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Processes controlling sediment yield from watersheds as functions of spatial scale

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Abstract

The need for estimates of sediment yield are ubiquitous throughout water resources analyses, modelling, and engineering as sediment is a major pollutant, a transporter of pollutants, and sedimentation rates and amounts determine the performance and life of reservoirs, canals, drainage channels, harbors, and other downstream structures and improvements. Moreover, as a 'watershed wide' measure of soil erosion, transport, and deposition, sediment yield reflects the characteristics of a watershed, its history, development, use, and management.

The major factors and processes controlling sediment yield from watersheds are described and discussed in the context of spatial scale. Historical sediment yield data from selected watersheds across a range of scales are used to illustrate variations of sediment yield with watershed scale. Generalized relationships between sediment yield and drainage area from the USA and Australia are used to show the statistical variations of sediment yield with watershed area. Area is shown to be an important predictor variable which usually, but not always, is correlated with sediment yield.

Experimental data from a small experimental watershed are used in a case study to illustrate processes controlling sediment yield. The case study summarizes and interprets simulation model studies using experimental field data from measurements distributed across a range of scales. Information presented here should help guide the conceptual development of sediment yield models and their mathematical formulation. It should also be useful in design and implementation of spatially distributed verification and validation studies. © 1998 Elsevier Science Ltd. All rights reserved

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1. Introduction

A watershed (as used herein, watershed is synonymous with the terms catchment and drainage basin) can be described with respect to surface runoff as being defined by a watershed perimeter. This perimeter is the locus of points where runoff produced inside the perimeter will move to the watershed outlet.

Sediment discharge from a watershed is the total quantity of sediment moving out of the watershed in a given time interval (mass/time). This sediment discharge is often termed sediment yield (e.g. ASCE, 1970). The total sediment discharge from a watershed relative to the watershed area is also called sediment yield (mass/area/time) (e.g. see ASCE, 1982). To avoid confusion and because of the emphasis on watershed scale, the term sediment yield as mass per unit time used herein will be denoted as sy and total sediment discharge relative to the contributing drainage area will be denoted as SY given in units of mass/area/time.

The need for estimates of sediment yield are ubiquitous throughout water resources analyses, modelling, and engineering as sediment is a major pollutant, a transporter of pollutants, and sedimentation rates and amounts determine the performance and life of reservoirs, canals, drainage channels, harbors, etc. Moreover, as a 'watershed wide' measure of soil erosion, transport, and deposition, sediment yield reflects the characteristics of a watershed, its history, development, use, and management.

The purposes of this paper are to: (1) list and discuss the major factors and processes controlling sediment yield from watersheds in the context of spatial scale, (2) examine historical sediment yield data from selected watersheds across a range of scales, (3) use experimental data from a small experimental watershed as a case study illustrating the controlling processes, and (4) briefly discuss selected hydrologic simulation procedures applicable for sediment yield prediction at various watershed scales.

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Although it is not possible to consider spatial scale problems without also considering temporal and process-intensity scales, the emphasis herein is on spatial scale, particularly watershed scale, affecting sediment yield.

2. The role of watershed scale in sediment yield

Two decades ago Schumm (1977) conceptualized an idealized fluvial system as consisting of three zones with connotations of sediment source, transport, and sink. Zone 1 was described as the drainage basin as a source of runoff and sediment, Zone 2 as the main river channels as the transfer component, and Zone 3 as the alluvial channels, fans, and deltas, etc. as sinks or zones of deposition. This conceptual model of Zone 1 as a sediment source, Zone 2 as the sediment transport loci, and Zone 3 as a sediment sink is useful in generalizing processes at the mid- to large watershed scale (i.e. on the order of 10^3 km^2 or larger).

However, as described by Horton (1932; Horton, 1945), Strahler (1957; Strahler, 1958; Strahler, 1964), and subsequently others, a high degree of similarity of planimetric features of watersheds has been found over a wide range of scales. Two watersheds of similar shapes but different sizes, or scales, exhibit near similarity if the scale ratio (l) of lengths in them is nearly a constant, the ratio of areas is proportional to l^2, and the ratio of volumes is proportional to l^3. These measures of similarity are most nearly met in the absence of strong geologic controls, which may distort watershed shapes.

Within watersheds exhibiting near similarity, subwatersheds also may be expected to show similarity across a range of scales. If this is the case, then the conceptual model of Schumm's sediment source, transport, and sink zones would be repeated across a range of scales. Thus, it would be possible to identify each of the three zones within watersheds defined by stream orders (a first order stream is the smallest unbranched feature in a channel-network map, two first orders combine to form a second order stream, and so on until the outlet of the watershed is reached).

As will be discussed later, physical features corresponding to Schumm's three zones can be identified in the field on topographic features as small as row sideslopes in cultivated fields and within 1 m^2 rainfall simulator plots on rangelands. Large-scale systems such as the Nile and Mississippi rivers also exhibit these features as is readily apparent on satellite images. Given the wide scale of application of the sediment source–transport–sink concept in describing processes controlling sediment yield, sediment yield should be strongly influenced by, but not completely determined by, watershed area.

2.1. Sediment yield vs. watershed area

Parker and Osterkamp (1995) recently compiled mean annual suspended sediment discharges from 24 gaged rivers in the United States. Drainage areas ranged from 1.6×10^3 to 1.8×10^6 km^2. Mean annual suspended sediment yields ranged from less than 5 to over 1480 t/km^2/yr. Linear and nonlinear regression analyses of mean annual suspended sediment yield vs. drainage area indicate no statistically significant relationships. At this scale (up to a significant portion of the continental USA part of North America), factors such as geology, climate, soils, vegetation, land use, runoff characteristics, and river regulation dominate over watershed area in determining sediment yield.

Dendy and Bolton (1976) used data from sediment deposits in reservoirs to examine watershed sediment yields vs. drainage area for 800 watersheds distributed throughout the USA. The data were ranked by drainage area and assembled into 43 logarithmic groups. Arithmetic averages for watershed areas, mean annual runoff, and mean annual sediment yields were then computed. Watershed areas ranged from 2.9 to 7.1×10^4 km^2, mean annual runoff ranged from 21 to 330 mm/yr, and mean annual sediment yields ranged from 56 to 695 t/km^2/yr.

