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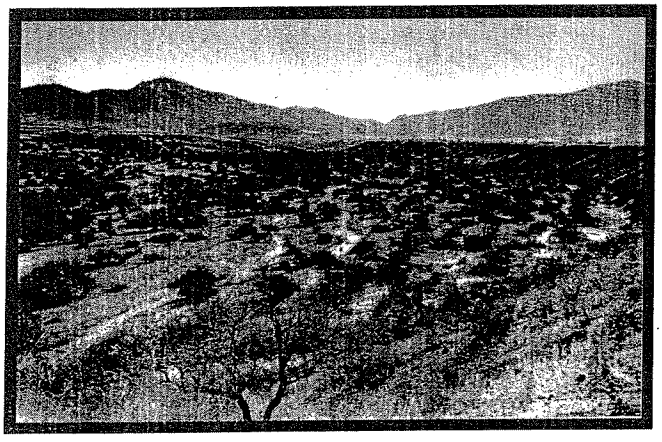

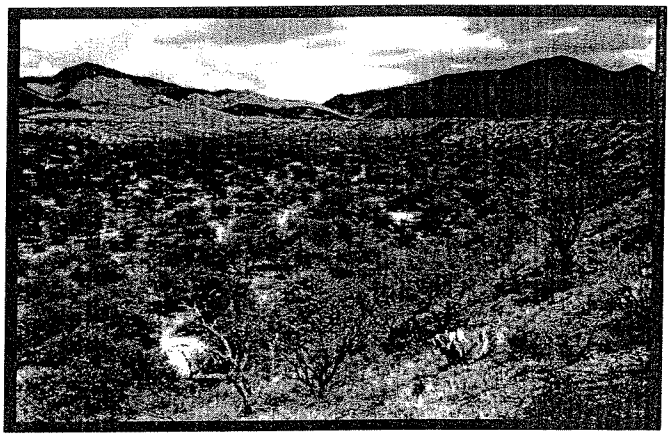

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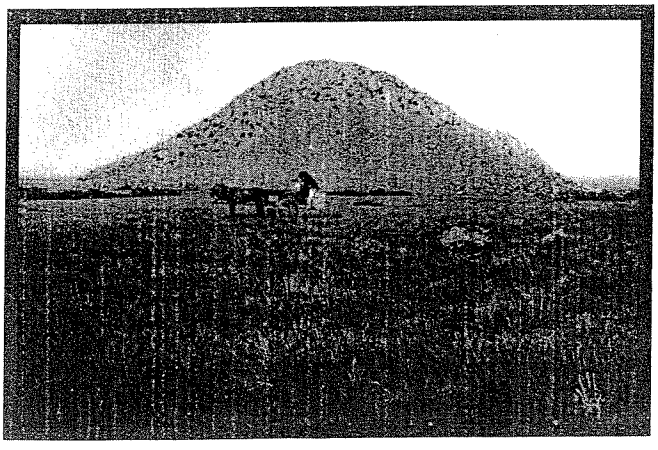

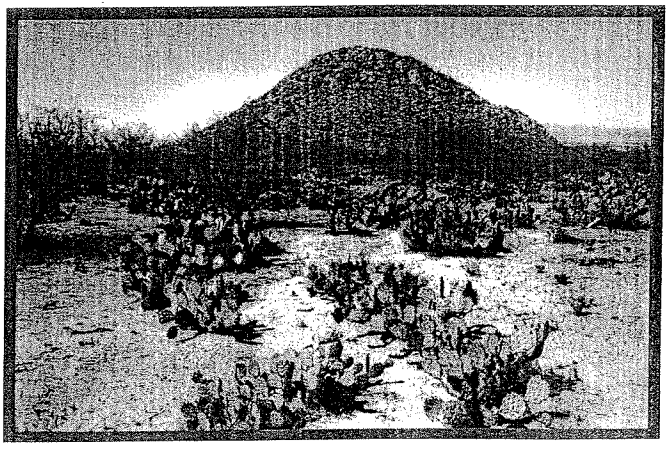

Leonard J. Lane
Mary R. Kidwell

Hydrology and Soil Erosion

Abstract: We review research on surface water hydrology and soil erosion at the Santa Rita Experimental Range (SRER). Almost all of the research was associated with eight small experimental watersheds established from 1974 to 1975 and operated until the present. Analysis of climatic features of the SRER supports extending research findings from the SRER to broad areas of the Southwest with similar climates. Conceptual models for annual water balance and annual sediment yield at the SRER were developed and supported by data from four very small experimental watersheds. The impacts of rotation and yearlong grazing activities, and of mesquite removal were analyzed using data from four small experimental watersheds. The analyses suggested that mesquite removal reduced runoff and sediment yield, but differences in hydrologic response from paired watersheds due to soil differences dominated grazing and vegetation management impacts. The 28 years of monitoring under the same experimental design on the four pairs of watersheds provides us with a long period of "pretreatment" data on the paired watersheds. New treatments could now be adapted and designed based on lessons learned from monitoring over nearly three decades. There is a unique opportunity to institute long-term adaptive management experiments on these experimental watersheds.

