Hydrologic Modelling and Monitoring for Sediment Budgets on Small Rangeland Watersheds

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Abstract: Determination of sediment budgets is necessary to quantify soil erosion processes and watershed sediment yield including upland erosion, gully erosion, mass movement, channel bed and bank erosion, sediment transport and deposition, and delivery of sediment to downstream locations. A methodology is developed using a mix of monitoring and hillslope erosion modelling to estimate sediment budgets on rangeland watersheds in the southwest USA. The methodology is applied to 4 small watersheds where watershed sediment yield and main channel (gully) erosion were monitored over a 16-year period. Mean annual values of sediment yield were derived from monitoring data or modelling results for each component in the sediment budget. Uncertainty in components of the sediment budgets is determined from analyses of the watershed sediment yield data and the hillslope modelling results. Based on these results, the need for distributed sediment yield measurements, sediment measurement apparatus with minimal impact on sediment yield, and improved modelling techniques are demonstrated.

Keywords: Erosion; Watersheds; Sediment Budget; Modelling

1. INTRODUCTION

Determining sediment budgets is a key part of watershed management, and increasingly, of assessment and prediction of downstream water quality. Sediment budgets are used to quantify soil erosion processes and watershed sediment yield including upland erosion, gully erosion, mass movement, channel bed and bank erosion, sediment transport and deposition, and sediment delivery to downstream locations. Since not all hillslopes, gullies, stream channels, watersheds and downstream watercourses and water bodies can be monitored, a mix of monitoring and modelling is required to estimate sediment budgets.

Currently, watershed science is not well placed to estimate sediment budgets because of gaps in knowledge of processes across a range of watershed scales, lack of distributed monitoring technology and data, and lack of distributed models to accurately estimate components of the sediment budget and to assess the uncertainties of those estimates [for example, see NRC, 1999]. We developed a methodology, using a mix of monitoring and modelling applications, to estimate sediment budgets for rangeland watersheds in southwest USA. This methodology was applied to 4 small rangeland watersheds to provide an example to illustrate gaps in knowledge, data, and modelling technology required for more accurate estimation of sediment budgets.

1.1. Study Sites

The USDA Agricultural Research Service operates 8 small experimental watersheds, established in 1974, within the Santa Rita Experimental Range (SRER) 50 km south of Tucson in southeastern Arizona, USA. Four of these small watersheds are the subjects of this study and their locations are shown in Figure 1. These watersheds enable scientists to study the effects of livestock grazing and vegetation management practices on runoff and sediment yield in the semidesert regions of the southwestern USA [Martin and Morton, 1993]. In 1974, 2 of the watersheds (6 and 7) were treated with basal applications of diesel oil to control the invasion of mesquite (*Prosopis velutina* Woot.), and were subsequently retreated as needed. Watersheds 5 and 8 remained untreated. Grazing practices include yearlong grazing on 2 watersheds

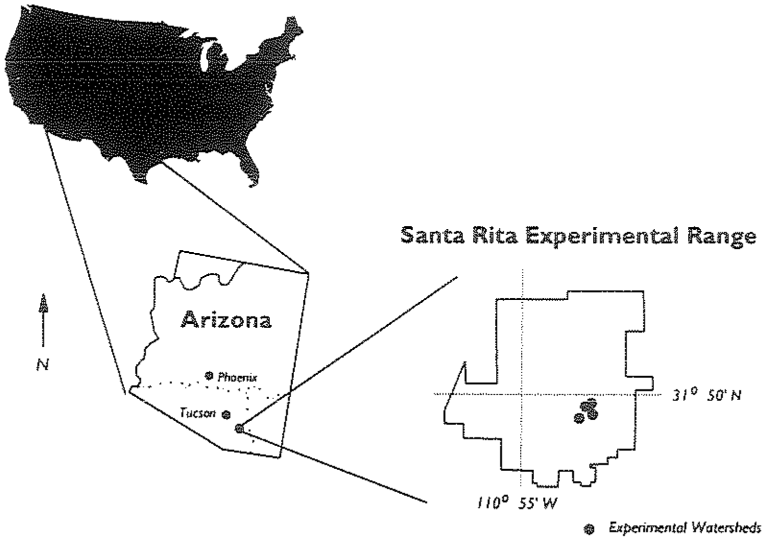

Figure 1. Location map of the Santa Rita Experimental Range, southeastern Arizona, USA

(7 and 8) and a rotation system on the other 2 (watersheds 5 and 6). Treatment and management have remained constant since the study's inception. The watersheds are instrumented to measure precipitation rate and depth, surface runoff, and sediment yield [Lawrence et al. 1996]. Channel cross-sections, using the method described by Osborn and Simanton [1989], and vegetation characteristics [Martin and Morton, 1993] have been measured periodically. Although this is a brief description, more information on the SRER can be found at the following web site: http://ag.arizona.edu/SRER

1.2. The Hillslope Erosion Model (HEM)

The HEM was developed to estimate erosion and sediment yield from runoff at the hillslope scale [see, for example: Lane et al., 1988; Lane et al., 1995a, 1995b]. This model is based on a time-averaged solution of the coupled kinematic wave equations for overland flow and the sediment continuity equation on plane segments. Hillslope topography is approximated as a cascade of plane elements, or hillslope segments, and the time-averaged solution is derived for the entire hillslope by treating each segment sequentially in the flow direction to the end, or toe, of the hillslope.