Linear and logarithmic regression analyses of the Dendy and Bolton (1976) data suggested no relationships between runoff and watershed area or runoff and sediment yield. However, there was a significant relationship between mean annual sediment yield (SY in t/km^2/yr) and drainage area (A in km^2) as suggested by the derived equation

$$SY = 674.A^{-0.16} \tag{1}$$

with $R^2 = 0.68$. This equation is of the general form $SY = aA^b$ or $sy = aA^{(b+1)}$ if sediment yield is expressed in t/yr.

There are many similar references to variations in sediment yield with watershed area in the USA, see, for example USIAC (1957), USDA (1973), and Vanoni (1977) for some of the more comprehensive tabulations.

Wasson (1994) compiled estimated sediment yields (t/yr) from 275 locations in Australia and compared them with estimates from around the world. The Australian data did not follow the global trend of higher sediment yield from regions with greater maximum elevation (a surrogate for tectonic activity) probably because the Australian data represent less range in topography and maximum elevation. However, the Australian data showed a remarkably similar variation with watershed scale as did the Dendy–Bolton data and are of interest herein. Particularly of interest are the 131 data points from Wasson's southeast Uplands region of Australia.

Within this region, the basins were grouped in six cumulative drainage area logarithmic groups from $<$ 0.1 to $<$ 10,000 km^2 (i.e. all 131 basins were less than 10,000 km^2 in size, 108 were less than 1000, 88 were less than 100, 80 were less than 10, 70 were less than 1, and 29 were less than 0.1 km^2 in size).

Wasson (1994, Tables 3 and 4, pp. 275–276) found values of b in Eq. (1) to vary from -0.07 with $R^2 = 0.88$ for the largest areas to $b = -0.23$ with $R^2 = 0.55$ for the areas less than 0.1 km^2. For the data grouped in the six area ranges, the b value as in Eq. (1) is $b = -0.18$ which is quite consistent with the value of $b = -0.16$ in Eq. (1).

Again, given the wide scale of application of the concept of a sediment source–transport–sink continuum in describing processes controlling sediment yield and the empirical relationships presented above, sediment yield should be strongly influenced by, but not completely determined by, watershed area.

2.2. *Sediment delivery ratios*

The previously cited conceptual and empirical analyses relating drainage area and sediment yield led to the concept of a sediment delivery ratio, D, most commonly defined (e.g. see Gottschalk and Brune (1950), Glymph (1951), Fleming (1969), and Vanoni (1977)) as the ratio of sediment yield to 'gross erosion'. In equation form this is expressed in non-dimensional terms as

$$D = SY/T \quad (2)$$

where D is delivery ratio, SY is sediment yield (mass/area/time) at the watershed outlet or point of interest, and is T gross erosion (mass/area/time) defined as the total eroded sediment on the eroding areas above the watershed outlet. If one then computes gross erosion and knows the delivery ratio, then sediment yield is simply computed as $SY = DT$.

Conceptually, Eq. (2) is a convenient way to estimate sediment yield to a downstream point of interest such as a reservoir site, a detention basin, etc. assuming that gross erosion is known. The problem here is that estimating gross erosion is at least as difficult as estimating sediment yield. This difficulty arises from several circumstances, the most important of which are discussed below.

The concept of sediment source–transport–sink has been shown to apply to scales from cropland furrow sideslopes to major river systems. Therefore, in an area where there is net erosion (the rate of soil detachment significantly exceeds the rate of sediment deposition) the delivery ratio might be expected to increase with drainage area. In an area of sediment transport (where the rates of soil detachment and sediment deposition are approximately equal) delivery ratio might be expected to be nearly constant and independent of drainage area. Finally, where the rate of deposition significantly exceeds the rate of detachment there is net deposition and sediment delivery ratio would decrease with drainage area. The fact that there is a continuum of these three cases on drainage area scales from $< 10^0$ m^2 to $> 10^7$ km^2 means that delivery ratio is very dependent on where within a watershed one looks. Although, to be fair, delivery ratio concepts are most often applied on watersheds with drainage areas in the 10^0 to 10^4 km^2 range and at points of interest likely to be depositional in nature (i.e. harbor sites, reservoir sites, estuaries, etc.) so that usually delivery ratios vary between 0.10 and 1.0 and tend to decrease with drainage area (e.g. Fig. 4.13, p. 460 of Vanoni, 1977).

Even if the relative position of the point of interest in the continuum discussed above is known, estimating gross erosion introduces uncertainty comparable to the uncertainty in estimating sediment yield so that their ratio is even more highly uncertain. As a matter of practical application of the delivery ratio concept, gross erosion is usually conceptualized and computed in the context of the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978). This introduces a severe limitation as the USLE is designed for application on eroding portions of fields or hillslopes and does not consider ephemeral gully erosion, gully erosion, river bed or bank erosion, or any sediment deposition. With these exclusions, the USLE is most properly applied on the steeper (where slope shape is not concave and is sufficiently steep to ensure net detachment of soil) portions of fields, commonly with slope lengths on the order of 10^0 to 10^2 m in length. Taken with the generally recognized inability to accurately estimate gully erosion and stream bank contributions, the USLE concepts severely limit the accuracy and precision with which gross erosion may be estimated.

Newer technology (e.g. models such as CREAMS (Knisel, 1980), RUSLE (Renard *et al.*, 1991), and WEPP (Laflen *et al.*, 1991)) may improve our ability to estimate gross erosion but this does not solve the problems of gully and stream bank erosion or all of the uncertainty in knowing the position of the point of interest in the continuum of source–transport–sink recurrences across the range of scales representing a watershed.

Given these problems, the concept of delivery ratio is useful in consideration of processes of soil erosion, sediment transport, and sediment deposition as they affect sediment yield from watersheds. Moreover, delivery ratios may be adequate for some purposes under certain circumstances. However, one should not expect a 'universal' relationship between drainage area and other morphometric properties of watersheds and sediment delivery ratios.

An alternative to the delivery ratio method for estimating sediment yield involves using direct sediment concentration measurements with streamflow data. This method is briefly described in the next section.

2.3. Sediment yield estimates from rating curves and flow duration

Reproducible graphs of sediment discharge rates (e.g. kg/s) vs. water discharge rates (m^3/s) can be used to derive a statistical relationship for a given stream channel cross-section. The result, a sediment rating curve, can then be used with a water discharge rate vs. percent of time the rate is exceeded relationship (called a flow duration curve) to estimate sediment yield.

