Erosion and Runoff Measurements from Semi-Arid Rangeland in Southwestern USA: an Overview

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Abstract

The research program at the Southwest Rangeland Watershed Research Center in Tucson, Arizona, USA, is aimed at obtaining information for assessing present and future water potential, developing water-management techniques, providing design concepts for flood and sediment control, evaluating nonpoint source pollution, developing rangeland revegetation techniques, and water-harvesting/runoff-farming techniques. Current studies are involved with (1) precipitation intensity and areal distribution; (2) infiltration and channel losses; (3) hydrologic balance of semi-arid rangeland watersheds; (4) runoff hydraulics and flood-water yield frequency relations; (5) erosion and sediment transport; (6) surface and groundwater quality; (7) vegetation manipulation and rangeland revegetation; and (8) water harvesting and runoff farming. Much of the research activity is focused on developing concepts and collecting data for use in modeling to extend the area of potential applicability of the research results.

Introduction

Major advances have been made in water resources research in arid and semi-arid regions in the past few decades, due in part to advances in computer technology, which permits the handling and analysis of many data. When matched with parallel development of sophisticated analytical models for various hydrologic processes, we are able to explain past events; but more importantly, we are now able to predict more accurately the hydrologic results, should various land- and water-management practices be implemented.

Research Facilities

The Southwest Rangeland Watershed Research Center is a facility of the U.S. Department of Agriculture, Agricultural Research Service. The main office and laboratory facilities are at Tucson, Arizona, with active experimental watersheds in southeastern Arizona, on the Walnut Gulch Watershed near Tombstone, and on the Santa Rita Experimental Range, U.S. Forest Service, south of Tucson. Watershed studies at Safford, Arizona, as well as Albuquerque, Santa Rosa, and Fort Stanton, New Mexico, are now terminated, the immediate research objectives having been achieved. The data obtained from these studies are used to complement ongoing research.

The major research area is the 150-km^2 Walnut Gulch watershed, an ephemeral tributary of the San Pedro river. The watershed is basically a high foothill alluvial fan with medium- to fine-textured soils that are gravelly or stony at the surface. The area is characterized by mild temperatures, limited rainfall (= 300 mm a^{-1}) and high evaporation (average pan evaporation of over 2600 mm a^{-1}). The climax vegetation is desert plains grasslands, with 60% of the watershed now supporting desert shrubs. Livestock grazing is the primary land use.

Stream-flow is measured with supercritical flumes (570 m^3 s^{-1} capacity) at 11 gauging stations, three on the main channel, and eight on major tributaries. In addition, there are 12 subwatersheds (0.2–60 ha)

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equipped with a smaller version flume (2.8 m^3 s^{-1} capacity) (Smith et al. 1982) and 11 subwatersheds (34–316 ha) where runoff and sediment yield are measured in earthen stockponds. Sediment transport is measured at most of the small flumes with solar batteries which power traversing slots or pump samplers. A network of 95 24-h weighing recording rain gauges distributed on the watershed are used for monitoring and recording precipitation amounts. Each small subwatershed has at least one recording rain gauge.

On the Santa Rita Experimental Range, eight small watersheds (1.1–4.0 ha) are equipped with small supercritical flumes (2.8 m^3 s^{-1} capacity) and solar-powered traversing-slot sediment samplers. Each watershed has a 24-h weighing-type rain gauge for monitoring precipitation.

Research Mission

The primary mission of the Center is to study the hydrologic characteristics of arid and semi-arid rangeland watersheds and the effects of changing land use and practices on the hydrologic cycle. Emphasis is on: (1) understanding and evaluating the effects of changing land use, including range renovations and conservation practices; and (2) developing the principles for such an understanding in order to apply the results and findings from research to areas where few or no research data are available.

Data from the experimental areas are used to study climate, soil, plant, chemical, and water relations from southwestern rangelands. Information obtained from the study watersheds is used for determining present and future water-resource potentials, developing water-management techniques for competing water users, providing design concepts and criteria for flood and sediment control, evaluating nonpoint source pollution, developing techniques for increasing and stabilizing forage production, and developing water-harvesting runoff-farming techniques for conserving and improving rangeland water supplies.

