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An Integrated Systems Approach To Modeling Sediment Yield From Rangeland Watersheds

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Abstract

Soil degradation in arid and semiarid ecosystems is a significant problem. Knowledge of sediment yield at the outlet of watersheds is insufficient to interpret internal watershed erosion and deposition processes. An integrated system is under development to incorporate databases containing channel cross section information, a sediment yield model (APOINT) that is applicable to individual cross sections along alluvial channels, and interpreted model output. The complexity of sediment transport processes is expressed in the APOINT simulation model. The APOINT sediment transport model was calibrated and validated at small semiarid watersheds within the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona. The APOINT model explained about 85 percent of the variation in observed sediment discharge from a 3.68 ha subwatershed located in the upper end of a 43.7 ha watershed. Results of model validation at the same watershed indicate that APOINT is able to explain 98 percent of the variation in observed sediment discharge. APOINT was further calibrated at the outlet of the 43.7 ha watershed by comparing model results with observed sediment accumulation in the pond located at the watershed outlet. APOINT was able to explain 77 percent of the variation in sediment accumulation during 7 time periods from 1962-1996. Following the establishment of APOINT as a viable model for simulating sediment discharge through individual channel cross sections, efforts were focused on integrating the model with a database containing field data collected at several points along the main channel within the 43.7 ha watershed. An integrated system is under development to link the model and the database, provide a user friendly interface, and interpret model results with respect to zones of erosion, transport, and deposition within the watershed. The result is a scientifically defensible, readily accessible, easy to use tool for simulating sediment yield from small semi-arid watersheds.

Introduction and background

Quantifying semiarid rangeland erosion and deposition is fundamental to practical application of sustainable land use and management strategies. Through the surface processes of runoff and erosion, soil and sediment are redistributed on the landscape. A small reservoir, or stock pond, at the watershed outlet will trap some of the redistributed material, as is evidenced by a reduction in pond storage capacity caused by the deposition of incoming sediment. As a first step toward quantifying watershed sediment yield rates, long term sediment accumulation in stock tanks can be measured. Accumulated sediment can provide a long-term, average sediment yield rate for a watershed, but provides little basis for inferring internal watershed processes and/or the relationship between runoff event characteristics and sediment movement. Interpretation of sediment yield at the watershed outlet with respect to internal watershed processes can be enhanced with knowledge of erosion and deposition in the contributing channel system because the watershed sediment yield is not independent of the internal processes.

The difference between the amount of material that is eroded within the watershed and the amount that reaches a stock tank at the watershed outlet can be expressed as a sediment delivery ratio. Because of inadequate methods to measure the amount of eroded material within the watershed, sediment delivery ratios are difficult to compute. Alternatively, models can be used to simulate erosion and sediment transport processes within the watershed and model results can be interpreted with respect to observed sediment discharges and accumulations. Ultimately, runoff and sediment exit the watershed via channels. Simulation models are available to estimate sediment transport based on input precipitation and the resulting runoff. This paper focuses on the application of a model to simulate sediment transport in the ephemeral channels of semiarid rangelands.

Modeling Sediment Transport

Modeling sediment transport and yield in semiarid channels offers the challenge of characterizing spatially varied precipitation (Osborn, 1983) and the ephemeral and intermittent character of resulting flows. In addition, variations in channel bed material, the magnitude of flow events, and reductions in flow resulting from transmission losses (Lane, 1982) must be accounted for to model sediment transport.

The complex interactions of flowing water, channel and bed material, and shear forces on the channel banks and bottom are incorporated in the APOINT model (Lane et al., 1985). Flowing water is represented by a hydrograph; channel and bed material is assumed to be alluvial, non-cohesive and spatially varied; and shear forces are accounted for mathematically through the application of the open channel flow equations.

APOINT Model description

The APOINT model (Lane et al., 1985) can be used to simulate sediment discharge throughout a hydrograph at specific cross sections measured along watershed channels (i.e. at a point on a stream channel). This model was designed to represent stream channel processes that partially control sediment yield and is used to estimate total sediment discharge in alluvial channels where total sediment load is approximately equal to total transport capacity.

There is a long recognized division of sediment transport processes into suspended and bed-load components. The magnitude of flow and sediment particle characteristics determine whether bed material travels in suspension or as bedload, and the processes transporting the sediment are controlled in part by local channel hydraulics. Based on the ideas presented by Einstein (1950), the APOINT model distinguishes between bedload and suspended load by incorporating sediment transport equations for particles larger than 0.062 mm (bedload) and smaller than 0.062 mm (suspended load). Coupled with a runoff hydrograph, such as that approximated using a distributed hydrologic model (called TLOSS herein, Lane, 1982), sediment transport and yield can be estimated for individual runoff events. The procedure has been applied to steady and uniform flow conditions at Muddy

Creek, Wyoming and the Rio Grande near Bernalillo, New Mexico, as well as to unsteady, nonuniform flow events in ephemeral steam channels on the Walnut Gulch Watershed, Arizona. The sediment transport equations computed bed material sediment discharge rates comparable to those measured and to those computed using several widely accepted sediment transport formulae (Lane and Nichols, 1997).