That is, if the long-term flow duration and water–sediment discharge relationships at a site are known, then this information can be used to estimate sediment yield on hourly, daily, monthly, and annual bases. Given a suitable long-term record of flow (usually 10–30 yr or more, Vanoni (1977), p. 589), the result is a synthesized long-term sediment yield estimate. The quality and the 'representativeness' of the sediment yield estimates are directly determined by the quality and representativeness of the flow duration and water–sediment discharge relationships.

The above discussion assumes that direct water discharge measurements and sediment concentration samples are used to define the flow duration curve and the sediment rating curve. Alternatively, as will be discussed later, hydrologic and hydraulic models used to estimate water discharge and sediment transport formulae can be used to estimate sediment transport capacity and thus sediment concentration and yield. The adequacy of the resulting sediment yield estimates will depend directly on the adequacy of the hydrologic/hydraulic models and the sediment transport formulae used.

The sediment yield estimation procedures described above are most often, and most appropriately, applied to perennial and intermittent streams. In ephemeral streams, the channels may be dry more than 99% of the time and flow periods may be episodic and brief. Under these circumstances measuring steady-state water discharge rate and sediment concentration may be difficult or impossible. The sediment rating curve concept may be modified to consider the relationship between runoff event water and sediment yields directly rather than through integration of water–sediment discharge rates.

The sediment rating curve and sediment yield estimation methods discussed above suffer the same uncertainty with respect to the sediment source–transport–sink continuum as do the sediment yield and sediment delivery ratio procedures.

The above discussion of sediment yield and delivery presents a broad general description of the processes controlling them. To add specificity, it is helpful to consider an example or case study illustrating the dominant processes controlling sediment source, transport, and sink zones at the plot and hillslope scale, at the subwatershed scale, and at the watershed scale.

3. Case study: the Walnut Gulch Experimental Watershed

The 149 km^2 Walnut Gulch Experimental Watershed (Walnut Gulch hereafter) is located in southeastern Arizona, USA at approximately 31° 45′ north latitude and 110° west longitude at elevations ranging from 1250 to about 1900 m above MSL (Fig. 1).

The climate of Walnut Gulch is classified as semiarid or steppe, with about 70% of the annual precipitation occurring during the summer months from convective thunderstorms of limited areal extent. Data from Tombstone, AZ for the period 1941–1970 were used to calculate mean annual precipitation as 324 mm and mean annual temperature as 17.6°C.

Walnut Gulch is located in the Basin and Range Province and, typical of this physiography, is bounded on the southwest, south, and east by mountain blocks separated by broad alluvium filled basins. A brief geologic description follows, based on Gilluly (1956), which should be consulted for more detailed and complete geologic descriptions of Walnut Gulch.

The northern 1/2 to 2/3 of the total 149 km^2 drainage area consists of Quaternary and Tertiary alluvium outwash, called the Tombstone Pediment. This area generally occupies the northern portions of Walnut Gulch (Fig. 1). Drainage densities (based on analyses for 1:24,000 scale maps) for Subwatersheds 3, 4, 8, 10, and 11 (Fig. 2) on this pediment range from 2.87 to 3.61 km/km^2 with a mean of 3.16.

The remaining southern part of the watershed (called the Tombstone Hills area herein) is composed of more

Fig. 1. USDA-ARS Walnut Gulch Experimental Watershed location map.

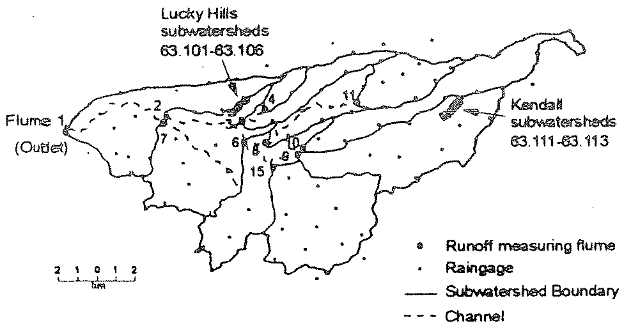

Fig. 2. USDA-ARS Walnut Gulch Experimental Watershed flume and subwatershed location map.

complex geologic structures. Areas along the southeast watershed boundary are composed of volcanics of late Tertiary age. Diked ridges, usually exposed on steeper terrain and by stream channels provide geologic controls on channel gradient and headwater extension. Subwatershed 9 includes this material as well as some of the Tombstone Pediment. As a result of the more complex geology and its surface expression, the drainage density of Subwatershed 9 is low at 1.36 km/km^2.

Areas along the southwestern and southern boundaries of the watershed comprise the Tombstone Hills. This area is composed of faulted and uplifted sedimentary rocks underlain by, and adjacent to on the west, igneous rocks of Tertiary age. These are areas with complex structure and composition including limestone, quartzite, and granite. Subsurface and surface features controlled by faulting, intrusive rhyolite dikes, and other features exhibit strong influence on channel incision and headwater extension. Subwatersheds 7 and 15 include these features as well as some of the Tombstone Pediment. The drainage densities for Subwatersheds 7 and 15 are 2.56 and 1.69 km/km^2, respectively.

The overall mean drainage density for the entire Walnut Gulch Watershed is 2.45 km/km^2 which is generally lower than drainage densities for subwatersheds on the Tombstone Pediment (average value 3.16) and higher than drainage densities for subwatersheds in the Tombstone Hills areas with more complex geology (average value 1.87). As will be discussed below, mean annual runoff and sediment yield are associated strongly with geologic parent material and are higher on subwatersheds with higher drainage densities.

Soils on Walnut Gulch are generally 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 (30–40% canopy cover) the lower two thirds of the watershed. The major grass species (10–80% canopy cover) on the upper third of the watershed are the gramma 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.

3.1. Dominant processes at the plot and hillslope scale

At the plot and hillslope scale (about 10^{-6} to 10^{-2} km^2) overland flow processes dominate as channelization at this scale is at the microtopographic level and larger channels are usually absent. As stated earlier, the sediment source–transport–sink concept applies at this scale and is observable in the field.

The first two rows of data in Table 1 represent runoff and sediment yield at the hillslope scale. Notice that the data for Watershed 63.105 are for eight individual runoff events. Mean sediment yield for these events is probably in excess of the corresponding mean annual values. However, the mean sediment concentration for these eight events may be representative of the mean annual sediment concentration because of the high linear correlation between runoff and sediment yield for these data. The runoff sediment yield relationship for these data was $sy = 14.0Q$ with $R^2 = 0.96$ where sy is sediment yield in kg and Q is runoff volume in m^3. This equation implies that sediment concentration, as the ratio of sediment yield to runoff, is constant. In any event, the predominantly brush covered hillslope yields an arithmetic mean sediment concentration at least twice as high as the grass covered hillslope. This relationship is consistent with the results from the other 13 subwatersheds as shown in Table 1 and as discussed in the next section.