Recent Research Progress

Precipitation intensity and areal distribution studies

Precipitation at Walnut Gulch, representative of much of the southwestern United States, is highly variable in annual quantities, storm amounts and intensities, and storm frequency. The annual amounts are distributed between two seasons: summer and winter. The summer storms result from moisture originating in the Gulf of Mexico or from tropical storms in the Pacific Ocean off lower Baja, Mexico. These storms are basically high-intensity, short-duration, air-mass convective thunderstorms of limited areal extent (see example mapped in Fig. 1). Such intense summer thunderstorms produce most of the runoff from the Walnut Gulch Watershed. The winter storms are from Pacific Ocean storm systems moving into the area from the northwestern Pacific. These are characteristically of low intensity, long duration, and large areal extent. There is usually no runoff measured from these winter storms, but they do contribute to providing soil water for plant growth.

A significant factor contributing to the progress in understanding runoff processes on the arid and semi-arid watersheds of the southwestern United States has been the development of a better description of the thunderstorm processes that dominate the annual precipitation total and produce most of the runoff in the area.

Three elements are needed for an analytic description of thunderstorm rainfall: (1) distribution of rainfall events; (2) distribution of rainfall depths at a point; and (3) areal distribution patterns (Renard 1977). The physical processes that cause precipitation are complex and not completely understood. One simplifying procedure for characterizing precipitation is to use probabilistic descriptions for predicting properties of future precipitation events as an input in hydrologic models. The work at the Center has two major research objectives in this area: (1) to develop regional models of point and areal distributions of rainfall (primarily for Arizona and New Mexico); and (2) to develop models of intrastorm rainfall intensities, amounts, and frequencies.

Current results are the following. (1) A stochastic model of point precipitation, using a Markov Chain for daily occurrence (Smith and Schreiber 1973) and a mixed exponential distribution for the daily depths (Smith 1974), was found to reproduce most measured precipitation sequences at Walnut Gulch and other southern Arizona stations. (2) A convective storm model, including the areal pattern, has been developed. Depth-area curves generated by the model are being used by hydrologists and engineers for flood forecasting. And (3), a simulation program for modeling time and space distribution of rainfall

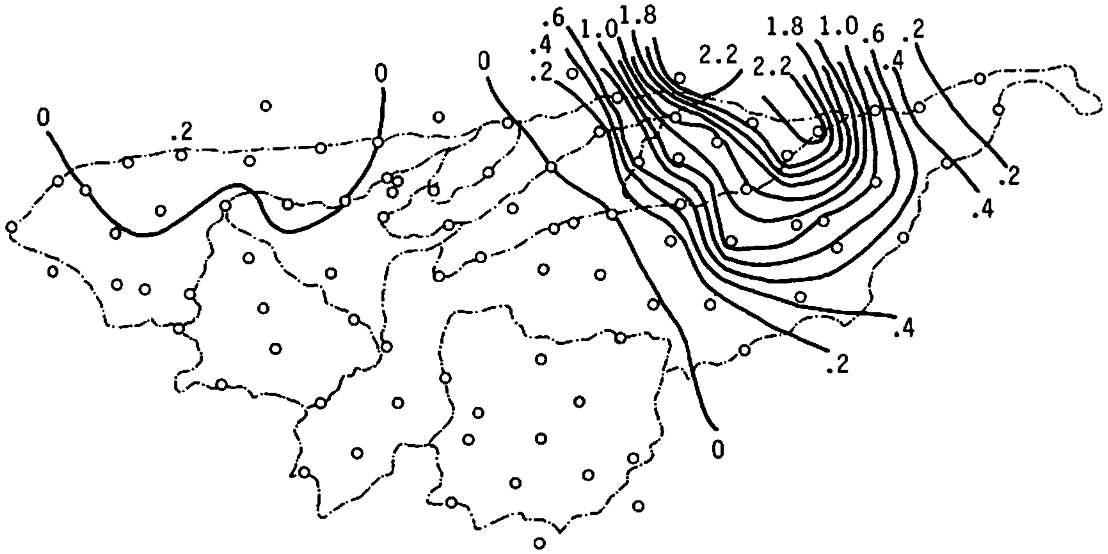

Figure 1. Isohyetal map of a storm on 30 Jul 1966 at Walnut Gulch watershed. (The small circles show the location of rain gauges.)

in Arizona and New Mexico has been developed (Osborn et al. 1980).