Keywords: water balance, runoff, sediment yield, watersheds

Acknowledgments: We gratefully acknowledge the dedicated technicians and scientists from the U.S. Department of Agriculture's Forest Service and Agricultural Research Service, and the University of Arizona, College of Agriculture, who have steadfastly operated and maintained the Santa Rita raingage network, and the land use and management metadata, conducted vegetation and soil surveys and monitoring, and installed and maintained the eight experimental watersheds used for the research described in this paper. Without their efforts, there would be no studies of hydrology and soil erosion on the Santa Rita Experimental Range. We also appreciate the reviewers' timely and helpful comments and suggestions that significantly improved the paper. We thank all of you.

Introduction

Background

Soil, water, air, the plants and animals they support, and human interaction with them are a central focus of natural resources research and management. In this paper we focus on hydrology (specifically surface water hydrology) and soil erosion (specifically soil erosion and sediment transport by water). The Santa Rita Experimental Range (the SRER or simply the Range hereafter) was established in 1903 (see, for example, Medina 1996). Since the end of World War II, several landmark programs have contributed to our current understanding of hydrology in desert (arid) and semidesert (semiarid) ecosystems. Notable examples include the following.

At the third General Conference of UNESCO held in Beirut in 1948, an International Institute of Arid Zone was proposed. In December of 1949 an International Council was approved, and it met in November, 1950. This effort led to the preparation of a series of reports on arid regions of the earth. In 1951 the Southwestern and Rocky Mountain Division of the AAAS

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established the Committee on Desert and Arid Zones Research to assist "study of the factors affecting human occupancy of semiarid and arid regions." This Committee was very active and productive for over two decades in a variety of natural and social science areas.

In 1953 the U.S. Department of Agriculture established the 150-km^2 Walnut Gulch Experimental Watershed near Tombstone, AZ. Research from this experimental watershed established an infrastructure and the scientific understanding and apparatus enabling measurement of surface runoff, soil erosion, and sediment yield from small rangeland watersheds. This nearby infrastructure and understanding led to the establishment of eight small experimental watersheds on the SRER in 1974 and 1975.

From 1967 to 1974 the United States participated in the International Biological Program. The National Science Foundation funded and supported the Desert Biome Program throughout the West from 1972 through 1977. Beginning in 1971 and continuing to the present the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona-Nevada Academy of Science has published "Hydrology and Water Resources in Arizona and the Southwest." In 1978, Academic Press, Inc., London, started publishing the "Journal of Arid Environments" as a forum for multidisciplinary and interdisciplinary dialogue on problems in the world's deserts.

Purpose

Although these programs and projects have immeasurably increased our knowledge and understanding of hydrology of deserts areas, none has produced a focused and indepth synthesis of surface water hydrology and soil erosion in arid and semiarid areas, and especially, on the SRER. Therefore, we propose to partially fill this gap with this paper. Toward this end, the paper focuses on surface water hydrology and soil erosion by water. Emphasis is on hydrology and erosion occurring on the SRER, but regional data and research findings are used for background information and as comparative studies to contrast and broaden similar findings on the SRER.

Scope and Limitations

Our review and analyses are focused on measurements and modeling of surface water hydrology, upland soil erosion by water, and yield of water and sediment from very small experimental watersheds. While major emphasis is on measured data and what we can learn from them, interpretation and understanding of the measured data require understanding and application of conceptual models of the dominant physical processes, and mathematical models (computer simulation models or simply simulation models) describing those processes. The inclusion of conceptual and simulation models is necessary to interpret the measured data, to add a dimension of predictability, and to help understand the processes across a continuum of space and time when measurements are limited to points in space over short time periods.

Review of Hydrologic and Soil Erosion Research at Santa Rita

Overview

Research has been conducted on the 21,500-ha SRER since 1903. The goal of research at the SRER is to investigate and understand the ecology and management of semiarid rangelands. The U.S. Department of Agriculture Bureau of Plant Industry operated the SRER from 1903 until 1915, and from 1915 until 1988 the U.S. Department of Agriculture Forest Service assumed responsibility. Since 1988 the SRER has been under the administration of the Arizona State Land Department and is managed by the University of Arizona for the purpose of conducting ecological and rangeland research (McClaran and others 2002).

According to Martin and Reynolds (1973), the SRER is representative of over 8 million hectares of semiarid (semidesert) grass-shrub ecosystems in southern Arizona, New Mexico, Texas, and northern Mexico. The extent to which research findings from the SRER are transferable over these broad geographical areas depends, in large part, upon how widespread climatic characteristics of the SRER are represented regionally.

Climate

Although the focus herein is hydrology and soil erosion, climate plays such a strong role that a brief climatic summary of the SRER is necessary. Green and Martin (1967) analyzed precipitation data from the Range. A common 26-year period, 1940 to 1965, for 22 raingages situated across the SRER was used for statistical analyses. Average annual precipitation for this period of record varied from about 282 mm at the northwest gage at an elevation of approximately 914 m MSL to 492 mm at an elevation of approximately 1,310 m. This range of 492 – 282 = 210 mm over an elevation difference of only 1,310 – 914 = 396 m indicates a strong trend of about 53 mm of precipitation per 100 m difference in elevation. These two raingages are located about 17.4 km apart so that the rate of change in mean annual precipitation is 210 mm per 17.4 km = 12 mm per km of distance.

