7ab	16.2b	8.3a	8.7ab	3.6ab	2.2a
SH	710b	184a	106ab	87a	15.1a	7.5ab	17.2b	8.1a	8.0ab	3.4ab	2.1a
BS	705b	167a	128a	98a	20.0a	9.6a	22.7ab	7.8a	8.3ab	3.2b	2.0a
TS	854a	80b	66bc	46b	16.9a	3.9ab	30.3a	8.2a	7.2b	3.5ab	2.2a
					Subwatershed 9						
SU	644a	194a	162a	108a	17.5bc	10.2ab	32.3a	7.3a	6.5a	3.0b	1.7ab
SH	697a	156a	147a	100a	24.6a	11.7ab	31.8a	7.7a	6.6a	3.2a	1.9a
BS	632a	193a	175a	119a	20.4ab	13.4a	32.4a	7.3a	6.6a	2.8b	1.7b
FS	699a	164a	137a	97a	11.6cd	9.0b	28.7a	7.3a	6.3a	3.0ab	1.8ab
TS	646a	206a	148a	99a	10.1d	8.9b	32.4a	7.4a	6.3a	2.9b	1.6b
					Subwatershed 10						
SU	670a	146a	184a	137a	14.6abc	10.8ab	28.2ab	6.8b	6.2b	3.1a	1.7ab
SH	688a	153a	159a	117a	20.9a	12.2a	27.0b	7.6a	6.6a	3.0a	1.4b
BS	707a	133a	160a	119a	17.8ab	12.3a	26.6b	6.9b	6.5ab	3.0a	1.8a
FS	677a	163a	160a	106ab	12.4bc	10.5ab	31.8ab	6.5b	6.2b	2.9a	1.7ab
TS	737a	153a	110b	74b	8.4c	7.7b	34.2a	6.8b	6.4ab	3.0a	1.9a
					Subwatershed 11						
SU	711a	161a	128a	96b	24.9a	12.1a	24.5a	8.3b	6.8a	3.2a	1.6ab
BS	741a	127a	132a	99b	29.3a	12.5a	25.2a	8.5a	6.9a	3.1a	1.5b
FS	693a	164a	143a	118ab	23.3a	10.6ab	18.4b	8.5a	6.9a	3.2a	1.8a
TS	694a	159a	147a	122a	12.3b	7.0b	16.3b	8.2b	6.3b	2.9b	1.8a
					Subwatershed 15						
SU	534a	327a	139a	83b	32.3a	18.6a	35.1a	7.6a	7.2a	3.1a	1.8a
SH	600a	250a	150a	94b	28.8a	17.2a	33.5ab	7.5a	7.3a	3.1a	1.6b
BS	621a	244a	135a	99ab	30.9ab	13.7ab	26.3b	8.0a	6.9a	3.2a	1.9ab
FS	601a	245a	154a	107ab	19.1b	10.1b	27.8ab	8.0a	6.7a	3.0a	1.8ab
TS	539a	292a	169a	120a	24.6a	18.5a	30.1ab	8.0a	6.0b	2.9a	2.0a

†SU, summit; SH, shoulder; BS, backslope; FS, footslope; TS, toeslope.

‡Values followed by the same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

§All hues are YR (yellow red).

drier south facing slopes, to the extent that more clay has been produced. The somewhat redder hues on the more northern slopes may indicate a higher degree of weathering. Additional research will be necessary to answer questions of this nature.

CONCLUSIONS

This study demonstrated that an AI derived from water dispersible and total clay ratios provides a value for soil erodibility that is responsive to slope class, position, and aspect-induced changes in soil properties. Using clay contents of suspended stream sediments as an indicator of relative sediment

Table 9. Distribution of watershed soil properties as a function of slope aspect.

