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MODELING SMALL SEMIARID WATERSHEDS IN SUPPORT OF EXPERT SYSTEM DEVELOPMENT

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ABSTRACT

An expert system for assessing rangeland health is being developed at the USDA-ARS Southwest Watershed Research Center. The system integrates data storage and retrieval, simulation models, knowledge bases, and interpreted results. Currently the system is applicable at the hillslope scale; however, the framework exists to extend the spatial scale of application to small watersheds. Extending the scale of application will be based on small-watershed hydrologic and erosion models. This paper describes a semiarid hydrologic model (TLOSS) coupled with a sediment transport model (APOINT) for inclusion in a small watershed-scale expert system to assess the soil stability/watershed function components of rangeland health. The TLOSS and APOINT models were calibrated and validated at small semiarid watersheds within the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona. The TLOSS model explained 91 to 97 percent of the variation in observed runoff volume during calibration and 74 percent of the variation during validation. The TLOSS model accounted for 62 to 73 percent of the variation in peak discharge rate for the calibration dataset and 39 percent of the variation during the validation events. The calibration of APOINT indicated that the model is explains about 85 percent of the variation in observed sediment discharge from the experimental watershed. The validation indicates that APOINT explains about 98 percent of the variation in observed sediment discharge. Within the framework of an expert system, model output indicating zones of erosion, transport, and deposition within the watershed can be interpreted as an indication of the health of rangeland watersheds with respect to the soil/site stability component of the assessment.

KEYWORDS expert system; hydrologic modeling; rangeland health; sediment modeling; semiarid watershed

1 Introduction and background

Scientists at the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center (SWRC) in Tucson, Arizona are developing an expert system to address natural resource problems. An expert system can be defined as a set or system of computer programs, which embodies organized data, organized knowledge, and sometimes simulation models in an area of expertise to perform as a skilled, effective consultant. The term "expert system" is used to signify that knowledge was acquired from human experts. The goal of the expert system under development at the SWRC is to assist decision-makers with assimilating the broad base of data and scientific understanding available to interpret complex natural resource problems. Currently, efforts are focused on the soil/site stability aspects of assessing rangeland health at the hillslope scale.

Rangelands make up approximately 40% of the earth's landmass and most of them are within arid and semiarid zones (Branson et al., 1981). The health of these rangelands must be assessed to determine the appropriate actions to protect and sustain their capacity to satisfy the needs and values of land owners, managers, and the public.

The National Research Council (NRC) has identified the need for technology for assessing rangeland health (NRC, 1994). Currently, the USDA-Natural Resources Conservation Service (NRCS) rangeland health assessment is based criteria describing 3 critical areas: soil/site stability, nutrient/energy cycling, and plant recovery mechanisms (NRCS, 1997). The assessment is implemented by way of a paper-based matrix to classify qualitatively the condition of specific indicators in each of the 3 critical areas. The assessment is conducted and interpreted by field personnel based on professional knowledge and experience.

The current rangeland health assessment methodology can be enhanced by quantifying the processes affecting the 3 critical areas described above. Mathematical simulation models embody the best current understanding of the processes, and produce repeatable, scientifically defensible results. However, simulation models are often difficult to use and their output often requires interpretation (NRC, 1999). In combination with an expert system to aid in model parameterization and interpretation of model output, and a Web based interface as the delivery mechanism, simulation models can be applied effectively by non-expert users. The benefits come not just from an efficient connection between the database and the simulation models, but through access to knowledge in the form of interpreted results. Incorporating the best available science and computer based delivery mechanisms will advance rangeland health assessment and improve its scientific defensibility.

The major components of the rangeland health expert system include databases and assistance with parameterizing a hillslope scale sediment yield model and knowledge bases for interpreting model output. The expert system also provides the framework for extending the spatial scale of rangeland health assessment, which can be accomplished by including watershed scale simulation models within the expert system. A first step in extending the spatial scale of application of the rangeland health expert system is to establish the validity of simulation models to describe rainfall, runoff, and erosion processes on small watersheds (Nichols, 1999). The objective of this paper is to describe the calibration and validation of small-watershed scale runoff and sediment transport models and the potential for incorporating them to extend the application of the hillslope scale expert system.

2 Semiarid watershed modeling

2.1 Site description

As part of a national effort to conduct watershed research, the ARS operates the Walnut Gulch Experimental Watershed (WGEW) in Southeastern Arizona (Figure 1). The 150 km^2 (58 mi^2) WGEW is in the transition zone between the Sonoran and Chihuahuan deserts and has been the site of hydrologic, erosion, and sedimentation research since 1953 (additional information is available via the World Wide Web at http://www.tucson.ars.ag.gov, and in Renard et al., 1993).