These statistics of 53 mm of mean annual precipitation change per 100 m of elevation change and 12 mm of mean annual precipitation change per km horizontal distance indicate a strong orographic effect in precipitation. The dry adiabatic lapse rate is about 9.8 °C per km of elevation so that mean annual temperature also varies with elevation. Taken together, the changes in mean annual precipitation and temperature with elevation mean that the Headquarters (Florida location or Santa Rita Experimental Range station) climate does not represent the average conditions over the 21,500 ha SRER. Rather, the Florida station represents an extreme in terms of high precipitation and cooler temperature. In fact, following Trewartha and Horn (1980), the Florida station is near the boundary between semiarid and subhumid climates, and the Northwest station is near the boundary between semiarid and arid climates. The average climate for the SRER is classified as semiarid or steppe.

Annual Water Balance

The term "hydrologic cycle" is the most general way of describing the cycling or movement of water through the lands, oceans, and atmosphere. The hydrologic cycle is usually described and quantified in terms of its components. These components include precipitation, evaporation, transpiration, runoff, ground water, and water temporarily stored such as in soil moisture, lakes, and reservoirs. The term "water balance" as used in hydrologic studies has a similar meaning to the term "hydrologic cycle," but it connotes a budgeting or balancing of components in the hydrologic cycle for a given place or area. In this paper, the area we use to make water balance calculations is the watershed.

A watershed is described with respect to surface runoff as being defined by a watershed perimeter (for example, see Lane and others 1997). This watershed perimeter is the locus of points where surface runoff produced inside the perimeter will flow to the watershed outlet. Therefore, water balance calculations are for a watershed and a specific time period such as annual, seasonal, daily, or hourly. Our emphasis herein is on an annual water balance and on storm event or daily values of water balance used to compute an annual balance on small watersheds in upland areas.

Conceptual Model for Annual Water Balance—In warm to hot semiarid regions with bimodal annual precipitation, such as the SRER, a conceptual model of an annual water balance can be described as follows. Precipitation varies seasonally with the most prominent period of precipitation in the summer (July to September), with a secondary peak in the winter (late December to March), and with relatively dry periods in the spring and fall. Mean annual precipitation varies between about 250 and 500 mm. Mean annual surface runoff from small upland watersheds (defined herein as small areas ranging in size from a few square meters up to a few hectares) varies from near zero up to about 10 percent of annual precipitation or from near zero to 50 mm. Actual mean annual evapotranspiration (the sum of the actual amount of evaporation from soil and cover material and the actual amount of plant transpiration) ranges from about 90 to near 100 percent of mean annual precipitation. During extremely high precipitation episodes (for example, heavy summer or fall rainfall from the influx of moisture from tropical storms and hurricanes and very wet winters when the winter storm track is over southern Arizona), soil moisture can increase to field capacity (the upper limit of soil moisture storage when percolation through the soil profile begins) and deep percolation of soil moisture below the plant rooting depth can occur (see for example, Lane and others 1984; Renard and others 1993). These periods of high soil moisture and deep percolation are relatively rare so that mean annual values derived from them are highly variable and highly uncertain.

The conceptual model is that there is little and very rare percolation below the root zone so that most soil moisture remains in the upper meter or so of the soil, surface runoff is due to rainfall rates exceeding the infiltration capacity of the soil, actual annual evapotranspiration is nearly equal to annual precipitation (minus infrequent surface runoff and very rare deep percolation), and that soil moisture storage is recharged and depleted on an annual basis so that the mean annual change in soil moisture is near zero.

Empirical evidence of the applicability of this conceptual model for an annual water balance at the SRER includes the general absence of (1) perennial and intermittent streams, (2) springs and seeps, and (3) shallow ground water. Exceptions to ephemeral streams may occur when perennial streams originating in the mountains flow onto the SRER. However, the conceptual model is for small upland areas on the SRER and is generally supported by observations and measurements (see Lawrence 1996, as discussed later).

Mathematical Model for Annual Water Balance—A mathematical model of annual water balance for upland watersheds, such as those on the SRER, can be written as follows. The one-dimensional water balance equation for a unit area, to plant rooting depth, ignoring runon (runoff originating out of the unit area and flowing onto it) and assuming subsurface lateral flow is zero, can be written as

$$dS/dt = P - Q - AET - L \qquad (1)$$

where dS/dt is the change in soil moisture (mm), P is precipitation (mm), Q is runoff (mm), AET is actual evapotranspiration (mm), L is percolation or leaching below the rooting depth (mm), and t is time (years for an annual water balance although the actual calculations may be made using a daily time step).

