Dominant Processes Controlling Sediment Yield as Functions of Watershed Scale

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Abstract Major factors and processes controlling sediment yield from watersheds are described and discussed in the context of spatial scale. Sediment yield data from selected watersheds across a range of scales are used to illustrate variations of sediment yield with watershed scale. Area is shown to be an important predictor variable which usually is correlated with sediment yield. Experimental data from a small experimental watershed are used in a case study to illustrate dominant 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 on the Walnut Gulch Experimental Watershed. Generalizations of dominance of processes as functions of watershed scale are summarized. The general trend is from soil detachment processes to sediment transport and deposition to sediment transport capacity dominating as watershed scale increases from 10^{-6} to $> 10^{+2}$ sq km. Information presented 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.

1. INTRODUCTION

Sediment discharge from a watershed (or catchment) is the total quantity of sediment moving out of the watershed in a given time interval (mass/time). This sediment discharge is often called sediment yield. The total sediment discharge from a watershed relative to the drainage area (mass/area/time) is also called sediment yield. Estimates of sediment yield are needed throughout water resources analyses, modeling, and engineering as sediment is a major pollutant, a transporter of pollutants, and sedimentation rates and amounts determine the performance and life of downstream structures and developments. Sediment yield is a distributed consequence of soil erosion, transport, and deposition, and thus is an indicator of watershed characteristics, history, development, use, and management.

In this paper we discuss the major factors and processes controlling sediment yield from watersheds as functions of spatial scale, illustrate the concepts with analyses of experimental data from a small experimental watershed as a case study, and briefly discuss selected simulation models used to predict sediment yield at various watershed scales.

2. WATERSHED SCALE AND SEDIMENT YIELD

Schumm (1977) described an idealized fluvial system as consisting of three zones with respect to 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 is useful in generalizing processes at the river basin scale (i.e. on the order of 10^3 sq km or larger).

Horton (1945), Strahler (1964), and subsequently others, described the high degree of similarity of planimetric features of watersheds. Two watersheds of similar shapes but different sizes 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.

In a watershed exhibiting near similarity, subwatersheds may show similarity at a range of scales. If true, then the conceptual model of Shumm's three zones would be repeated across a range of scales. As discussed elsewhere (e.g. Lane and Hernandez, 1997), features analogous to Schumm's three zones can be identified in the field on topographic features as small as row sideslopes on croplands and microtopographic features less than the scale of a meter on rangelands. 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) compiled mean annual suspended sediment discharges from 24 gaged rivers in the United States. Drainage areas ranged from 1.6×10^3 to 1.81×10^6 sq km and sediment yields ranged from less than 5 to over 1480 t/sq km/y. 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 especially 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 2.87 to 7.1 x 10^4 sq km, mean annual runoff ranged from 21 to 330 mm/y, and mean annual sediment yields ranged from 56 to 695 t/sq km/y.

Regression analyses 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/sq km/y) and drainage area (A in sq km) as suggested by the derived equation

$$SY = 674.\ A^{-0.16} \qquad (1)$$

with $R^2 = 0.68$.

Wasson (1994) compiled estimated sediment yields (t/y) from 275 locations in Australia and compared them with estimates from around the world. Data from the southeast Uplands region were grouped in 6 area ranges. The exponent, as in Eq. 1, was found to be -0.18, which is quite consistent with the value of -0.16 in Eq. 1.

These discussions of sediment yield and watershed scale presents a broad general description. To add specificity, it is helpful to consider an example or case study.

3. CASE STUDY: THE WALNUT GULCH EXPERIMENTAL WATERSHED

The 149 sq km Walnut Gulch Experimental Watershed (Walnut Gulch hereafter) is located in southeastern Arizona, USA (Fig. 1) and elevation of the watershed ranges from 1250 to about 1900 m above MSL. 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. Mean annual precipitation as about 320 mm and mean annual temperature is about 18 degrees 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 geologic description of the Walnut Gulch area is given by Gilluly (1956). The northernmost 1/2 to 2/3 of the total 149 sq km drainage area consists of Quaternary and Tertiary alluvium, called the Tombstone Pediment (Fig. 1). The southern part of the watershed (called the Tombstone Hills area herein) is composed of more complex geologic structures. Subsurface and surface features controlled by faulting, intrusive rhyolite dikes, and other features exhibit strong influence on channel incision and headwater extension.

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 to 40% canopy cover) the lower two thirds of the watershed. The major grass species (10 to 80% canopy cover) on the upper third of the watershed are the 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.

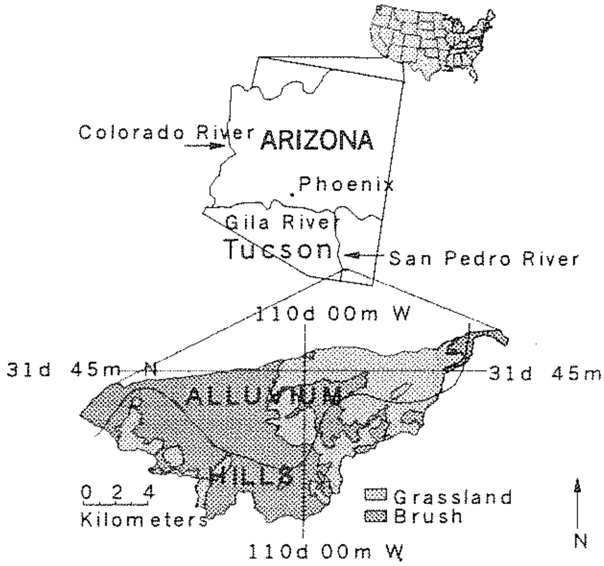

Figure 1. USDA-ARS Walnut Gulch Experimental Watershed location map with geologically distinct pediment and hills areas roughly indicated.