Building on the success of researchers to characterize and quantify precipitation, runoff, and erosion processes on the watershed, efforts are underway to quantify rangeland health and its indicators. Because of the extensive semiarid rangeland database and history of rainfall, runoff, and erosion model development at the WGEW, rangeland health research is being directed toward quantifying the soil/site stability component of the NRCS rangeland health assessment methodology.

Watershed 63.223 is a 43.7 ha (108 ac) watershed within the WGEW. Watershed 63.223 is on the Tombstone Pediment, has shrub dominated vegetation, and is being eroded through a sequence of water driven events which are monitored at several locations including the Lucky Hills subwatersheds. Lucky Hills subwatersheds 63.101(1.29 ha), 63.103 (3.68 ha) are in the uplands of watershed 63.223. Watershed 63.223 has been the site of data collection and simulation model development to describe the unique characteristics of hydrologic and erosion processes in semiarid areas.

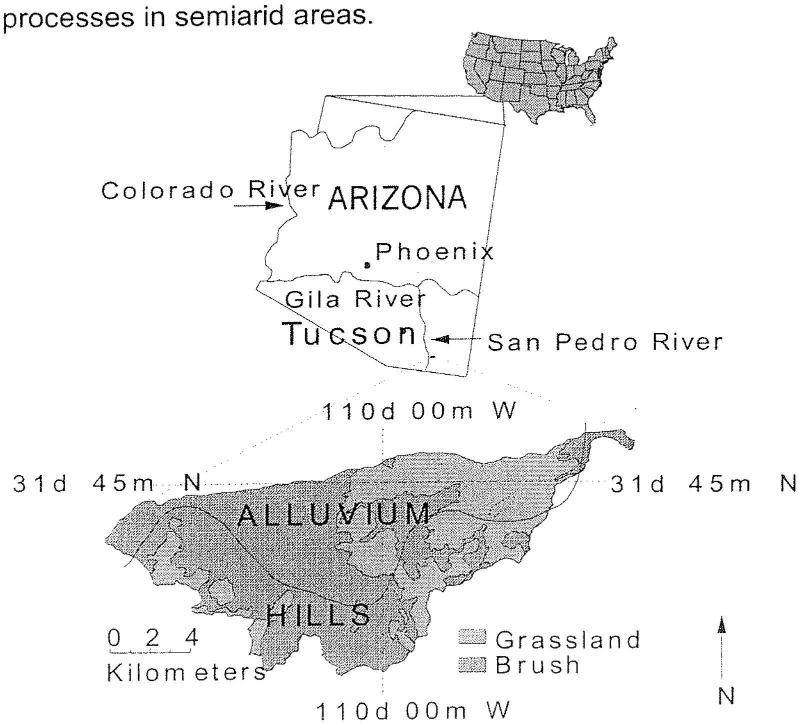

Figure 1. Map showing features of the USDA-ARS Walnut Gulch Experimental Watershed.

2.2 Semiarid watershed hydrology - TLOSS

The Transmission Loss (TLOSS) model (Lane 1983, Lane 1982, and Lane et al., 1994) is a distributed, event model that can be used to compute runoff volume, peak discharge rate, and transmission losses (infiltration losses to channel bed and banks) on semiarid watersheds. The model is applicable for areas of approximately 1 hectare to approximately 25 sq. km. Model input values, such as rainfall, runoff curve number, and channel characteristics, accommodate spatial variations. TLOSS computations are based on Soil Conservation Service runoff curve number methods combined with the solution to the differential equation describing the relationship between runoff volume and distance downchannel. Channel infiltration losses, or transmission losses, are accounted for by modeling changes in runoff volume along the channel length as a function of channel width, effective hydraulic conductivity of the channel alluvium, mean duration of flow in the channel, and lateral inflow volume.

2.3 Semiarid watershed sediment transport – APOINT

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. 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 the TLOSS model, 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 (Lane and Nichols, 1997). The sediment transport equations allowed computation of bed material sediment discharge rates comparable to those measured and to those computed using several well accepted sediment transport formulae (Andrews,1981, Nordin, 1964)

2.4 Model applications to Watershed 63.223

The TLOSS model was calibrated (Nichols, 1999) based on observed runoff volume and peak runoff rates during the years 1963 through 1981 at interior watersheds 63.103 and 63.101 (Tables 1 and 2). The calibrated model includes the combination of SCS curve number and hydrograph shape parameter values that resulted in the best match between observed and simulated runoff volumes and peak runoff rates.