Example Water Balance Calculations Using a Simple Model—We selected a simple water balance model that could be operated based on limited available climatic, soils, vegetation, and land use data. The CREAMS Model (Knisel 1980) solves equation 1 for a daily time step and then sums the results for monthly and annual values. The CREAMS Model has previously been applied at arid and semiarid sites somewhat similar to the SRER, including the Walnut Gulch Experimental Watershed near Tombstone, AZ (see Renard and others 1993 and Goodrich and others 1997 for details on modeling and descriptions of Walnut Gulch).

The CREAMS Model was applied to Watershed Lucky Hills 3, a small semiarid watershed on the Walnut Gulch Experimental Watershed. Rainfall and runoff data were available for 17 years (1965 to 1981), and were used to optimize the model parameters for runoff simulation. As P and Q were measured, the model was calibrated to match observed values of runoff, Q, and then AET and L were estimated using a form of equation 1. These calculations are summarized in table 1. In table 1, column 1 lists the month or the annual period, column 2 lists measured precipitation in mm, column 3 lists measured surface runoff in mm, column 4 lists the estimated actual evapotranspiration in mm, column 5 lists estimated percolation below the plant rooting depth in mm, and column 6 lists the estimated average plant available soil moisture in mm. Notice that the annual values in Columns 2 to 5 are annual summations, whereas the annual value for plant available soil water is an average annual value. Values of Q, AET, and L in table 1 do not exactly sum to P because dS/dt was not exactly equal to zero over the simulation period. However, dS/dt was relatively small, about 1.4 mm in the entire soil profile for the data shown in table 1.

Table 1—Average annual water balance for Watershed 63.103 at Walnut Gulch, Arizona, as calculated with the CREAMS Model calibrated using 17 years of rainfall and runoff data, 1965 to 1981 (adapted from Renard and others 1993).

Month	Precipitation	Runoff	AET	Percolation	Plant available soil water
1	2	3	4	5	6
			mm		
January	18.0	0.58	18.6	0.03	22.2
February	14.2	.28	18.0	.17	2.7
March	15.0	.18	21.2	.0	16.1
April	3.8	.0	11.8	.0	6.6
May	5.3	.13	7.4	.0	2.0
June	8.3	.28	8.4	.0	1.3
July	87.9	7.24	62.2	.0	9.8
August	63.3	4.78	63.7	.0	14.9
September	39.1	3.45	34.8	.0	15.7
October	21.0	1.70	16.5	.0	16.0
November	7.7	.05	9.7	.0	16.0
December	19.3	1.02	12.1	.0	18.8
Annual	302.9	19.7	284.4	.20	11.8

The mean monthly precipitation distribution at Walnut Gulch is bimodal (table 1) with a strong summer peak from July through September and a small secondary peak from December through March. Soil moisture storage (plant available soil water) follows this trend with recharge occurring July through October and again in December and January. Rapid soil moisture depletion occurs from February through June (table 1, last column).

Annual Water Balance for Small Watersheds on the Santa Rita—In cooperation with the USDA Forest Service and the University of Arizona, the USDA Agricultural Research Service established and instrumented eight small experimental watersheds during 1974 to 1975 within the Santa Rita Experimental Range. These experimental watersheds were established to study the impact of cattle grazing and vegetation manipulation methods on hydrology and soil erosion. Four of the watersheds (WS1 to WS4) were located at an approximate elevation of 976 to 1,040 m, while the other four watersheds (WS5 to WS8) were located at a higher elevation of about 1,170 m. The four upper watersheds are emphasized in this paper 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 semiarid regions of the Southwestern United States (Martin and Morton 1993). In 1974, two of the watersheds (WS6 and WS7) 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 two watersheds (WS7 and WS8) and a rotation system on the other 2 (WS5 and WS6). 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 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 in Medina (1996) and McClaran and others (2002).

Lawrence (1996) used measured data and experts' judgment in a multiobjective decision support system to evaluate management systems on the upper four small watersheds described above. Available precipitation and runoff data from these watersheds were compiled for a 16-year period, 1976 to 1994 (Lawrence 1996). Therefore, an annual water balance could be constructed by estimating actual evapotranspiration and percolation below the root zone. These estimates are summarized in table 2. The drainage area for each watershed and its generalized soil texture are shown in column 1 of table 2. The mean annual values of actual evapotranspiration (AET) (column 5) and percolation below the rooting depth (L) (column 6) were estimated based on the water balance equation (equation 1) and the CREAMS water

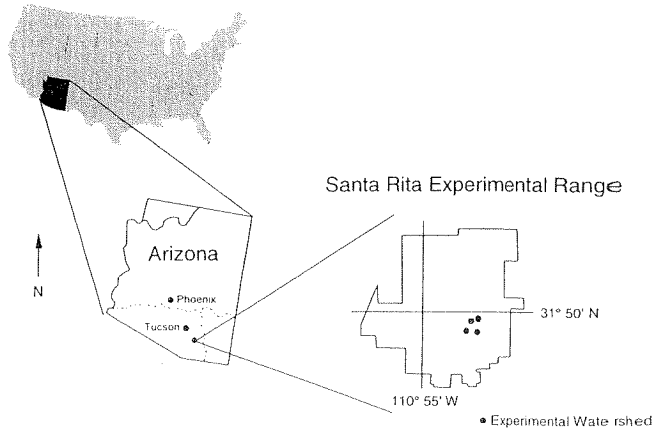

Figure 1—The Santa Rita Experimental Range showing the location of the upper four experimental watersheds.