Slope	Particle-size distribution				Carbon		Aggreg.		Soil color		
aspect	Sand	Silt	Clay	WDC	Total	Organic	index	pH	Hue	Value	Chroma
	g kg^{-1}										
					Subwatershed 3						
N†	740ab‡	133ab	126a	105ab	17.1b	9.2ab	17.2a	8.6ab	7.2a§	3.0ab	1.8ab
NE	727ab	135ab	139a	114ab	20.3ab	9.0ab	17.7a	8.6ab	6.9a	3.3a	2.2a
E	753ab	127ab	121a	102ab	19.4ab	6.4b	15.3a	8.9a	7.0a	3.1a	2.1ab
SE	685b	186a	130a	104ab	26.7ab	11.5ab	19.5a	8.6ab	7.2a	3.2a	2.0ab
S	750ab	123ab	127a	101ab	29.3a	13.7a	20.5a	8.3b	7.4a	3.1a	1.7b
SW	723ab	139ab	138a	115a	23.0a	11.6ab	16.6a	8.6ab	7.3a	3.1a	1.9ab
W	781a	108b	111a	93b	17.8b	11.8ab	15.6a	8.3b	7.0a	2.8b	1.9ab
NW	N/A										
					Subwatershed 7						
N	792a	112c	96bc	83ab	10.1d	5.1a	13.8c	7.7a	9.3a	3.2bc	1.9b
NE	790a	123bc	87c	62b	15.5cd	5.8a	30.7a	7.9a	9.1a	3.4b	1.9b
E	695b	173ab	132ab	104a	22.3abcd	12.7a	20.9bc	7.8a	8.4a	3.0c	1.9b
SE	651b	215a	134ab	98a	30.3a	11.5a	27.3ab	7.8a	8.3a	2.9c	1.8b
S	677b	218a	105abc	83ab	29.4ab	6.2a	21.2bc	8.2a	8.5a	3.9a	2.0b
SW	715ab	166abc	118abc	91ab	23.2abc	9.2a	21.9abc	8.0a	9.0a	3.4b	1.9b
W	669b	185a	145a	110a	17.1bcd	11.3a	24.6ab	7.7a	7.2b	3.0bc	2.2ab
NW	723ab	164abc	113abc	88ab	18.4abcd	6.9a	22.2abc	8.1a	7.2b	3.4b	2.3a
					Subwatershed 9						
N	473c	324a	203a	121a	20.6b	18.7b	38.4a	6.6b	7.0a	2.5c	1.4c
NE	694ab	145cd	161ab	101a	35.5a	23.3a	37.5a	7.7a	6.6ab	3.0ab	1.7b
E	704a	148cd	148b	107a	23.9b	12.4c	30.2bc	7.5a	6.8a	2.9b	1.7b
SE	736a	111c	153b	113a	10.9c	7.5d	27.7c	7.5a	6.6ab	3.0ab	1.8b
S	668ab	184bc	148b	102a	20.3b	9.7cd	30.6bc	7.5a	6.6ab	3.0ab	1.8b
SW	680ab	154bcd	166ab	118a	19.9b	11.4c	30.4bc	7.5a	6.1b	3.1a	2.1a
W	732a	129cd	139b	92a	23.9b	13.2c	35.0ab	7.4a	7.0a	2.8b	1.7b
NW	609b	212b	179ab	121a	16.4bc	12.6c	32.1abc	7.4a	6.3b	2.9b	1.6b
					Subwatershed 10						
N	742a	142a	116c	85b	28.7a	12.0ab	26.1a	8.3a	6.9a	3.2a	1.5bc
NE	597b	165a	238a	187a	16.7bc	14.2a	22.4a	7.0b	6.0b	2.8c	1.5bc
E	711a	130a	160bc	116b	19.4bc	11.7ab	26.9a	7.3b	6.6ab	2.9bc	1.4c
SE	690a	134a	175bc	136b	23.6ab	13.8a	24.5a	7.2b	6.5ab	3.0abc	1.7abc
S	712a	138a	150bc	112b	11.9c	9.8ab	27.9a	6.4b	6.1b	3.2ab	2.0a
SW	749a	132a	119bc	85b	11.8c	8.8b	29.8a	7.0b	6.5ab	3.0abc	1.9ab
W	740a	120a	141bc	98b	13.0c	10.6ab	29.0a	7.1b	6.8a	2.9bc	1.6abc
NW	655ab	163a	183ab	126b	14.7c	12.3ab	31.0a	6.4b	6.2b	2.9bc	1.8abc
					Subwatershed 11						
N	805a	100bc	95b	82b	14.1b	7.4c	14.0c	8.5ab	6.4c	3.0a	2.0a
NE	745bc	97c	158a	116a	23.0ab	10.7bc	24.5a	8.5a	7.2a	3.1a	1.7b
E	755ab	108bc	137a	97ab	28.8a	14.0ab	28.7a	8.2b	7.1a	3.0a	1.4cd
SE	733bc	139abc	128a	97ab	30.2a	11.0abc	25.2a	8.5a	7.1ab	3.2a	1.6bc
S	720bc	147ab	133a	104ab	22.1ab	9.8bc	22.2ab	8.4ab	6.5bc	3.1a	1.5bcd
SW	768ab	106bc	126a	93ab	24.3ab	10.8bc	26.2a	8.5ab	6.5bc	3.0a	1.2d
W	689c	164a	147a	103ab	27.5a	14.0ab	29.8a	8.5a	6.9abc	3.0a	1.6bc
NW	719bc	147ab	135a	113ab	33.7a	15.6a	17.0bc	8.5ab	7.1a	3.2a	1.6bc
					Subwatershed 15						
N	606a	259a	135a	100ab	31.3abc	12.1ab	25.8bc	8.1a	6.5b	3.2bcd	2.0abc
NE	607a	267a	126a	95ab	35.4ab	11.3b	24.7bc	8.2a	6.9ab	3.4a	2.2a
E	555a	293a	153a	108ab	29.6bc	12.8ab	29.0ab	7.8ab	7.2a	3.3ab	2.0ab
SE	621a	248a	130a	103ab	38.1a	12.9ab	20.2c	8.3a	7.4a	3.3abc	1.8bcd
S	575a	279a	146a	99ab	29.6bc	17.9a	28.5ab	7.7ab	7.0ab	3.1bcd	1.9bcd
SW	642a	219a	139a	89b	24.5c	16.2ab	33.9a	7.5b	6.7b	3.0d	1.7d
W	602a	238a	160a	111a	24.1c	13.0ab	27.4ab	7.7ab	7.0ab	3.0d	1.7d
NW	620a	251a	130a	90ab	30.7abc	15.4ab	29.2ab	8.0ab	7.2a	3.1cd	1.8cd

†N, 338-23°; NE, 23-68°; E, 68-113°; SE, 113-158°; S, 158-203°; SW, 203-248°; W, 248-293°; NW, 293-338°.

‡Values followed by the same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

§All hues are YR (yellow red).

yields, this aggregation/erodibility index explained 90% of the variability in enrichment ratios calculated for suspended sediments and soil clay contents. Thus, the relative erodibility of a watershed can be ascertained from this index, especially since suspended sediments reflect the contributions of all types of erosion in watersheds including rill, interrill, and gully.

The ability to link soil erodibility zones with slope factors in watersheds will contribute to the design of best management practices that will affect the greatest reduction in sediment and chemical contaminant loads in watersheds. Such information also has the potential to improve the accuracy of soil erosion/sediment transport models at the watershed scale.

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