Table 1. Summary of TLOSS runoff volume calibration results

	63.101 Runoff Volume (mm)		63.103 Runoff Volume (mm)	
	Observed	Simulated	Observed	Simulated
n = 12				
Mean	13.26	12.70	11.42	11.07
SD	12.46	13.98	11.46	12.27
SSE		199.41		62.42
Regression Equation	y = 1.07x – 1.51		y = 1.05x – 0.95	
R^2		0.91		0.97
Nash-Sutcliffe		0.92		0.97

Table 2. Summary of TLOSS peak runoff rate calibration results

	63.101 Peak Runoff Rate (mm/hr)		63.103 Peak Runoff Rate (mm/hr)	
	Observed	Simulated	Observed	Simulated
n = 12				
Mean	46.12	34.85	31.97	25.43
SD	28.08	38.54	20.53	28.21
SSE		7797.11		2999.08
Regression Equation	y = 1.08x – 15.0		y = 1.18x – 12.2	
R^2		0.62		0.73
Nash-Sutcliffe		0.55		0.66

Validation consisted of running the calibrated model without further adjustment on a dataset not used in the original calibration. Runoff volumes and peak runoff rates were simulated for 9 runoff events at 63.103 during 1982 through 1992 (Table 3). Reported results are limited to watershed 63.103 because data collection at 63.101 was discontinued in 1986.

Table 3. Summary of TLOSS validation results including observed and simulated runoff volumes and peak runoff rates at 63.103

	63.103 Runoff Volume (mm)		63.103 Peak Runoff Rate (mm/hr)	
	Observed	Simulated	Observed	Simulated
n = 9				
Mean	10.15	11.56	32.40	26.56
SD	5.47	6.50	14.78	14.94
SSE		106.82		1632.03
Regression Equation	y = 1.02x + 1.20		y = 0.63x + 6.08	
R^2		0.74		0.39
Nash-Sutcliffe		0.84		0.73

The calibrated TLOSS model explained 91 to 97 percent of the variation in the observed runoff for the calibration data on watersheds 63.101 and 63.103, respectively, and 74 percent of the variation on an independent set of validation data on watershed 63.103. As expected, the model did not capture the variation in peak runoff rates as well as it explained variation in runoff volumes. The TLOSS model accounted for 62 to 73 percent of the variation in peak discharge rate for the calibration dataset and 39 percent of the variation during the validation events. As a further validation of the TLOSS model, simulations were conducted on an extended data set consisting of 53 events with concurrent observed records at 63.101, 63.103, and the pond at the outlet of watershed 63.223 (Table 4).

Table 4. Summary of results of TLOSS applied to Watershed 63.223 with additional calibration

		Equation	R^2	Nash-Sutcliffe
63.101 (1.24 ha)	Runoff Volume	Y = 0.65x + 0.85	0.75	0.72
	Peak Runoff Rate	Y = 0.59x – 1.71	0.62	0.40
63.103 (3.68 ha)	Runoff Volume	Y = 1.02x + 0.21	0.88	0.86
	Peak Runoff Rate	Y = 0.71x-1.73	0.67	0.77
63.223 (43.7 ha)	Runoff Volume*	Y = 0.84x + 0.12	0.78	0.77

* note: no peak runoff rate data are available at 63.223

Success in modeling the hydrologic relationships is critical to modeling accurately sediment transport within the watershed. The calibration and validation efforts described above provide confidence in applying the TLOSS model on small semiarid watersheds.

Observed sediment data were collected during 49 runoff events occurring from 1982 through 1992 at watershed 63.103. These data were used to calibrate and validate the APOINT model. The results of calibrating APOINT indicated that the model explains about 85 percent of the variation in observed sediment discharge. The validation results indicate that APOINT explains 98 percent of the variation in observed sediment discharge (Table 5).

Table 5. 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

TLOSS and APOINT calibration and validation results provide confidence in simulating runoff and sediment yield at the small watershed scale in semiarid areas.

Establishing the models as a viable method of estimating sediment yield is a first step in incorporating a small watershed scale application within the current expert system framework described in the following section.

3 Incorporating watershed scale models into the existing Expert System framework

The current problem domain is the soil/site stability component of the rangeland health assessment. An expert system framework has been established based on a hillslope scale application. The 3 critical components of the expert system are the database, the simulation model(s), and the expert knowledge base. The interaction between these components and the user are diagramed in Figure 2.