Additional experimental data from rainfall simulator studies have been collected on Walnut Gulch by a variety of investigators (e.g. Simanton *et al.*, 1986 and Abrahams *et al.*, 1988). These data are valuable in process studies and in determining model parameter values (i.e. hydraulic roughness coefficients, Abrahams *et al.*, 1993 and Gilley *et al.*, 1993) but were not used to estimate mean annual runoff or sediment yield.

Vegetative canopy cover intercepts raindrops reducing their impact energy at the soil surface (on Walnut Gulch, vegetation is sufficiently small such that drop re-formation and fall result in much less energy than unobstructed rainfall). At the soil surface, ground cover (rock, gravel, litter, and plant basal area) shields the soil surface from direct raindrop impact and significantly enhances infiltration (Lane *et al.*, 1987). Surface ground cover also significantly influences the hydraulics of overland flow (Weltz *et al.*, 1992), reduces flow detachment capacity, and reduces sediment transport capacity of the flow. Finally, small sediment particles and litter combine with basal vegetation and microtopography to produce debris dams which result in water ponding and sediment deposition.

Taken together, these impacts of vegetative canopy cover, surface ground cover, and topography have been shown to be dominant processes (along with rainfall

Table 1
Summary of mean annual runoff, sediment yield, and sediment concentration for 15 sites on Walnut Gulch (two at the hillslope scale and the remainder at the watershed scale)

Watershed, features and data sources	Area (km^2)	Runoff (mm)	Sediment yield ($t/km^2/yr$)	Sediment concentration (%)
63.105 bpu[1] hillslope scale	0.0018	12.7[2]	151.0[2]	1.19[2]
63.112 gpu[3]	0.0186	19.7	51.2	0.26
63.103 bpc[4] subwatershed scale	0.0368	22.1	356.4	1.61
63.104 bpc[4]	0.0453	18.3	122.7	0.67
63.201 bpc[5]	0.440	23.0	313.0	1.36
63.201 gpc[5]	0.440	14.0	81.0	0.58
63.207 bhc[5]	1.11	7.52	69.0	0.92
63.208 gpc[5]	0.922	11.6	81.0	0.7
63.212 bhc[5]	3.41	7.39	69.0	0.93
63.213 mhc[5]	1.60	5.16	58.0	1.12
63.214 gpc[5]	1.50	19.7	233.0	1.18
63.215 bpc[5]	0.352	19.8	442.0	2.23
63.216 gpc[5]	0.841	11.2	325.0	2.9
63.223 bpc[5]	0.438	22.2	204.0	0.92
63.006 mmc[6,7]	95.1	5.7	107.	1.88
63.001 mmc[6,7,8]	149.0	4.7	162.	3.45

1. Symbols:
g/b/m = predominantly grass (g), brush (b), or mixed (m),
p/h/m = Tombstone Pediment (p), Tombstone Hills areas of more complex geology (h), or mixed (m), and u/c = ungullied or without significant stream channels (u) and gullied and/or with significant alluvial stream channels (c).
2. Means are for eight individual events, 1973–1976, and do not represent mean annual values. See text for discussion.
3. Tiscareno-Lopez *et al.* (1994)
4. Osborn and Simanton (1989)
5. Renard and Stone (1982)
6,7. Sediment yield as the average of values reported by Renard and Lane (1975) and Lane and Nichols (1997).
6,7,8. Sediment yield as the average of values reported by Renard and Lane (1975), Lane and Nichols (1997), and Renard and Laursen (1975).

amount and intensity) in controlling infiltration and runoff as well as sediment detachment, transport, and deposition in overland flow (e.g. Lane *et al.*, 1995b).

In summary, rainfall amount and intensity, vegetative canopy cover, surface ground cover, and topography (and their spatial variability) largely determine sediment yield at this scale. This influence is apparently through controlling soil detachment and runoff and thus, the supply of sediment available for transport and yield and the amount of runoff available to transport sediment. Of course, soil erodibility, land use, etc. are also important and significantly influence sediment yield at this scale. However, their expression of significant impacts on sediment yield are often masked, or 'dominated', by rainfall amount and intensity, vegetative canopy cover, surface ground cover, and topography as expressed through the processes described above.

3.2. Dominant processes at the subwatershed scale

At the subwatershed scale, about 10^{-2} to 10^{1} km^2, the 'hillslope' processes described above remain important. However, spatial variability of rainfall, partial area response, gully erosion, channel processes such as bed and bank erosion, sediment transport, and deposition, and transmission losses (infiltration of water to channel beds and banks) become important in controlling sediment yield. Also, characteristics of parent geologic material, soils, their interaction and their variations in space assume increasing significance.

Mean annual runoff, sediment yield, and sediment concentration for 14 subwatersheds and the entire Walnut Gulch Watershed are summarized in Table 1. Except as noted earlier with respect to the data at the hillslope scale, and as noted in the footnotes and Table 2, periods of record for the data in Table 1 varied from 10 to 18 yr. Logarithmic regression of mean annual runoff volume, Q in mm, with watershed area, A in km2, produced a power relationship of the form $Q = 11.9A^{-0.18}$ with $R^2 = 0.61$. There was no significant relationship between sediment yield and drainage area, and thus, annual mean sediment concentration, Cb in %, was related to area as $Cb = 1.16A^{0.16}$ with $R^2 = 0.35$. The exponent (-0.18) in the relationship between mean annual runoff, Q, and drainage area, A, is significantly less then the values normally reported for variations in runoff peak discharge values (exponents commonly in the range of -0.3 to -0.5 as in Eqs. (3)–(5)) with drainage area. Decreases in runoff peak rate with drainage area reflect all sources of attenuation, such as those due to changes in streams

Table 2
Summary of measured runoff and sediment yield and simulated sediment yield from the WGHM applied at Flume 1 (63.001) and Flume 6 (63.006) on Walnut Gulch