For irregular slopes made up of a cascade of segments as plane elements, inputs for the entire hillslope model are runoff volume per unit area and a dimensionless, relative soil-erodibility parameter. Input data for each individual segment are the slope length and steepness, percent vegetative canopy cover, and percent surface ground cover.

Finally, the model is used to simulate erosion processes as a function of position on a hillslope and to simulate the influence of spatial variability on hillslope properties including topography, vegetative canopy cover and surface ground cover on erosion/deposition rates for interrill and rill areas, sediment yield, and mean sediment concentration. The model and its technical documentation are available at the following web site: http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel

2. METHODS

Lawrence et al. [1997] used measured data and expert opinion in a multiobjective decision support system to evaluate management systems on the 4 small watersheds on the Santa Rita Experimental Range. As part of the analyses, annual runoff and sediment yield data measured at the watershed outlets for the period 1976-1991 were compiled and summarized. The main channel in each watershed was designated as the channel from the watershed outlet along its course to its termination in the upper areas of the watershed. Changes in the main channel (gully) cross-sectional areas were used to estimate net erosion and deposition for the period 1976-1994.

Therefore, main channel erosion/deposition and watershed sediment yield data from 1976-1991/1994 were available for analyses in the current study. Sediment yield estimates from the hillslopes and from the unmeasured (no cross-sectional data available) stream channels were needed to determine a watershed sediment budget. A stream order analysis using 1:500 scale maps, derived from aerial photography, was conducted on each of the watersheds to determine the number and total length of unmeasured channels. The HEM was applied to 5 representative profiles on each watershed. Mean annual runoff amounts, as tabulated by Lawrence et al. [1997], were used with topography, vegetative canopy cover, and surface ground cover data obtained via field survey in May 2001. Default soil erodibility values were determined from soil textural data on each watershed. These data were used as input to the HEM to estimate hillslope erosion and sediment yield on each watershed. The remaining component of the sediment budget, sediment yield from unmeasured stream channels, was then estimated using a continuity equation as follows:

$$WSY = HSY + UMCSY + MCSY \qquad (1)$$

where WSY is watershed sediment yield, HSY is hillslope sediment yield, UMCSY is unmeasured channel sediment yield, and MCSY is main channel sediment yield, all in T/ha. Measured data and model estimated data were available for WSY, HSY, and MCSY, so the unmeasured channel sediment yield was estimated as:

$$UMCSY = WSY - HSY - MCSY \qquad (2)$$

where the variables in (2) are as described above.

3. RESULTS

Sediment budgets for each of the 4 watersheds are summarized in Table 1. The first column lists the watershed number, its drainage area, its status as a control or treated (mesquite removed) watershed, and its grazing system. The second column lists each component considered in the sediment budget. The third column lists the mean annual sediment yield for each component with percentages of the watershed sediment yield given in parentheses. Net sediment deposition values are listed as negative values. Brief comments and interpretations of the data are given in Column 4. For example, the range in HEM sediment yield estimates from the hillslopes on watershed 5 was 0.81 to 1.39 T/ha (Table 1, Column 4).

4. DISCUSSION

With respect to the 4 watersheds and the data presented in Table 1, we make several comments and interpretations as follows. Mean annual watershed sediment yield at the outlet ranged from a low of 0.06 T/ha on Watershed 6 to a high of 4.21 T/ha on watershed 5. The corresponding HEM estimates of hillslope sediment yield ranged from a low of 0.035 T/ha on watershed 6 to 1.54 T/ha on watershed 8. As a percentage of watershed sediment yield, the hillslope sediment yield ranged from approximately 25% on watershed 5 to about 60% on watershed 6.

As shown in Table 1, estimated sediment yield from unmeasured channels was a major component, ranging from about 75% (watershed 5) to over 500% of the watershed sediment yield (watershed 6). This illustrates a major gap in our monitoring data, and thus, a major uncertainty in calculating a sediment budget.

An additional uncertainty is caused by installation of a runoff-measuring flume at each watershed outlet. The flume has a fixed elevation at the invert that stabilized main channel elevation at the outlet. Stabilizing the main channel elevation at the watershed outlet produced a hydraulic control (necessary for runoff measurement) and a fixed base level preventing further downcutting of the main channel at that point and for some unknown distance upstream. As shown by the minus signs on the sediment yield in the main channels, net sediment deposition was observed in the main channel on all watersheds. The maximum estimates of watershed sediment yield shown in column 3 of Table 1 are derived by assuming that the main channel eroded at the same rate per unit length as estimated in the unmeasured channels. The resulting ratio of maximum estimated to measured watershed sediment yield varied from a low of 1.10 (watershed 5) to a high of 7 (watershed 6) indicting that the hydrologic measurement apparatus may be significantly modifying sediment yield on these small watersheds. This uncertainty in watershed sediment yield emphasizes the need for distributed sediment yield measurements, even at the small watershed scale, to quantify more components of the sediment budget. It also indicates that periodic cross-sectional measurements, separated by several years, on the main channel of these watersheds are inadequate to quantify the impacts of base level control by the runoff measuring flumes.