Given runoff volume from a known watershed area, the peak rate of runoff, and the approximate mean duration of runoff, a hydrograph is approximated using the double triangle hydrograph method to generate a piecewise normal approximation of an event hydrograph. A measured hydrograph and this method of approximation are shown in Figure 1. Sediment yield is then predicted for each time interval represented in the hydrograph. The piecewise normal flow approximation is used to approximate a nonuniform, unsteady flow hydrograph by a series of step functions that are assumed to represent the steady, uniform flow conditions under which the sediment transport equations, described in the following sections, are applicable (Figure 2.).

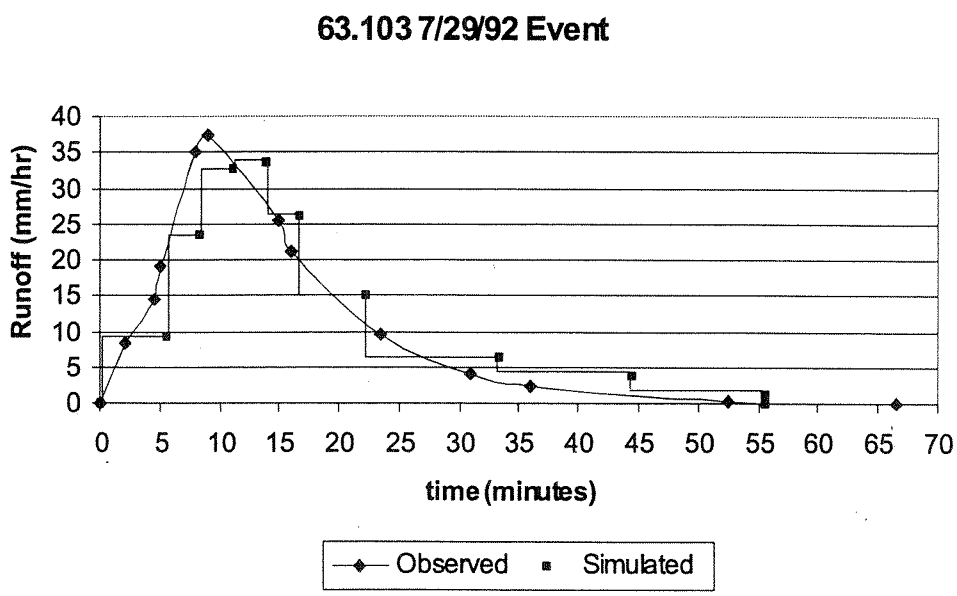

Figure 1. Measured and simulated hydrographs representing the 7/29/92 flow event at watershed 63.103, USDA-ARS Walnut Gulch Experimental Watershed

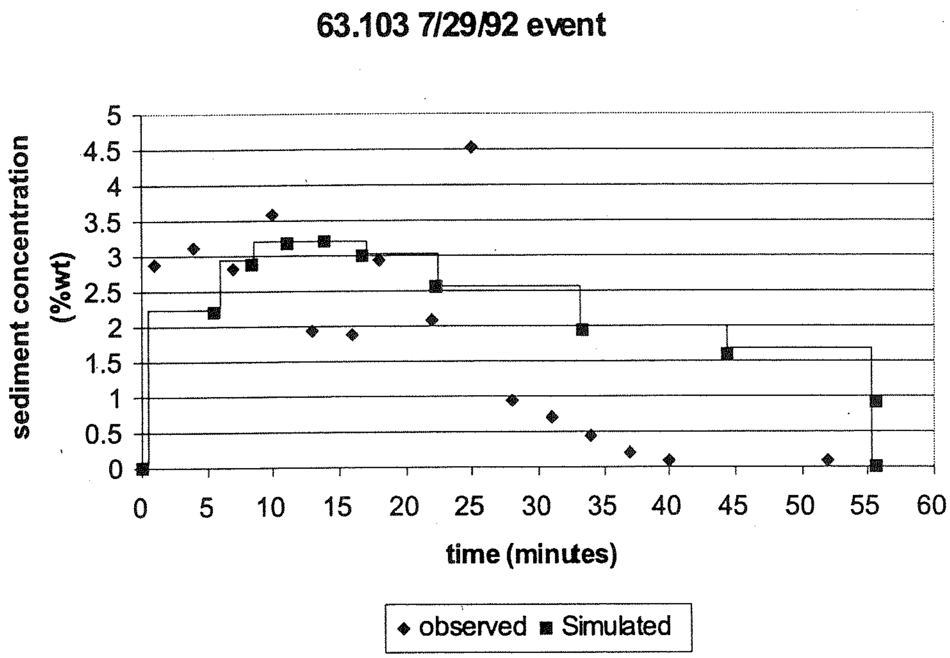

Figure 2. Measured and simulated sediment concentration representing the 7/29/92 flow event at watershed 63.103, USDA-ARS Walnut Gulch Experimental Watershed