	Measured values			Simulated values	
	Runoff	Sediment		Sediment	
Flume and date	Volume (mm)	Yield (t)	Concentration (%)	Yield (t)	Concentration (%)
Flume 1					
31/07/64	0.28	1100	2.63	890	2.13
02/08/64	0.28	1410	3.37	910	2.18
08/08/64	0.08	270	2.26	150	1.26
08/09/64	0.91	3440	2.53	3260	2.40
09/09/64	0.38	1710	3.01	1310	2.31
10/09/64	4.68	20,310	2.9	20,760	2.97
11/09/64	1.98	8840	2.99	8780	2.97
09/05/96	0.005	13.8	1.61	10.6	1.23
Flume 6					
19/08/63	2.97	5490	1.94	5410	1.92
22/07/64	5.38	11,940	2.33	13,220	2.58
11/09/64	3.83	7440	2.04	7560	2.08

Notes:
1. The WGHM explains over 99% of the variance of measured sediment yield for Flume 1. Most of this explanatory power comes from knowing the observed runoff volume. For example, knowledge of runoff volume alone explains 86% of the variance in WGHM calculated sediment yield and knowledge of observed runoff volume and knowledge of WGHM calculated sediment concentration together determine all of the variance in WGHM calculated sediment yield.
2. Only three events for Flume 6, no statistical comparisons were made.

channel slope and shape normally associated with flood routing, including transmission losses, while decreases in runoff volume represent losses and not attenuation.

Osborn *et al.* (1978) interpreted data from four small watersheds on Walnut Gulch (63.112, 103, 104, and one other) as suggesting 2–3 times higher sediment yield from the gullied watershed 63.103 than from the ungullied, but containing alluvial channels, watershed 63.104 and the data in Table 1 support this conclusion. They also suggested that watersheds with predominantly brush cover produce a factor of 10 greater sediment yields than comparable watersheds with predominantly grass cover.

Analyses of data from Table 1 do not support this conclusion. For example, watersheds 63.201g, 208, 214, and 216 are predominantly grass covered, on the Tombstone Pediment, and channelled with gullies and/or alluvial stream channels. Their mean annual values for runoff, sediment yield, and mean concentration are 14.1 mm/yr, 180 t/km^2/yr, and 1.34%, respectively. Watersheds 63.103, 104, 201b, 215, and 223 are also on the Tombstone Pediment, channelled, but have predominantly brush cover. Their mean annual values of runoff, sediment yield, and mean concentration are 21.1 mm, 288 t/km^2/yr, and 1.36%, respectively. This suggests about 50–60% greater runoff and sediment yield from the brush covered watersheds in comparison with the grass covered ones. But, the mean sediment concentrations, 1.34% and 1.36%, respectively, are quite similar. This suggests that most of the differences in sediment yield can be explained by differences in runoff.

However, when one considers the brush covered watersheds, 63.207, 212, and 213, on the southern portion of Walnut Gulch with more complex geology (called herein the Tombstone Hills area for simplicity) in comparison with the brush covered watersheds on the Tombstone Pediment, the results are quite striking. Their mean annual values of runoff, sediment yield, and mean concentration are 6.7 mm, 65 t/km^2/yr, and 0.99%, respectively. This suggests that runoff and sediment yield from watersheds in the Tombstone Hills area may be 3–4 times less than corresponding values from watersheds on the Tombstone Pediment. Apparently, parent geologic material–soils interactions have a significant impact on runoff and sediment yield. But, the mean sediment concentrations are similar, 1.36% for the brush covered watersheds on the Tombstone Pediment and 0.99% from those in the Tombstone Hills area.

Comparing runoff, sediment yield, and mean sediment concentration from the grass covered and unchannelled watershed 63.112 with the average values from the other grass-covered watersheds with channels the following observations are made. Runoff is slightly higher at 19.7 vs. 14.1 mm, sediment yield is 3–4 times less at 51 vs. 180 t/km2/yr, and mean sediment concentration is a factor of 5 less at 0.26 vs. 1.34%. This supports the earlier assertion of dominance of overland flow processes, particularly soil detachment and runoff generation, in determining sediment yield from unchannelled hillslopes.

In summary, rainfall amount and intensity, geologic parent material–soils interactions, gully and alluvial channel densities and properties, and vegetation type (and their spatial variability) largely determine sediment yield at this scale. This influence is apparently primarily through controlling the runoff generation process and channel detachment, transport, and deposition processes. Of course, vegetative canopy cover, surface ground cover, soil erodibility, topography, land use, etc. are also important and significantly influence sediment yield at this scale. However, their expression of significant impacts on sediment yield are often masked, or 'dominated', by rainfall amount and intensity, geologic parent material–soils interactions, channel erosion and sedimentation processes, and vegetation type as expressed through the processes described above.

3.3. Dominant processes at the watershed scale

At the watershed scale (about 10^1 to $> 10^2\,\mathrm{km}^2$) partial watershed coverage of rainfall (e.g. Osborn and Laursen, 1973) and transmission losses in the alluvial stream channels (Lane, 1982) exert dominant controls on amounts and rates of runoff.

A distributed watershed model directly incorporating transmission losses (Lane, 1982) was calibrated using observed data for the mean annual flood peak discharge, $Q2$ in mm/h, on watersheds 63.001, 002, 003, 006, 007, 008, 009, 010, 011, and 63.015. Values of watershed area ranged from 8.23 to 149 km^2 and values of the 2-yr flood peaks from the database ranged from 1.1 to 8.8 mm/h.

The data-based flood peaks were related to drainage area as

$$Q2 = 9.29A^{-0.43} \tag{3}$$

with $R^2 = 0.53$. The corresponding relationship for the calibrated model with transmission losses was

$$Q2 = 13.1A^{-.50} \tag{4}$$

with $R^2 = 0.79$. The calibrated hydrologic model was also applied without consideration of transmission losses (by setting hydraulic conductivity of the channel alluvium to zero) with the resulting relationship as

$$Q2 = 11.1A^{-0.27} \tag{5}$$

with $R^2 = 0.66$.

Although the statistical relationships between mean annual flood peaks and drainage area were moderate (R^2 values from 0.53 to 0.79), they do suggest the following interpretations. Annual flood peaks decrease about as the drainage area to the − 1/2 power as a result of partial area storm coverage, flood peak attenuation due to storage, hydraulic roughness, etc., and increasing transmission losses with increasing drainage area. On Walnut Gulch and for watersheds ranging in size from 8 to 149 km^2, about half of the rate of decrease in runoff peaks with watershed area can be explained by transmission losses in the main channel system. Thus, at this scale transmission losses become a dominant factor in determining flood peaks and volumes.