Infiltration and channel transmission loss studies

Stream channels in most arid and semi-arid areas are usually dry. Normally, channel flows occur only from intense rainfall events. During a runoff event, water infiltration into these normally dry alluvial streambeds is characteristically high, with dramatic effects on the resulting hydrograph. These losses of surface runoff as the flow moves through the channel are referred to as transmission losses; significant quantities of the infiltrating water may, however, eventually reach the regional groundwater. Much of the groundwater recharge in the semi-arid areas of the southwestern United States results from this infiltration into stream beds. The magnitude of this groundwater recharge is controlled by alluvial characteristics, geology beneath and adjacent to the channel, frequency of flow, and the type or quantity of vegetation along the channel which, if mesic, may use large quantities (for transpiration) of water when moisture is available.

Seven channel segments within the Walnut Gulch Watershed have been isolated so that the magnitude of transmission losses can be measured. These segments have widely different characteristics, and facilitate quantifying some of the factors controlling the magnitude of transmission losses. The actual magnitude of loss is determined by comparing hydrographs at upstream and downstream stations in a channel reach, for events where there is little or no runoff from intervening drainage points (a frequent occurrence with air-mass thunderstorms). Figure 2 illustrates these transmission losses for a 6.4-km reach of the Walnut Gulch for the storm of 30 Jul 1966. Results show that the magnitude of transmission losses for any flow event is variable and related to (1) flow duration, (2) channel length and width, (3) antecedent moisture conditions, (4) peak discharge, (5) flow sequences, (6) volumes and characteristics of the alluvium, and (7) amount of clay in suspension in the runoff. These studies led to the development of a design procedure for determining transmission losses (Lane 1982).

Hydrologic balance of a semi-arid rangeland watershed

The relative magnitudes of the various components of the hydrologic balance on Walnut Gulch watershed are shown in Figure 3. Over 80% of the annual precipitation leaves the watershed as evaporation and transpiration.

The various water losses from surface runoff have a marked effect on the response of a watershed to a

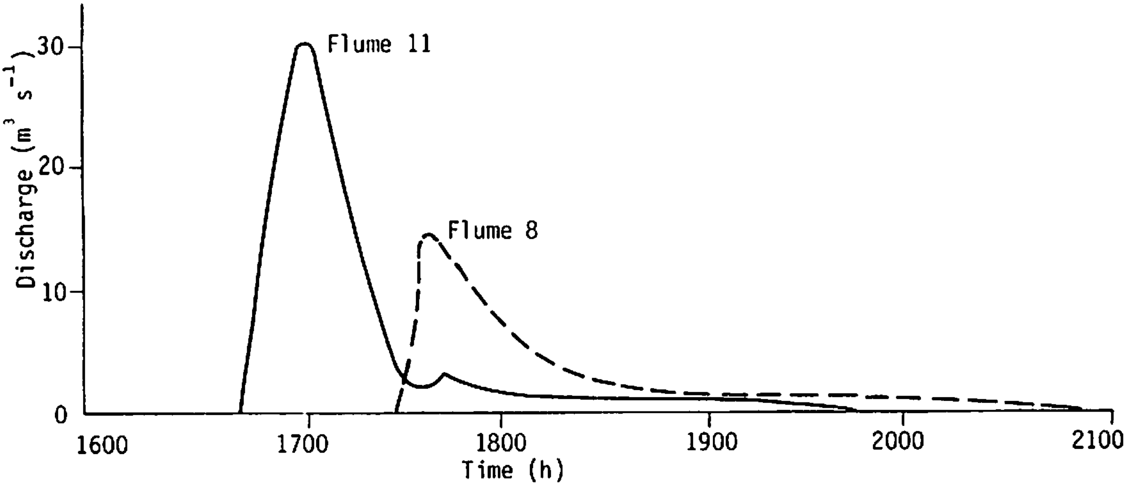

Figure 2. Hydrographs at two flumes for the storm on 30 July 1966, showing channel transmission losses. (Between flumes 11 and 8 there is a reach of 6.4 km.)

precipitation event. On semi-arid watersheds, annual water yield significantly decreases with increase in drainage area. In more humid areas, annual water yield per unit area may increase with drainage area (Fig. 4).