Bed-load formula. Transport capacity for bed-load size particles is computed using the following modified Duboys-Straub formula (see Graf 1971, pp. 124-127 for the original, unmodified version of the formula):

$$g_{sb}(d_i) = \alpha f_i B_s(d_i) T\left[T - T_c(d_i)\right] \tag{1}$$

Where:

$g_{sb}(d_i)$ = transport capacity per unit width for particle of size d_I (kg/s-m)

a = a weighting factor to ensure that the sum of the individual transport capacities equals the total transport capacity computed using the median particle size,

f_i = proportion of particles in size class i,

d_i = representative diameter of particles in size class i (mm),

$B_s(d_i)$ = sediment transport coefficient ($m^{3-}s/kg$),

T = effective shear stress acting on the sediment (N/m^2), and

$T_c(d_i)$ = critical shear stress for particles in size class i (N/m^2)

Equations relating $T_c(d_i)$ and $B_s(d_i)$ to particle size were presented in English units by Lane et al. (1985).

$$B_s(d_i) = \frac{a}{(d_i)^{1.5}} \tag{2}$$

$$T_c(d_i) = \begin{matrix} b + cd_i & , & 0.062 \le d_i \le 1.0 \\ e + fd_i & , & 1.0 < d_i \end{matrix} \tag{3}$$

Values of a,b,c,e, and f are presented in English units in Lane et al. (1985).

Suspended-load formula. Transport capacity for suspended-load size particles is computed based on the following modification of Bagnold s equation (Bagnold, 1966):

$$g_{sus} = f_{sc}\, CAS\, TV^2 \quad (4)$$

Where:
g_{sus} = suspended sediment transport capacity (kg/s-m),
f_{sc} = proportion of particles smaller than 0.062 mm diameter in the channel bed material,
T = effective shear stress (N/m^2),
V = average velocity (m/s), and
CAS = suspended sediment transport coefficient (s^3/m^3)

Study Site

The 150 sq km USDA-ARS Walnut Gulch Experimental Watershed (Renard et al., 1993 and http://www.tucson.ars.ag.gov) is located in SE Arizona.

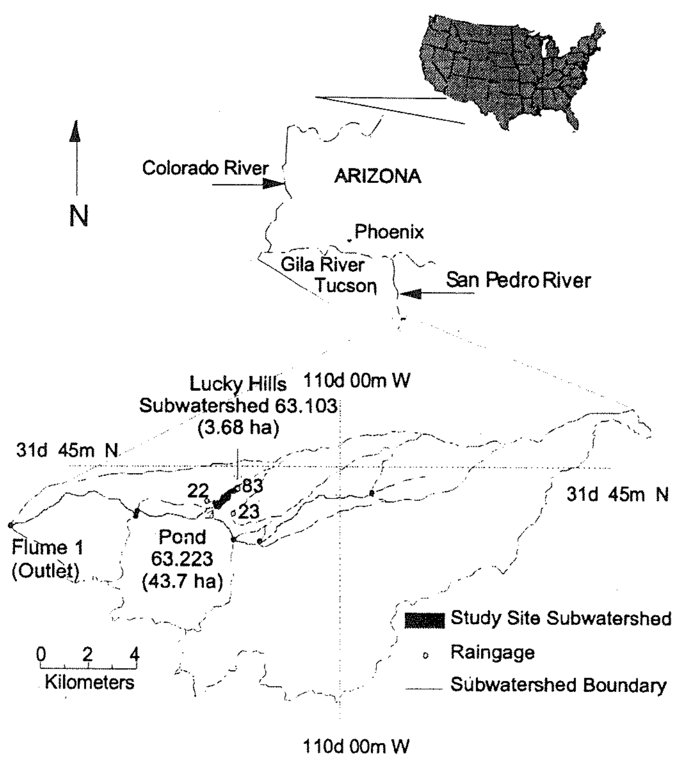

Figure 3. USDA-ARS Walnut Gulch Experimental Watershed study site location map

The watershed contains a series of nested subwatersheds where runoff, sediment discharge, and sediment accumulation data are available (Figure 3.). Subwatershed 63.223 (43.7 ha), which contains subwatershed 63.103 (3.68 ha) and drains into a pond at the outlet, was the site of the model applications described in this paper.