Table 2—Summary of estimated annual water balance on the upper four experimental watersheds at the Santa Rita Experimental Range from 1976 to 1991. Precipitation is for a centrally located raingage on Watershed 5. All values are annual means in mm and values in parentheses are coefficients of variation, in percent, for the measured variables.

Watershed 1	Treatment 2	Measured precipitation 3	Measured runoff 4	Estimated AET 5	Estimated percolation 6
WS5 (4.02 ha) sandy loam	Rotation grazing, mesquite retained	440.0 (27.0)	16.7 (102.0)	423.0	0 to 1
WS6 (3.08 ha) loamy sand	Rotation grazing, mesquite removed	440.0 (27.0)	1.6 (138.0)	438.0	0 to 1+
WS7 (1.06 ha) sandy loam	Continuous grazing, mesquite removed	440.0 (27.0)	25.2 (123.0)	415.0	0 to 1
WS8 (1.12 ha) sandy loam	Continuous grazing, mesquite retained	440.0 (27.0)	30.1 (92.0)	410.0	0 to 1

balance model (described earlier as applied at the Walnut Gulch Experimental Watershed). The coefficient of variation (CV), defined as the standard deviation of the annual values divided by their mean, was about 27 percent for measured mean annual precipitation and between about 90 and 140 percent for measured mean annual runoff. Values of AET, and especially L, are extremely uncertain as they contain the natural variability of the measured data as well as all the errors and uncertainty due to modeling. Therefore, we did not show estimate CVs for AET and L.

Lawrence (1996) interpreted the data summarized in table 2 as follows. Watersheds with mesquite removed appeared to produce less runoff than their paired watershed with mesquite retained (runoff from WS6 < WS5 and runoff from WS7 < WS8). The observed reductions in runoff from mesquite removal for both grazing systems are consistent with the findings from experiments reported in the literature (for example, Carlson and others 1990).

However, Watersheds 5, 7, and 8 have sandy loam soils, while Watershed 6 has loamy sand soils. Runoff differences due to differences in soils (WS6 versus WS5) were more significant than the differences due to grazing system and mesquite removal. The technique of using paired watersheds and treating one of each pair is based on the assumption that the paired watersheds have similar hydrologic behavior. This is not the case for Watersheds 5 and 6 where different soils (sandy loam versus loamy sand) result in different hydrologic response to precipitation events. One way to determine if the watersheds are similar in response is to instrument and monitor them for a sufficient period of time before the treatments are imposed. Unfortunately, this was not done on the four pairs of watersheds on the SRER, rather, treatments were imposed at the same time that hydrologic monitoring was initiated.

Finally, the computed annual water balance for the upper four experimental watersheds at the SRER agrees quite well with the previously described conceptual model for water balance on small semiarid watersheds. Although mean annual runoff was relatively small (0.37 percent of mean annual precipitation on WS6 to 6.84 percent of mean annual precipitation on WS8), this does not mean that runoff in not an important part of the water balance. Runoff amounts, although small when compared with precipitation, are responsible for flooding, soil erosion, sediment transport and yield, and significant landscape evolution over time.

Surface Water Hydrology

Although measuring or modeling an annual water balance involves measuring or modeling individual rainfall runoff events, and thus surface water hydrology for individual storm events, there are other studies at SRER providing additional insight into the dynamics of rainfall infiltration-runoff during individual storm events. It should be noted that the number of such studies on SRER are small compared with more comprehensive watershed studies in the region (such as Walnut Gulch in southeast Arizona and the lower watershed studies on Beaver Creek in north-central Arizona). Therefore, quantitative determination of hydrologic processes during individual runoff events is somewhat lacking and almost entirely based on the eight experimental watersheds established on SRER.

Diskin and Lane (1976) studied the applicability of unit hydrograph concepts at SRER. Unit hydrographs provide a means of computing runoff hydrographs from a small watershed given rainfall and infiltration data. They analyzed a number of rainfall and runoff events on one of the lower small watersheds (Watershed 1). Double triangle unit hydrographs were fitted to individual storm events. The differences in the shapes of individual unit hydrographs were found to be small so that they could be approximated by a single double-triangle-unit hydrograph.

Significant errors in estimating surface runoff and erosion rates are possible if a watershed is assumed to contribute runoff uniformly over the entire area, when actually only a portion of the entire area may be contributing. Generation of overland flow on portions of small semiarid watersheds was analyzed by three methods: (1) an average loss rate procedure, (2) a lumped-linear model, and (3) a distributed nonlinear model. These methods suggested that, on the average, 45, 60, and 50 percent, respectively, of the drainage area was contributing runoff at the watershed outlet. Infiltrometer data support the partial area concept and indicate that the low infiltration zones are the runoff source areas as simulated with a distributed and nonlinear kinematic cascade model (Lane and others 1978a). A subsequent herbicide tracer study was conducted to provide empirical data to test the partial area concept at SRER.