Runoff hydraulics and flood-water yield frequency studies

In arid and semi-arid environments, it is difficult to measure runoff and sample water quality because of high runoff velocities, large but infrequent flow occurrences, and rapid changes in flow depths (Renard 1982).

Stepwise multiple regression analysis of small plot data showed that the average runoff for any one location-year increased as the precipitation quantity increased; it decreased as the vegetative-crown spread increased, and increased as antecedent soil moisture increased (Schreiber and Kincaid 1967). Many models use precipitation data, which are usually more extensively available and of longer duration than runoff records, as the primary input

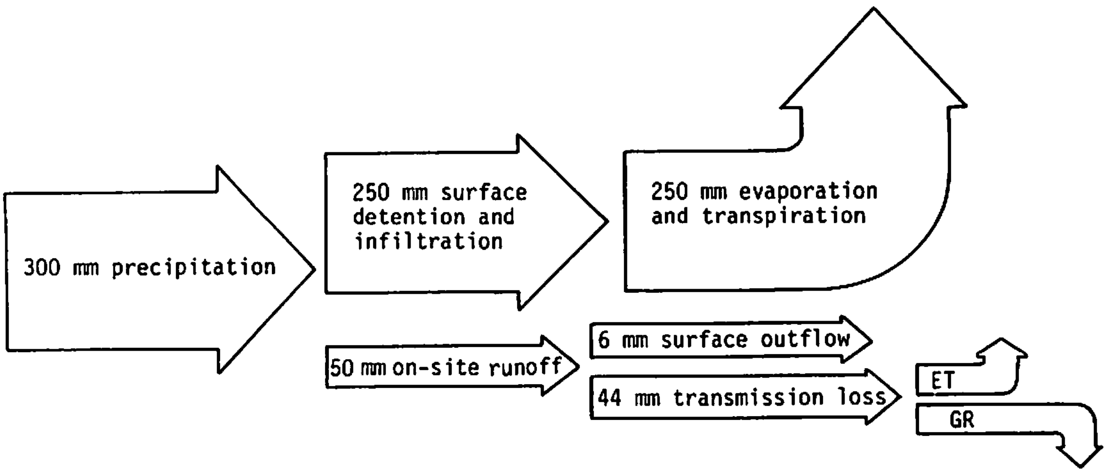

Figure 3. Hydrologic balance at Walnut Gulch. (ET = evaporation and transpiration; GR = groundwater recharge.)

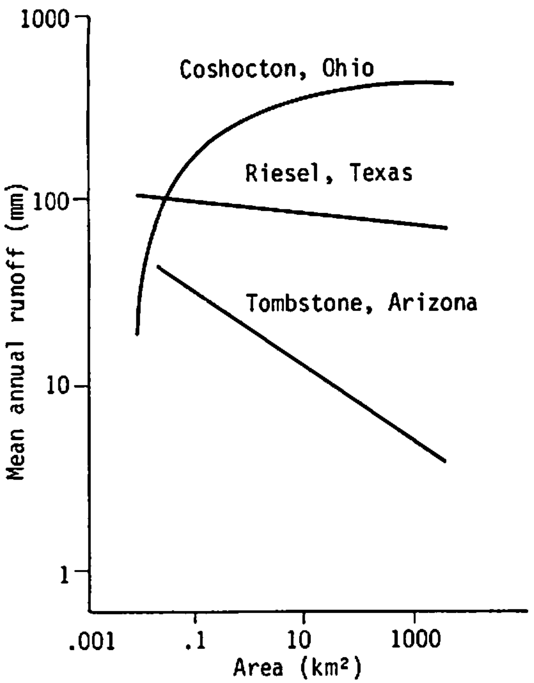

Figure 4. Mean annual runoff versus size of drainage area for several locations.

variable. These models can give only estimates, the accuracy of which depends upon the validity of the input data and the degree to which the model emulates the physical system.