Finally, the HEM sediment yield estimates ranged from about –20% to –70% of the mean on the low side to +14% to +80% on the high side (Table 1, Column 4) representing an uncertainty of as much as +/- 70% to 80%. This uncertainty is entirely due to sampling different hillslopes around the watershed area (spatial variability) and says nothing about the true accuracy of the HEM sediment yield estimates. Model error would be in addition to the uncertainty from spatial variability in hillslope characteristics.

Table 1. Estimated and measured components for a sediment budget on Santa Rita watersheds 5, 6, 7, and 8. *Hillslopes*: upland erosion from the HEM; *Unmeasured Channels*: unmeasured, lower order streams by continuity from other components;*Main Channel (Gully)*: erosion/deposition by cross-section measurements; and *Watershed Yield*: sediment yield measured at watershed outlet from hydrologic records and sediment concentration samples. Watershed Sediment Yield = Hillslopes Yield + Unmeasured Channels Yield + Main Channel Yield.

WATERSHED	COMPONENT	SEDIMENT IN T/HA (%)	COMMENTS
5 4.02 ha Rotation Grazing Mesquite Retained	Hillslopes	1.05 (24.9)	0.81 to 1.39 T/ha = 7.2 to 12.2 kg/m[1]
	Unmeasured Channels	3.16 (75.1)	1270 m total length, 10 kg/m
	Main Channel (Gully)	-0.001 (-.02)	170 m long, -0.02 kg/m
	Watershed Yield	4.21 (100.) 4.63 maximum estimate[2]	4.63/4.21 = 1.10[3]
6 3.08 ha Rotation Grazing Mesquite Removed	Hillslopes	0.035 (58.3)	0.027 to 0.040 T/ha = 0.19 to 0.29 kg/m[1]
	Unmeasured Channels	0.345 (575.)	854 m total length, 1.2 kg/m
	Main Channel (Gully)	-0.320 (-533.)	95 m long, -10.4 kg/m
	Watershed Yield	0.06 (100.) 0.42 maximum estimate[2]	0.42/0.06 = 7.0[3]
7 1.06 ha Year Long Grazing Mesquite Removed	Hillslopes	0.59 (39.9)	0.40 to 1.06 T/ha = 2.5 to 6.7 kg/m[1]
	Unmeasured Channels	1.975 (133.)	325 m total length, 6.4 kg/m
	Main Channel (Gully)	-1.085 (-73.3)	187 m long, -6.2 kg/m
	Watershed Yield	1.48 (100.) 3.69 maximum estimate[2]	3.69/1.48 = 2.49[3]
8 1.12 ha Year Long Grazing Mesquite Retained	Hillslopes	1.54 (42.0)	0.40 to 2.63 T/ha = 3.0 to 19.2 kg/m[1]
	Unmeasured Channels	2.994 (81.6)	446 m total length, 7.5 kg/m
	Main Channel (Gully)	-0.864 (-23.5)	129 m long, -7.5 kg/m
	Watershed Yield	3.67 (100.) 5.40 maximum estimate[2]	5.40/3.67 = 1.47[3]

1. Range of values from applying the HEM on 5 profiles.
2. Maximum estimated watershed sediment yield if the main channel eroded at the same rate per unit length as the unmeasured channels and the runoff measuring flumes at the watershed outlet did not induce sediment deposition in the main channel.
3. Ratio of maximum to measured watershed sediment yield.

Research findings from the scale studied here (i.e. approximately 1x10^1 to 4x104 m^2) might be scaled up to larger watersheds if additional measurements across the larger range of spatial scale were combined with understanding of dominant processes across the same range of scale. These additional monitoring data (at interior watershed locations) and the knowledge of dominant processes could be used to construct models for the unmeasured components to compute sediment budgets.

5. CONCLUSIONS

To quantify sediment budgets on small watersheds such as those studied here, more distributed measurements are required. Particularly important are distributed measurements of sediment yield along the main channel and from the unmeasured channels. A nested, or interior subwatershed, measurement approach is needed even at this small scale (1 to 4 ha). In the absence of such distributed sediment yield measurements, uncertainties such as those illustrated by the analyses summarized in Table 1 will remain.

Moreover, the measurement apparatus must not alter sediment yield, or if they do, methods must be developed to quantify the degree of modification so their impacts can be factored into sediment budget calculations.

Finally, improvements in model accuracy will always help in estimating unmeasured components of the sediment budget. But currently, application of hillslope scale models, such as the HEM, are still plagued by scale issues and spatial variability as illustrated by the uncertainties introduced in modelling multiple hillslope profiles on these small watersheds.

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