At the watershed scale, the principal alluvial stream channels are ephemeral and characterized as broad, sand and gravel bedded streams. Sediment supply is generally abundant and non-limiting. Under these conditions, sediment discharge rates are highly correlated with runoff rates and the concept of sediment transport capacity can be used to estimate suspended and bedload sediment discharge rates (e.g. see Renard and Laursen, 1975).

For example, US P61 and DH48 suspended sediment samplers were used at watershed 63.001 (Flume 1) to collect 76 suspended sediment concentration samples during seven runoff events in 1964 and one in 1996. These instantaneous sediment concentration values were used with corresponding water discharge rates to compute total sediment yield (sy in t) for each runoff event. The relationships between event sediment yield, sy in t, and event runoff volume, Q in mm, for the eight runoff events was

$$sy = 4290.Q^{1.07} \tag{6}$$

with $R^2 = 0.99$. It should be noted that the range in Q was 0.0052–4.68 mm and the range in sy was 13.8–20,300 t so that the high R^2 represents fitting the large sy value (the next largest sy value was 8840 t) more than it indicates a precise relationship. Nonetheless, runoff rates and amounts are strongly related to sediment discharge and yields in the larger alluvial stream channels at Walnut Gulch.

In summary, rainfall amount and intensity and its degree of partial coverage of the watershed area, transmission losses, alluvial stream channel properties, runoff rates and amounts, and sediment transport capacity largely determine sediment yield at the watershed scale. Processes at the hillslope and subwatershed scale remain important, especially in the aggregate, but are subordinate to the watershed scale processes on Walnut Gulch.

3.4. Cautionary notes

Specific data and relationships, for example the data in Table 1 and the relationships expressed by Eqs. (3)–(6), must be interpreted with caution and seen as qualitative rather than quantitative expressions. Short record lengths, measurement errors, small samples, and unreplicated observations in the face of very high temporal and spatial variability of hydrologic processes make the data and relationships subject to revision as more data and understanding are gained.

While it is likely that more data and understanding may switch the relative order of the dominant processes described in the case study of Walnut Gulch, and the coefficients and the significance of the statistical relationships will undoubtedly change, we feel the key processes described in discussion of the case study will remain significant and dominant. However, this assertion must be seen in the context of the sediment source–transport–sink continuum concept discussed herein and its shifts in time and space over geomorphic and geologic time. At the longer time scales, short-term subtleties and interactions may assume increasing importance. Finally, it should be noted that the case study represents results from a semiarid watershed with runoff generated by high intensity storms and where transmission losses significantly influence runoff rates and amounts.

4. Selected hydrologic and sediment yield models

The purpose of this section is to describe the strengths and weaknesses of a few selected simulation models used in support of the analyses presented in the case study. Although simulation models have been applied across a range of watershed scales and conditions on the Walnut Gulch Experimental Watershed, modelling applications are more numerous at the plot to hillslope scale.

For additional information on the broader topic of hydrologic and erosion/sediment yield modelling and the application of models under conditions different from those at Walnut Gulch, the reader should see more comprehensive analyses and reviews, including at least the following: Haan *et al.* (1982), Anderson (1988), and Singh (1995).

4.1. Models at the plot and hillslope scale

Several sediment yield models have been applied at the plot and hillslope scale on Walnut Gulch. Most of the applications can be classified into four broad categories: (1) empirical models such as the USLE (e.g. Wischmeier and Smith, 1978) and its modifications (e.g. Renard *et al.*, 1991), (2) distributed field scale models such as CREAMS (e.g. Knisel, 1980) which use USLE concepts in their detachment components, (3) distributed process-based models such as hillslope models with analytic solutions (e.g. Shirley and Lane, 1978; Rose *et al.*, 1983a), and (4) distributed process-based models based on numerical solutions (e.g. WEPP, Flanagan and Nearing, 1995).

Simanton *et al.* (1980) applied the USLE to four small watersheds on Walnut Gulch. Two of the watersheds were without gullies or significant alluvial channels (63.101, 1.3 ha and 63.112, 1.86 ha) and represented (except for depositional areas at the toes of hillslopes) somewhat reasonable applications of the USLE model. Predicted values for these two applications were within about a factor of two of the measured sediment yields. Application of the USLE on two other small watersheds with significant gullies and alluvial channels (63.103, 3.68 ha and 63.104, 4.53 ha) represented a gross misapplication of the USLE model. This example illustrates the need to properly apply erosion prediction models such as the USLE to the conditions to which they were developed. In the case of the USLE, this is for eroding portions of hillslopes in the absence of sediment deposition and concentrated flow. Thus, the USLE is limited in its application to the sediment source component of the sediment source–transport–sink continuum at the hillslope scale when overland flow dominates the hydrologic response to rainfall.

Renard and Simanton (1990) applied the USLE and the Revised USLE (RUSLE) to rainfall simulator plots from studies on rangelands, including Walnut Gulch. Using data from 181 rainfall simulations, RUSLE explained about 66% of the variance in soil loss and USLE explained about 62% of the variance in the same data. However, when data for the bare soil plots were removed from the analyses, RUSLE performed considerable better than the USLE (R^2 = 0.36 vs. R^2 = 0.08, respectively). However, RUSLE has the same limitations as the USLE vis à vis sediment deposition and concentrated flow. Finally, it should be noted that the data used by Renard and Simanton (1990) in the RUSLE–USLE comparisons were appropriate for these models as they were from erosion plot studies.

Foster and Lane (1982) discussed applications of the CREAMS erosion model to rangelands and validation studies on agricultural areas. However, applications of CREAMS to small watersheds on Walnut Gulch (e.g. Renard *et al.*, 1993) have included those with gullies and alluvial channels so that plot and hillslope studies were not isolated from small watershed applications. Finally, CREAMS was specifically designed to include overland flow as well as concentrated flow and impoundment areas so that it fits within the sediment source–transport–sink continuum conceptual model.

Shirley and Lane (1978) and Rose *et al.* (1983b) applied an analytic solution of a model composed of the coupled kinematic wave flow equations and interrill and rill erosion equations for a plane to produce a spatially and temporally varying model for watershed 63.101. Shirley and Lane (1978) also integrated the solutions through time to produce an event (temporally fixed) but spatially varying sediment yield model for the same small watershed. Both studies reported that the results of fitting, or parameter optimization, produced results superior to the previously cited results from the USLE applied to the same small watershed. However, the simplifications resulting from modelling the watershed as a single plane distorted topography and thus obscured influences of slope concavity upon deposition. Moreover, all other properties (i.e. canopy and ground cover) were lumped for the entire hillslope. These represented severe spatial lumping.