Runoff modeling efforts at the Southwest Rangeland Watershed Research Center include the instantaneous unit hydrograph approach, a stochastic approach, and a physical-based kinematic cascade approach (involving planes-and-channels). A double triangle unit hydrograph approach has been demonstrated to be superior to the single triangle unit hydrograph (Diskin and Lane 1976). The stochastic model developed by Diskin and Lane (1972) has been found to be a good representation of the conditions encountered in thunderstorm-dominated runoff where each runoff event begins and ends with zero flow. This model was incorporated in a sediment-transport equation to estimate sediment yield as a function of watershed characteristics (Renard and Lane 1975).

Where the momentum equation can be approximated using only terms expressing bottom slope and friction slope, the flow is called kinematic. If the watershed geometry is represented by a series of planes and channels in cascade, and the overland flow and/or open channel flow are described by the kinematic-wave equations, the resulting mathematical model is called the "kinematic cascade model." Given rainfall, runoff, and topographic data for a small watershed, it is possible, during simulation, to define a kinematic cascade geometry that will preserve selected hydrograph characteristics (Lane and Woolhiser 1977).

These surface-water models have progressed from modeling subunits of a watershed to combining the subunits into more comprehensive models of entire watersheds. Such models have now been extended to include partial differential equations for sediment detachment and transport (Smith 1977). In the process, such models have become complex and relatively expensive to use (Renard 1977).

Erosion and sediment transport studies

Recent emphasis in the United States on water quality, as affected by soil loss/sediment yield, has created a need for nonpoint pollution data for conservation planning aimed at reducing soil erosion. In pursuit of this need, emphasis is placed on collecting data for a better understanding of the processes of sediment detachment, transport, and deposition. Suspended sediment samples are collected at runoff-measuring sites on two tributaries and the outlet to Walnut Gulch. Automatic sampling equipment is used on several small subwatersheds. Precise gully measurements are being made on selected small watersheds to determine direct and indirect gully contribution to watershed erosion and sediment transport. Data are used to calibrate a deterministic sediment-transport relationship. When used with a stochastic runoff model, the frequency distribution of sediment yield has been obtained (Renard and Laursen 1975, Renard and Lane 1975). The data are also used for estimating the parameters of the universal soil loss equation (USLE) (Wischmeier and Smith 1978).

Major research emphasis is currently on adapting and providing USLE parameter values for arid and semi-arid rangelands. A trailer-mounted rotating-boom rainfall simulator is being used to provide USLE parameter estimates for rangelands (Simanton and Renard 1982).

Surface and groundwater quality

Various studies are being conducted to develop improved procedures for evaluating the impact of land-use and watershed/river-basin management on runoff water quality. Runoff water quality samples, collected at selected small subwatersheds and at the watershed outlet, are used for determining the influence of soil type, land use, and vegetative cover on water quality (Schreiber and Renard 1978). Samples of precipitation are collected. Groundwater samples are collected from wells for assessing their variation in quality. These data are used as inputs for various models of nonpoint source pollution and erosion-productivity research. Some typical models are described below.

CREAMS (Chemical, Runoff, Erosion, and Agricultural Management Systems). This describes a mathematical model developed to evaluate non-point source pollution from field-sized areas. CREAMS consists of three components: hydrology, erosion/sedimentation, and chemistry. The general logic of the model is that the hydrologic processes provide the transport medium for sediment and agricultural chemicals. Thus the hydrology component is the major input to the other model components. The erosion/sediment yield component provides estimates of sediment yield and silt/clay/organic matter enrichment to be used in the chemical transport components where absorbed chemicals are involved (Knisel 1980).