The goal of the expert system is to incorporate knowledge that is generally available to scientists, such as data and the mathematical expression of natural processes, but not necessarily accessible to decision makers and land managers. At the watershed scale data consist of the information required to characterize the physical site characteristics and climate. In exchange for basic information describing the topography, channel geometry, bed material characteristics, and rainfall and runoff, the user receives an interpreted assessment of the soil/site stability of the area with respect to zones of erosion, transport, and deposition.

Within the system, data are assembled in a relational database that is largely populated with field data collected from experimental watersheds. Extending the application of the expert system beyond the geographic boundaries of specific watersheds requires expert assistance. Relationships are being developed and incorporated within the expert system to extend the applicability based on generalized rainfall-runoff relationships, land use, vegetative cover, and soil characteristics.

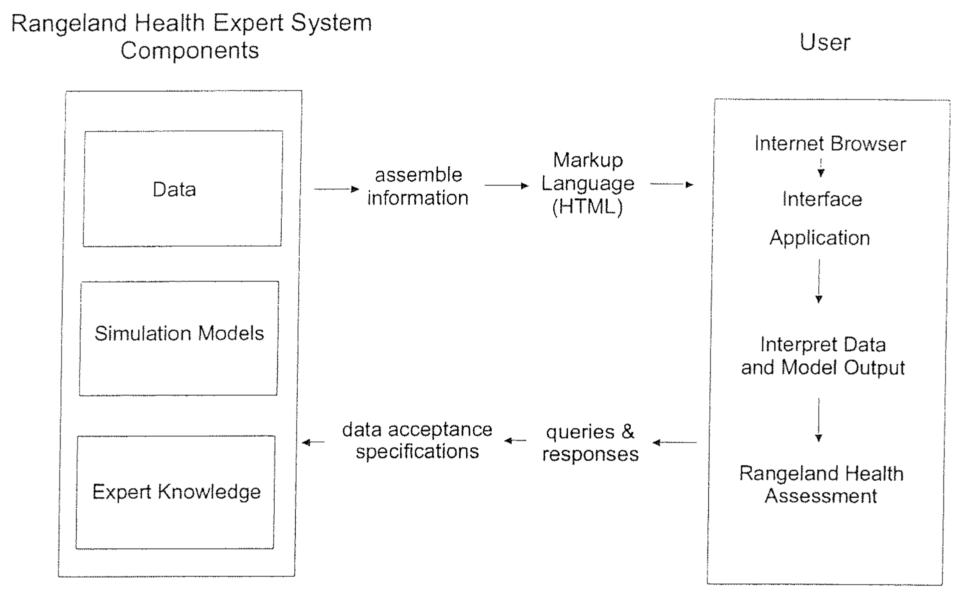

Figure 2. Schematic of Prototype Rangeland Health Expert System

The relational database is accessed programmatically to parameterize the simulation models. User interaction with the structure of the database is hidden. Data include such variables as precipitation event characteristics and runoff event characteristics. In addition, watershed physical characteristics, such as area and slope, channel cross section geometry, channel lengths, widths, and bed material sediment particle sizes, may be stored in the database. In the absence of site specific measured data, the user is assisted with determining model input values. In addition to physical characteristics, simulation models often require parameters that are more difficult to determine. For example, the TLOSS model requires an input of an SCS curve number, which may be entered by the user, or provided to the user based on watershed characteristics and information contained within a knowledge base.

The assessment of the health of the soil/site stability of the watershed is based on an interpretation of model output with respect to eroding, transporting (equilibrium), and deposition zones. The results of simulating erosion and deposition within a small watershed, the knowledge of experts in the fields of natural resources, and a review of the literature are synthesized to define a rule-based system for interpreting simulation model output. The long-term consequences of accelerated water erosion can be seen in the form of soil degradation. The effects of soil degradation are reflected in watershed ecological attributes such as plant germination, establishment, growth, and reproduction. Identifying degraded portions of the watershed is necessary to efficiently direct management and remediation efforts and to maintain the long-term integrity of the watershed.

4 Conclusions

The integrity of soils and maintenance of watershed function are broad societal concerns. Qualitatively, soil movement within a watershed is indicated by characteristics of the soil surface such as the presence of rills and gullies. Simulation models can be used to quantify the interactions among variables and the effects of these interactions through time. The coupled TLOSS and APOINT simulation models provide a viable tool for estimating the rates of soil loss from small, semiarid watersheds. The functioning of complex, small watershed systems, can be interpreted based on relationships among influential variables described by the models. Understanding these relationships and developing the mathematical expressions describing them is a goal of natural resources scientists. Additionally, the technology exists to extend research results and applications to decision makers and land managers. A watershed scale expert system to assess rangeland health will provide an accessible scientific basis for land use planning and decision making.

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