Based on the concept of partial area response, Lane and others (1978b) conducted a runoff tracer study on two small watersheds (Watersheds 1 and 2). The watersheds were partitioned into four geomorphic subzones or hydrologic response units. Each of the four zones on both watersheds

was treated with about 1 kg per ha of an individual water-soluble herbicide. Runoff volumes and sources estimated using the tracers were consistent with results from simulation studies and thus supported the partial-area concept of surface runoff generation at SRER.

The cited studies of surface water hydrology at SRER provided additional insight into rainfall-runoff processes, how they are nonuniform over even small watersheds (partial-area response), that unit hydrograph and kinematic routing methods can be used to develop runoff hydrographs from small watersheds at SRER, and that concepts of overland flow and ephemeral streamflow in alluvial stream channels are applicable at SRER. That these findings are consistent with findings at Walnut Gulch and at other semiarid watersheds suggests that research findings from small watersheds at SRER have broader regional applicability and significance.

Soil Erosion and Sediment Transport

Observations and measurements of water erosion at the SRER suggest that soil erosion by water dominates over wind erosion. However there are no long-term studies of wind erosion comparable to the long-term runoff and water erosion studies on the eight small watersheds. Nonetheless, we describe a conceptual model for soil erosion, sediment transport, and sediment yield for small semiarid watersheds based on water erosion and neglecting wind erosion.

A Conceptual Model for Soil Erosion, Sediment Transport, and Sediment Yield—Schumm (1977) presented a description of an idealized fluvial system (a conceptual model) as consisting of three zones 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, as sinks or zones of deposition. This conceptual model of Zone 1 as a sediment source, Zone 2 as the sediment transport component, and Zone 3 as a sediment sink has proven useful in generalizing processes at the mid to large watershed scale (such as rivers as large as the Missouri-Mississippi system).

Watersheds contain interior or subwatersheds, and there often exists a similarity of shape and structure across the range of scales from the watershed to its smaller sub-watersheds. Building on this similarity concept and the three-zones concept, we can define the basis for a conceptual model of soil erosion and sediment yield. The basis is that there is a continuum of "sediment source-transport-and sink zones" across a range of scales from the watershed down to its smallest components.

The conceptual model we propose is that within a semiarid watershed there is a continuum of sediment source-transport-sink zones and that different erosional processes are dominant at different spatial scales. Further, at the plot to hillslope to very small watershed scale (about a square meter up to perhaps a few hectares) hillslope topography, vegetative canopy cover, surface ground cover, soil and soil detachment processes are dominant. At the subwatershed scale (that is, one to perhaps a thousand hectares) geology, soils, gully and channel processes, vegetation type, and sediment transport and deposition processes are dominant. Although beyond the scope of this paper, at the watershed scale (from about a thousand to greater than 10,000 ha) partial rainfall coverage of the watershed, infiltration of streamflow (transmission losses) to the channel bed and banks, sediment transport capacities, geology, and soils are dominant. Of course, all processes are important within a watershed, but we are describing dominance as a function of watershed scale. In summary, soil erosion, sediment transport and deposition, and thus sediment yield vary as a function of spatial scale with identifiable factors and processes dominating them depending upon spatial scale (table 3).

Hillslope Erosion and Sediment Yield From Very Small Watersheds—At the plot, hillslope scale, and very small watershed scale (from a square meter up to a few hectares appropriate for the experimental watersheds at the SRER) overland flow processes dominate on hillslopes, as channelization at this scale is at the microtopographic level and larger channels are usually absent. At the small watershed scale, hillslope processes are important, but flow becomes channelized, and processes of sediment transport and deposition are also important in determining watershed sediment yield. This is the spatial scale appropriate for the eight experimental watersheds on the SRER. The sediment source-transport-sink concept applies at this scale and is observable in the field. At the scale of a meter or less, one can see debris dams caused by accumulation of litter behind a plant, rock, or other small feature, and that these debris dams induce sediment deposition and thus trap sediment. At the hillslope scale, one can see areas of no apparent soil erosion (unless closely observed with a trained eye), areas of rill or concentrated flow erosion, and areas of sediment deposition such as at the toe of a slope. Hillslopes contribute water and sediment to small ephemeral channels that drain to the watershed outlet, and in these channels one can observe areas of scour or degradation, areas in which no scour or deposition is apparent, and areas of sediment deposition. Sediment passing the watershed outlet (in the case of the SRER watersheds, the runoff measuring flumes) is called sediment yield. It is customary to speak in terms of sediment mass flux per unit time or sediment mass flux per unit time per unit area (for example t/ha/y).

As part of his analyses, Lawrence (1996) tabulated annual runoff and sediment yield data measured at the outlets of the upper four SRER watersheds for the 16-year period 1976 to 1991. 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.