SWAM (Small Watershed Model). SWAM is intended for use on watersheds composed of a number of field-sized areas. This model incorporates features that facilitate transition from field-sized areas to watersheds of larger size, where spatial rainfall variability as well as variations in topography, soils, crops, etc., affect the results. A major feature of the model is to route the outputs from CREAMS-derived elements to points downstream. This model, which is still being developed, will use a fully dynamic version of CREAMS.

EPIC (Erosion-Productivity Impact Calculator). This consists of physically-based components for simulating erosion, plant growth and related processes, and economic components for assessing the cost of erosion and determining optimal management strategies. Commonly-used EPIC input data (weather, crop, tillage, and soil parameters) are available from a computer-filing system assembled especially for applying EPIC throughout the USA. EPIC is generally applicable, computationally efficient (operates on a daily time step), and capable of computing the effects of management changes in outputs. The components of EPIC can be grouped into major categories that include hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics. The many potential uses of this model include its application in (a) national-level program planning and evaluation, (b) project-level planning and design, (c) field-level studies to aid technical assistance, and (d) as a research tool (Williams et al. 1983).

SPUR (Simulation of Production and Utilization of Rangelands). SPUR is a rangeland simulation model based on physical processes developed to aid resource managers and researchers. It can be applied to a wide range of conditions with a minimum of "tuning" or "fitting." As a management tool, it provides a basis for management decisions by predicting herbage yields, livestock production, runoff, and erosion. SPUR has five basic components: (1) climate, (2) hydrology, (3) plant, (4) animal (domestic and wildlife), and (5) economic (Wight 1983).

Vegetation manipulation and rangeland revegetation

Studies are being conducted to determine the influence of range renovation and grass seeding on runoff, erosion, cattle-grazing potential, and the hydrologic consequences of different range improvement practices. Typical results from two studies are presented in Table 1. Ripping reduced runoff for up to 5 years after treatment, but had little effect on reducing the density of the existing brush vegetation cover. Root-plowing and reseeding did not reduce runoff until 4 years after treatment, but was effective in converting the vegetation from brush to grass (Kincaid and Williams 1966, Simanton et al. 1978, and Tromble 1976).

Water harvesting and runoff farming

Water-harvesting techniques can be divided into five basic approaches: (1) vegetation management, (2) natural impervious surfaces, (3) land alternation, (4) chemical treatment of the soil, and (5) covering the ground with a membrane. The methods vary widely in terms of cost, performance, and durability (Frasier and Myers 1983). The major objectives of research on water harvesting are as follows.

1. To determine the feasibility of using water-harvesting methods for augmenting and conserv-

Table 1. Effects of two mechanical brush-control treatments on runoff and sediment yield from a semi-arid rangeland watershed.

Period	Average summer precipitation (mm)	Average summer runoff (mm)	Sediment yield (t ha^{-1} a^{-1})
Ripped			
Pretreatment (1955-64)	205	18	nm[1]
Posttreatment (1965-76)	185	4.7	nm
Posttreatment (1965-69)	191	0.5	nm
Posttreatment (1970-76)	180	7.8	nm
Root-plowed, reseeded			
Pretreatment (brush vegetation) (1966-70)	240	23	3.7
Transition (1971-73)	237	34	2.6
Posttreatment (grass vegetation) (1974-76)	174	3	0.3

1. nm = not measured.

ing water supplies to increase rangeland forage production.

2. To develop and evaluate catchment treatments and water-storage facilities for use on water-harvesting systems in remote areas.
3. To develop criteria relating to waterproofing efficiency and the durability of water-repellent treatments to soil and climatic parameters.

Water-harvesting systems for domestic supplies can employ many of the techniques used for harvesting water for livestock. These techniques are also adaptable to runoff-farming applications by increasing precipitation and concentrating runoff on adjacent strips of cropped land (Schreiber and Frasier 1978). At present, the cost of water-harvesting treatments developed for livestock is probably too high for many runoff-farming applications.

Information on the quality of water collected by water-harvesting systems is limited. With a few exceptions, precipitation is almost pure water; and contaminants contained are insufficient to harm animals and humans (Frasier 1983). Water-harvesting systems could be designed to furnish drinking water for both human beings and animals plus water for runoff-farming applications.

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