Lane *et al.* (1995a) extended the analytic sediment yield model to a cascade of plane elements thus allowing analyses of spatially varying topography as well as spatially varying vegetative canopy cover and surface ground cover. These spatial variations were found to be highly significant, and necessary to fit the sediment source–transport–sink continuum concept. This simple hillslope model for sediment yield (time-averaged, but spatially varying) requires an external estimate of runoff (from observed data or a hillslope infiltration model (e.g. IRS, Stone *et al.*, 1992)) and thus emphasizes erosion and sediment yield processes. It represents a potentially valuable tool but remains unvalidated in the absence of distributed runoff and sediment yield validation data along hillslopes (Lane *et al.*, 1995b).

It should be noted here that the absence of distributed validation data is a problem that limits all distributed simulation models. This problem represents a good example of field experimental procedures lagging simulation model development. Most current, and recently used, rainfall simulator procedures were designed within the context of lumped or spatially averaged models such as the USLE, and emphasize measuring runoff and sediment yield at the lower end of the simulation plots rather than along their length in the direction of flow. New experiments designed to address spatially distributed data collection in the context of the sediment source–transport–sink continuum concept are needed to validate process-based, distributed simulation models.

Examples of application of process-based, numerical simulation models for erosion and sediment yield at the hillslope scale include recent analyses using the WEPP model. Nearing *et al.* (1989) developed optimization techniques to estimate soil erodibility parameters from rainfall simulator plot data for an early version of WEPP. Hernandez (1991) applied a process-based erosion model on rainfall simulator plots and treated them as micro watersheds by explicitly separating interrill and rill areas using stereo-paired photographs and detailed micro topographic data. Results from the analysis showed that model parameter identification may not be successfully achieved if the driving erosion processes are not well activated. Thus, yielding parameter estimates that may be only acting as fitting parameters. Parker (1991) analyzed the impact of spatially varying input variables on the WEPP model output at the bottom of hillslopes on watershed 63.103 at Walnut Gulch. The modelling results were summarized in the form of a sensitivity analysis. Greatest differences in model output for lumped vs. distributed input data were found for soil characteristics and vegetative canopy cover. In a similar analysis of the hillslope component of WEPP, Tiscareno-Lopez *et al.* (1993) found the most sensitivity to rainfall characteristics and saturated hydraulic conductivity of the soil. Similar analyses for watershed 63.103 at Walnut Gulch (Tiscareno-Lopez *et al.*, 1994) found the same sensitivities to the hillslope parameters and that the channel hydraulic resistance coefficient (Manning's *n* value) was highly significant in determining simulated sediment yield. Although well structured and tested via sensitivity analyses, rangeland parameter estimation techniques for WEPP have not been finalized (e.g. see Kidwell, 1994) and thus, its applicability under the case study conditions remains uncertain.

4.2. Models at the subwatershed scale

At the smaller end of this scale, Tiscareno-Lopez *et al.* (1994) modelled erosion and sediment yield from the 3.68 ha watershed 63.103 using the watershed version of WEPP. As stated earlier, the objective was a sensitivity analysis and determination of significant model interactions as part of the overall effort to develop a watershed version of WEPP.

The most comprehensive sediment yield simulation modelling effort to date on Walnut Gulch at the subwatershed scale was conducted by Renard and Stone (1982). They applied six sediment yield models: (1) the PSIAC (Interagency Committee, PSIAC, 1968) procedure, (2) the Dendy and Bolton (1976) equation, (3)–(4) two methods from Flaxman (1972; Flaxman, 1974), (5) a method by the authors (Renard and Laursen, 1975), and (6) the Modified USLE, MUSLE model (Williams and Berndt, 1977) to data from 10 small watersheds (see the watersheds denoted 63.201 to 63.223 in Table 1 herein). The watersheds ranged from 0.352 to 3.41 km^2 is size. The simulation results were discouraging. Values of R^2 ranged from a high of 0.72 for the Flaxman (1974) method to a low of near zero for MUSLE. Perhaps most discouraging was the slopes of the regression lines between observed and predicted sediment yield. These ranged from a high value of 0.326 for the PSIAC method to a low of 0.067 for MUSLE and Flaxman (1972). A far less comprehensive, but more successful, simulation modelling exercise was conducted for watersheds 63.103 (3.68 ha or 0.0368 km^2) and 63.223 (0.438 km^2) by Renard *et al.* (1987) using the hydrologic component of the SPUR model. Watershed 63.103 is a subwatershed of and comprises the uppermost area of watershed 63.223 so that the watersheds are nested. Values of R^2 for the model calibrated to 17 yr of annual runoff data were 0.94 and 0.81 for the 0.0368 and 0.438 km^2 watersheds, respectively and the R^2 value for the corresponding annual sediment yield data on the 0.0368 km^2 upper watershed was 0.81. Finally, it should be noted that these are calibration, or fitting, results.

4.3. Models at the watershed scale

As stated earlier, distributed sediment yield modelling at the watershed scale may more directly depend on dynamic hydrologic and hydraulic data than distributed sediment yield modeling at smaller scales. In a sense, the need for hydrologic/hydraulic data and simulation models is cumulative because of the sediment source–transport–sink concept and its applicability across watershed scale processes.

In a recent review article, Goodrich and Woolhiser (1991) examined the state-of-the art in understanding of entire catchment response. They concluded that at watershed scales of 0.01–500 km^2 hydrologists lacked detailed and processes-based understanding, and thus, the ability to develop simulation models to adequately describe hydrologic response.

Results of recent attempts to model the hydrologic response of the entire 149 km^2 Walnut Gulch Watershed tend to support the above assessment. Michaud and Sorooshian (1994) applied a distributed, kinematic cascade event model KINEROS (Woolhiser *et al.*, 1990), a simple lumped model (SCS, 1964) and a distributed version of the SCS model to Walnut Gulch. Because these three models are event models, the continuous simulation model CREAMS was used to estimate moisture content of the soil at the beginning of each storm event. KINEROS and the distributed SCS model were comparable in their ability to fit measured data when calibrated and both were superior to the lumped model. Also, KINEROS was more accurate when used without calibration. This modelling effort was not successful in accurately simulating peak flows or runoff volumes from individual events. Nichols *et al.* (1994) used a distributed, continuous simulation model (SWRRB, Arnold *et al.*, 1990) to simulate runoff from Walnut Gulch. When calibrated, the model accurately simulated average annual runoff volumes, but not maximum peak flows. However, no attempt was made to model sediment yield because subwatershed peak rates are used in the model to estimate subwatershed sediment yields. These two examples illustrate limitations in our ability to model sediment yield at the watershed scale arising from our inability to accurately simulate runoff rates and amounts, i.e. the hydrologic response at the watershed scale.