Mean annual sediment yield (along with mean annual precipitation and runoff for completeness) are summarized in table 4. The annual means vary from under 0.1 t per ha from Watershed 6 to over 4 t per ha from Watershed 5. Also shown in column 5 of table 4 is the mean annual sediment concentration, C_b, in percent by weight. Values of mean sediment concentration varied from a low of 0.38 percent (3,800 mg per L) from Watershed 6 to a high or 2.5 percent (25,000 mg per L) from Watershed 5. As was the case for mean annual runoff, the very low sediment yield from Watershed 6 is more the result of its different soil (loamy sand on WS6 and sandy loam on WS5, WS7, and WS8) than as a result of the treatments. Watershed 6 produced significantly less runoff and correspondingly significantly less

Table 3—Summary of dominant processes controlling sediment yield from semiarid watersheds such as those at Walnut Gulch and the SRER. Table adapted from Lane and others 1997 to illustrate a conceptual model for soil erosion and sediment yield on semiarid watersheds.

Approximate scale (ha) on the sediment source transport sink continuum		
Plot to hillslope (10^{-4} to 10^{0} ha)	Subwatershed (10^{0} to 10^{3} ha)	Watershed (10^{3} to 10^{4} ha)
← Dominant processes at the indicated scale →		
← Range of scales studied at the SRER →		
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, channell processes, sediment transport capacities, and soils
← Processes more or less in common across scales →		
Rainfall, runoff amounts, and Intensities		
Spatial variability and interactions		

sediment yield than the other three watersheds. Again, there is a suggestion in the data that removing mesquite reduces runoff and sediment yield, but differences in the soils dominated the impacts of grazing and mesquite removal on runoff and sediment yield. Given the high variability in sediment yield (CVs of mean annual sediment yield in table 4 range from 83 to 107 percent), it is instructive to examine the role of extreme years (years with annual sediment yield significantly larger than the mean) in determining mean annual sediment yield.

Erosion and sediment yield monitoring programs are often conducted over short time periods, and the resulting short-term databases are used for a variety of purposes including estimation of mean annual soil erosion rates, mean annual sediment yield, and the resulting rates of landscape evolution. Since by definition large events are rare, a short monitoring period may or may not sample any large events. Annual sediment yields for each of the 16 years from 1976 through 1991 were computed, and from them a mean annual sediment yield for all 16 years was computed for each of the small watersheds. Contributions of sediment yield from the individual years (not events) were used to analyze the relationship between sediment yield in "large sediment yield years" and the 16-year mean annual sediment yield. The relation between sediment yield in the years with the largest annual sediment yields to the 16-year mean annual sediment yield from the four upper watersheds on the SRER is illustrated in figure 2.

We interpret the data shown in figure 2 as follows. During 16 years of measurements, the year with the largest sediment yield (fraction of years = $1/16 = 0.0625$) accounted for about 18 to 26 percent of the mean annual sediment yield. The four years with the largest sediment yield (25 percent of the period of record of 16 years) accounted for about 54 to 66 percent of the mean, and the 8 years with the largest sediment yields accounted for about 80 to 90 percent of the mean annual sediment yields on the four watersheds. Similar statistics and

Table 4—Summary of mean annual sediment yield from the upper four experimental watersheds at the Santa Rita Experimental Range from 1976 to 1991. Precipitation is for a centrally located raingage on Watershed 5. The values are annual means in mm for precipitation and runoff and in t per ha for sediment yield. The values in parentheses are coefficients of variation, in percent, for the measured variables.

Watershed 1	Treatment 2	Measured precipitation 3	Measured runoff 4	Measured sediment yield 5
WS5 (4.02 ha) sandy loam	Rotation grazing, mesquite retained	440.0 (27.0)	16.7 (102.0)	4.21 (94.0) (C_b = 2.5 percent)[a]
WS6 (3.08 ha) loamy sand	Rotation grazing, mesquite removed	440.0 (27.0)	1.6 (138.0)	0.06 (107.0) (C_b = 0.38 pe rcent)
WS7 (1.06 ha) sandy loam	Continuous grazing, mesquite removed	440.0 (27.0)	25.2 (123.0)	1.48 (106.0) (C_b = 0.59 pe rcent)
WS8 (1.12 ha) sandy loam	Continuous grazing, mesquite retained	440.0 (27.0)	30.1 (92.0)	3.67 (83.0) (C_b = 1.2 percent)

[a] C_b = Mean sediment concentration in percent by weight. Note: 1-percent sediment concentration = 10,000 mg per L.

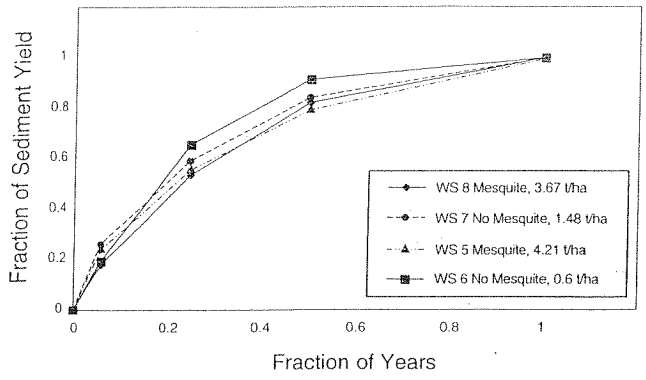

Figure 2—Relation between sediment yield in the years with the largest annual sediment yields to the 16-year mean annual sediment yield on four watersheds at the Santa Rita Experimental Range in southern Arizona.

graphs could be computed for annual runoff, and they would show similar results.