Model calibration and validation

The APOINT model was calibrated and validated based on data collected during 49 runoff events at Flume 63.103 (Table 1). The flume is located in the main channel that drains the 3.68 ha upper end of watershed 63.223. A relational database containing information describing each runoff event was integrated with the simulation model to efficiently provide model input, as well as to capture model output.

Table 1. Summary of APOINT calibration and validation results at 63.103

	Total Sediment Yield (tons)			
	Calibration		Validation	
	Observed	Simulated	Observed	Simulated
Number Of Events	24	24	25	25
MEAN	1.49	1.26	1.32	1.31
SD	1.98	1.94	2.45	3.05
SSE		14.97		11.91
Regression Equation	y = 0.90x-0.09		y = 1.23x-0.32	
R^2		0.85		0.98
Nash-Sutcliffe		0.83		0.91

where y = simulated sediment yield (tons) and x = observed sediment yield (tons)

Following model calibration and validation at the upper end of the watershed, the model was further validated at the watershed outlet based on recorded inflow to the pond and accumulated sediment in the pond for the time period from 1962 through 1996. Model results were compared with observed sediment accumulation in the pond located at the watershed outlet. Sediment that accumulated continuously from 1962 to 1996 was quantified based on periodic surveys and computed changes in pond volume. A total of 8 pond sediment surveys conducted during the 35 years from 1962-1996 defined 7 time periods for which sediment yield was computed. For the 35 year period of record at the watershed outlet, the modeled mean annual sediment yield was 2.91 tons/ha/year (1.30 tons/acre/year) and the measured was 3.07 tons/ha/year (1.37 tons/ac/year). APOINT was able to explain 77 percent of the variation in sediment accumulation during the 7 time periods (Nichols, 1999). This suggests that the model is accurately simulating sediment yield from this small semiarid watershed.

The amount of sediment transported through successive cross sections can be compared to determine zones of sediment erosion, transport, and deposition. A net increase in sediment through successive cross sections indicates erosion, and a net decrease indicates deposition. Interpreting APOINT model output based on simulated amounts of sediment transported along the channel extends the spatial scale of analysis and interpretation from a point (a single cross section) to the watershed scale. Interpreted results from the model application were written to the relational database.

Improving the utility of the model

The goals of developing simulation models include improving our understanding of watershed processes and, ultimately, providing useable information for addressing watershed management problems. Simulation models are notoriously difficult to use. If watershed management is to be successfully based on science, scientific efforts and results must be integrated to produce effective, readily accessible, and easy to use tools.

The National Research Council (NRC 1999) published a recent review of the range of scientific and institutional problems related to watersheds. An important conclusion of the committee was that effective watershed management requires integration of theory, data, simulation models, and expert judgement to solve practical problems and provide a scientific basis for decisionmaking at the watershed scale.

An Integrated Systems Approach. As indicated in NRC 1999, improving the connection between science and decisionmaking is a major challenge to watershed management. Recently, an integrated systems approach to addressing hillslope-scale erosion processes was undertaken at the USDA-ARS —Southwest Watershed Research Center (SWRC) in Tucson, Arizona.

A prototype integrated information system is under development with the goal of providing an efficient assessment and management tool for rangelands. The hillslope scale sediment yield simulation model embodied in the prototype system has been used to quantify sediment yield within a semiarid ecosystem in the western U.S (Lane et al., 1999). Currently, the prototype system contains an operational simulation model linked with databases and knowledge bases for evaluating soil and site stability. The hillslope model is accessed through an Internet browser and runs within a website currently maintained by personnel at the USDA-ARS SWRC. The web-based interface is designed to be intuitive and easily navigable and includes online help and supporting documentation. Technology development and transfer will be facilitated through convenient access to the model, documentation, scientific publications, and contact with scientists and system developers.

The successful coupling of the hillslope scale sediment yield model with a database and the use of the Internet as a technology transfer and delivery mechanism has provided the basis for expanding the spatial scale of application of erosion prediction tools. Watershed scale problems are inherently more complex than hillslope scale problems. The APOINT model has been established as a viable tool for simulating sediment transport through channel cross sections where the sediment discharge is transport limited.

The APOINT model captures the knowledge of sediment transport processes of engineers and scientists working toward advancing our understanding of watershed processes. Linking the model with a common database of spatially distributed cross sections and hydrologic data provides an efficient means for providing model-input data. Data are developed and stored once, and the database is maintained to keep it current. Further improvements to the utility of the model include incorporating assistance with interpreting model output and identifying problem areas on the landscape within the watershed.

Identification of internal watershed problems is a first step in implementing soil erosion mitigation strategies. Integrated systems should facilitate the efficient use of land management resources to reduce soil erosion on semiarid rangelands. An integrated systems approach to developing erosion prediction tools provides a scientific basis for effectively and efficiently addressing erosion problems on semiarid rangeland watersheds.

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