As described earlier, at the watershed scale on Walnut Gulch the principal alluvial stream channels are ephemeral and characterized as broad, sand and gravel bedded streams. Sediment supply is generally abundant and non-limiting. Under these conditions, sediment discharge rates are highly correlated with runoff rates and the concept of sediment transport capacity can be used to estimate suspended and bedload sediment discharge rates (e.g. see Renard and Laursen, 1975 and Lane and Nichols, 1997). These transport capacity estimates and sediment rating curve concepts can be used to estimate sediment yield at a point of interest.

The Walnut Gulch Hydrologic Method (WGHM) for computing sediment transport capacity and sediment yield was described by Lane and Nichols (1997). The hydrograph approximation, hydraulics component, and the sediment transport component of the WGHM comprise a stand alone sediment transport and yield model which requires runoff volume, peak rate, and flow duration as hydrologic input and stream cross-sectional properties, stream gradient, particle size distribution of the bed material, and estimates of Manning's n value as channel characteristics input.

The WGHM uses a hydrograph approximation technique for small semiarid watersheds, modifications of the Bagnold (1966) equation for suspended sediment transport and the Duboys–Straub formula (e.g. Graf, 1971) for bed material transport. The WGHM emphasized applications in ephemeral streams where sediment supply is non-limiting and runoff is in direct response to rainfall. The method was developed and calibrated using data from Arizona and Nebraska in the USA. Validation studies conducted by Lane and Nichols (1997) used data from New Mexico, Wyoming, and Walnut Gulch in Arizona, USA.

Data for the WGHM validation studies at Walnut Gulch are summarized in Table 2. Several important relationships are shown by the data in this table. First, there is a strong relationship between observed runoff volume and sediment yield. This illustrates the dominance of runoff at this scale. Second, simulation results closely match the observed sediment yield data with observed runoff explaining about 86% of the variance in simulated sediment yield and calculated sediment concentration (i.e. transport capacity) explaining about 52%. Together they explain all of the variance in simulated sediment yield and over 99% of the variance in measured sediment yield. This illustrated the dominance of runoff and sediment transport capacity at this scale.

The 'point of interest' for the above sediment yield estimates may be a watershed outlet or a specific channel cross-section. This implies calculation of sediment discharge and yield as a function of localized conditions where runoff amount and sediment transport capacity largely determine sediment discharge and yield. Although the localized conditions may reflect the entire contributing watershed area on longer time scales, on the time scale of an individual runoff event the conditions and calculations remain localized. In the context of the sediment source–transport–sink continuum emphasis is on the sediment transport component. This is a severe limitation in our ability to understand erosion and sediment yield processes as functions of spatial scale. Although 'point of interest' calculations can be made at different positions within a watershed to approximate spatially varying sediment transport and yield processes, understanding and modelling distributed sediment yield processes at the watershed scale require adequate understanding and modelling of distributed hydrologic processes. In our opinion, inability to accurately model hydrologic processes at the watershed scale will remain a challenge and a problem for the foreseeable future.

Table 3
Summary of dominant processes controlling sediment yield from watersheds in the Walnut Gulch case study

Approximate scale (km^2) on the sediment source–transport–sink continuum		
Plot to hillslope (10^{-6} to 10^{-2})	Subwatershed (10^{-2} to 10^{1})	Watershed (10^{1} to $> 10^{2}$)
←Dominant processes at the indicated scale→		
Topography, vegetative canopy cover, surface ground cover, soil, and soil detachment	Geologic parent material—soils, gully and channel processes, vegetation type, sediment transport and deposition	Partial rainfall coverage, transmission losses, channel processes, sediment transport capacities, and soils
←Processes more or less in common across scales→		
Rainfall, runoff amounts and intensities Spatial variability and interactions		

5. Summary and conclusions

We have described soil erosion by water, the transport of detached sediment particles (sediment), the deposition of sediment, and the resulting sediment yield as the time–space aggregation of these processes. These processes were seen as operating at all scales within a watershed. In shorter notation, we refer to this conceptually as the sediment source–transport–sink continuum.

Generalized relationships between sediment yield and drainage area from the USA and Australia were used to show the statistical variations of sediment yield with watershed area. Area was shown to be an important predictor variable, which usually, but not always, is correlated with sediment yield.

The concept of a sediment delivery ratio was described and discussed as conceptually valuable, but highly uncertain in its application. Sediment delivery ratio as the ratio of sediment yield to gross erosion is highly uncertain. First, gross erosion is at least as difficult to estimate as sediment yield. Second, their ratio is even more uncertain.

Dominant processes controlling sediment yield across a range of scales from 10^{-6} to $> 10^{2}$ km^2 were discussed and illustrated using data and information from the case study of Walnut Gulch in Arizona, USA. Empirical data from this study across a range of scales are summarized in Table 1 and simulation results at the watershed scale are summarized in Table 2. These specific data and relationships, for example the data in Tables 1 and 2, the relationships expressed by Eqs. (3)–(6) and the footnotes in Table 2, must be interpreted with caution and seen as qualitative rather than quantitative expressions. Short record lengths, measurement errors, small samples, and unreplicated observations in the face of very high temporal and spatial variability of hydrologic processes make the data and relationships subject to revision as more data and understanding are gained.

Nonetheless, generalizations of relative importance, or dominance, of processes as functions of watershed scale are summarized in Table 3. Notice the general trend from soil detachment to sediment transport and deposition to sediment transport capacity dominating as watershed scale increases. Recall the specific applicability of the sediment source–transport–sink continuum concept at and across all scales.

Finally, information in Table 3 is not intended to stand alone, but should be interpreted with the restrictions and limitations presented in detail in the text. The thesis herein is that the information presented in the text and summarized in Table 3 should guide the conceptual development of sediment yield models, their mathematical simplifications, implementation, and verification, as well as simulation model validation studies using field data from measurements distributed across a range of scales.

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