The significance of these results is clear. Runoff and sediment yield estimates from short periods of record on semiarid watersheds (such as those at SRER) are highly variable (CVs of mean annual runoff and mean annual sediment yield are on the order of 100 percent or more), and thus there is a great deal of uncertainty in the means estimated from short periods of record. For data such as these in tables 2 and 4, the natural high levels of variability and the resulting high levels of uncertainty make it very difficult to evaluate the impacts of land use and management (in this case, alternative grazing systems and mesquite removal) on runoff and sediment yield. In the face of such high natural variability in time, relatively longer periods of record (at least greater than 16 years) are needed to evaluate the impacts of land use and management practices. In addition, the technique of using paired watersheds and treating one of each pair loses much of its power if the watersheds are significantly different in their rainfall-runoff and runoff-sediment yield relationships before imposition of treatments or alternative land management practices. This argues eloquently for pretreatment monitoring and modeling to ensure that the paired watersheds are as similar as is possible in their hydrologic and erosional characteristics.

Discussion

Summary

We reviewed hydrologic and soil erosion research on the SRER. Almost all of that research was associated with the eight small experimental watersheds established in 1974 to 1975 and operated until the present. Analysis of climatic features of the SRER supports the concept of extending research findings from the SRER to broad areas of the Southwest with similar climatic regimes.

Conceptual models for annual water balance and annual sediment yield at the SRER were developed. Analyses and interpretation of measured and modeled hydrologic data on water balance, soil erosion, and sediment yield from four small experimental watersheds supported these conceptual models and added specificity to their general scientific content.

Due to its long history and rich databases of vegetation characterization, grazing, and land management activities, the SRER is well suited for evaluating the impacts of land use and management practices upon hydrology, soil erosion processes, and watershed sediment yield. The impacts of cattle rotation and yearlong grazing activities and mesquite removal were analyzed using data from four small experimental watersheds. The analyses suggested that mesquite removal reduced runoff and sediment yield, but differences in hydrologic response from paired watersheds due to soil differences dominated grazing and vegetation management impacts.

High levels of variability in components of the water balance and in sediment yield suggest that long duration watershed studies are required to quantify components of the water balance and sediment yield.

Some Lessons Learned

- Climatic features of the SRER are similar to broad areas of the American Southwest and Northern Mexico so that research findings from hydrologic and erosion studies on the SRER have broad geographical applicability.
- Hydrograph development techniques such as unit hydrographs and kinematic cascade models can be successfully applied on the SRER.
- Variations in topography, soils, and vegetative cover within very small watersheds on the SRER result in what is called a partial area response where only portions of a watershed may be producing surface runoff. These simulation modeling results were verified by herbicide tracer studies.
- A conceptual model of annual water balance developed for semiarid watersheds is applicable on the SRER.
- A conceptual model for annual sediment yield from semiarid watersheds is applicable on the SRER.
- Paired watershed studies were used to study the impacts of grazing systems and mesquite removal on runoff and sediment yield, but the results were ambiguous because of significant differences in hydrological responses resulting from variations in soil properties between the paired watersheds (WS5 and WS6).
- Paired watershed studies should include a period of pretreatment monitoring and modeling before treatments are imposed to determine if the paired watersheds are indeed hydrologically similar.
- Extreme natural variability in components of the water balance and sediment yield from very small watersheds suggest that long periods of observation and monitoring are required to evaluate impacts of land use and management practices on runoff, erosion, and sediment yield.

Path Forward for Hydrology and Soil Erosion Research at Santa Rita

Twenty-eight years of hydrologic data and observations are now available for the eight paired experimental watersheds at SRER. Treatments (yearlong versus continuous

grazing, and mesquite removal versus mesquite retained) have been maintained over this entire period of record. This presents us with unique and invaluable opportunities.

If new treatments were imposed now, these 28 years of monitoring under the same experimental design on the four pairs of watersheds would provide a long period of "pretreatment" monitoring on the paired watersheds (WS1 versus WS2, WS3 versus WS4, WS5 versus WS6, and WS7 versus WS8). New treatments could now be adapted and designed based on lessons learned from monitoring and modeling activities over nearly three decades. There is a unique opportunity to institute long-term adaptive management experiments on these eight experimental watersheds. Institutional control of the watersheds, scientific databases, modeling expertise, and "corporate knowledge" of monitoring, modeling, and interpretation exist within the cooperating organizations. No other experimental range or watershed program has such a rich background of three decades of "pretreatment" baseline results on paired watersheds to begin a carefully designed and long-term adaptive management research program.

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