3.1 Dominant Processes and Models at the Plot and Hillslope Scale

At the plot and hillslope scale (about 10^{-6} to 10^{-2} sq km) overland flow is a dominant process controlling sediment yield as channelization at this scale is at the microtopographic level and larger channels are usually absent.

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.

Several sediment yield models have been applied at this scale on Walnut Gulch. Shirley and Lane (1978) and Rose et al., (1983) 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 a small subwatershed on Walnut Gulch. Both studies reported the results of fitting, or parameter optimization, producing results closely matching observed data. However, the simplifications resulting from modeling the watershed as a single plane distorted topography and thus obscured influences of slope concavity upon deposition. All other properties (i.e. canopy and ground cover) were lumped for the entire hillslope, representing severe spatial lumping.

Lane et al. (1995a, 1995b) 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, thus supporting the sediment source-transport-sink continuum concept.

3.2 Dominant Processes and Models at the Subwatershed Scale

Examples applications of process-based, numerical simulation models for erosion and sediment yield at the hillslope scale include recent analyses using the Water Erosion Prediction Project (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. Parker (1991) analyzed the impact of spatially varying input variables on the WEPP model output at the bottom of hillslopes on a small watershed at Walnut Gulch. The modeling 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. 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.

At this scale, about 10^{-2} to 10^{+1} sq km, 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.

Relative sediment yields from 12 subwatersheds on Walnut Gulch (drainage areas ranged from 0.0186 to 3.41 sq km, see Lane and Hernandez, 1997) are shown in Fig. 2. Comparison of the bars in the left most portion of Fig. 2 with those on the right suggest that sediment yield from shrub dominated watersheds is about twice that from comparable grass dominated ones. Also, on the grassed watersheds on the Tombstone Pediment, sediment yield from watersheds dissected by gullies and alluvial channels is about 3 times that from upland, ungullied areas. Finally, comparison of the two left most bars in Fig. 2 suggest that sediment yield from the Tombstone Pediment area is as much as 5 times as much as from watersheds in the Tombstone Hills area.

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 through controlling the runoff generation process as well as channel sediment detachment, transport, and deposition processes.

The most comprehensive sediment yield simulation modeling 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 (1968) procedure, 2) the Dendy and Bolton (1976) equation, 3-4) two methods from Flaxman (1972, 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. The watersheds ranged from 0.352 to 3.41 sq km is size. The 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).

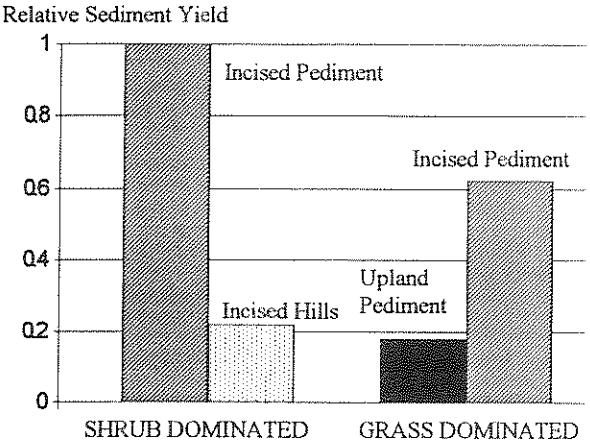

Figure 2. Walnut Gulch sediment yield as related to geology, geomorphology, and vegetation.

3.3 Dominant Processes and Models at the Watershed Scale

At the watershed scale (about 10^{+1} - $>10^{+2}$ sq km) 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. 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).

A distributed watershed model directly incorporating transmission losses (Lane, 1982) was calibrated using observed data for the mean annual flood peak discharge, Q_2 in mm/h, on 10 subwatersheds of Walnut Gulch. Values of watershed area ranged from 8.23 to 149 sq km and values of the 2 year flood peaks from the database ranged from 1.1 to 8.8 mm/h. The relationship between data-based (X) and simulated (Y) mean annual flood peaks was $Y = 0.71 + 0.88X$ with $R^2 = 0.76$.

Statistical relationships between observed and simulated mean annual flood peaks and drainage area suggest the following. 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. About half of the rate of decrease in runoff peaks with watershed area can be explained by transmission losses in the simulation model. Thus, at the watershed scale transmission losses become a dominant factor in determining flood peaks and volumes. It should be noted that these are calibration results and no predictions were made.

Results of recent attempts to predict the hydrologic response of the entire 149 sq km Walnut Gulch Watershed are less encouraging than the model calibration results described above. 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. 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. However, none of the models accurately simulated 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. The model accurately simulated average annual runoff volumes but not maximum peak flows. These examples illustrate limitations in our ability to model sediment yield at the watershed scale arising from our inability to accurately predict runoff rates and amounts at the watershed scale.

4. DISCUSSION

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.

Dominant processes controlling sediment yield across a range of scales from 10^{-6} to $>10^{+2}$ sq km were discussed and illustrated using data and simulation modeling results from a case study on Walnut Gulch in Arizona, USA. Generalizations of relative importance, or dominance, of processes as functions of watershed scale were summarized. The general trend was from soil detachment to sediment transport and deposition to sediment transport capacity dominating as watershed scale increases. Recall the applicability of the sediment source-transport-sink continuum concept at and across all scales and that the generalizations are for a case study.

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