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AGRICULTURAL IMPACTS IN AN ARID ENVIRONMENT: WALNUT GULCH STUDIES

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ABSTRACT

Semiarid lands such as the USDA-ARS Walnut Gulch Experimental Watershed located in southeastern Arizona are characterized by extreme variability of precipitation, soils, vegetation, infiltration, runoff, and erosion. Research results are presented which describe and summarize this temporal and spatial variability and the impact of management decisions in altering the hydrologic and sedimentation cycles. Potential impacts of global change on the natural resources of such semiarid lands are also reported. Specific results include frequency relationships for runoff amounts. Analytical simulation models such as CREAMS, RUSLE, WEPP, and KINEROS, developed using Walnut Gulch data, are described and used to illustrate the impact of management on the hydrologic cycle in a semiarid environment. Finally, data and research findings from the Walnut Gulch watershed are being used to develop new technology for natural resource modeling and management. Specific examples for erosion control and water quality impacts are presented.

INTRODUCTION

More than one-third of the world's land surface is either arid (generally receiving less than 250 mm of precipitation annually), or semiarid (annual precipitation between 250 mm and 500 mm). More precise definitions of arid and semiarid areas include climatic classifications based on precipitation, temperature, and their seasonal fluctuations. Irrespective of the differences in classification, the importance of limited water resources in such climates is well recognized as a major impediment to economic development and resource utilization and protection in such areas.

Most arid areas on Earth are located approximately 30 degrees latitude north and 30 degrees south of the equator. In these subtropical belts, winds are generally descending and dry much of the time. Semiarid areas associated with arid deserts are generally north and/or south of the deserts (Africa, Asia, and Australia) or inland and at slightly higher elevations (North America, South America, Middle East, Africa, and Asia).

The Mojave, Sonoran, and Chihuahuan deserts dominate the arid and semiarid areas of the United States and Mexico. The Walnut Gulch Experimental Watershed, in southeastern Arizona, is located just north of the transition between the Chihuahuan and Sonoran deserts and will be used for subsequent illustration.

The Walnut Gulch Experimental Watershed (Figure 1) was selected as a research facility by the United States Department of Agriculture (USDA) in the mid-1950's. Prior appropriation water laws resulted in conflicts between upstream land owner conservation programs and downstream water users. Technology to quantify the influence of upland conservation on downstream water supply was not available. Thus, scientists and engineers in USDA selected Walnut Gulch for a demonstration/research area which could be used to monitor and develop technology to address the problem. In 1959, facilities needed for soil and water research in the USDA were identified in a United States Senate Document (U.S. Senate Committee 1959). The Southwest Watershed Research Center in Tucson, Arizona, USA, was created in 1961 to administer and conduct research on the Walnut Gulch watershed. Subsequent legislation (Clean Water Legislation of the 1970's) added water quality thrusts to the research program.

Research at the Southwest Watershed Research Center, and specifically on the Walnut Gulch Experimental Watershed, is part of the Agricultural Research Service (ARS) Program Plan: 6-Year Implementation Plan, 1992-1998 (USDA, 1992). The plan includes six research objectives with Walnut Gulch research contributing to two of them: Soil, Water, and Air; and Integration of Systems. The research contributes to four of the five soil, water, and air objectives and the single objective for systems integration. ARS has also identified seven high priority Special Programs and Walnut Gulch research also contributes to two of them, the Global Climate Change Research Program and the Water Quality Protection Program.

WALNUT GULCH WATERSHED

Description

The Walnut Gulch Experimental Watershed encompasses the 150 square kilometers in southeastern Arizona, U.S.A. (31° 43'N, 110° 41'W) (Figure 1) that surrounds the historical western town of Tombstone. The watershed is representative of approximately 60 million hectares of brush and grass covered rangeland found throughout the semiarid southwest and is a transition zone between the Chihuahuan and Sonoran Deserts. Elevation of the watershed ranges from 1250 m to 1585 m MSL. Cattle grazing is the primary land use with mining, limited urbanization, and recreation making up the remaining uses. Within the USDA-ARS national hydrologic database, Walnut Gulch is designated as Location 63. With this convention Watershed 1 at Walnut Gulch is designated as Watershed 63.001, and so on for the other subwatersheds. Two intensive study areas of particular interest are the Lucky Hills and Kendall unit source watershed areas. For convenience, the watersheds at Lucky Hills are often referred to as LH-101, LH-102, etc., and the watersheds at the Kendall area are K-1, K-2, etc. This designation will be used later in the description of research results.

Geology

The Walnut Gulch watershed is located primarily in a high foothill alluvial fan portion of the larger San Pedro River watershed. Cenozoic alluvium is very deep and is composed of coarse-grained fragmentary material, the origin of which is readily traceable to present-day mountain flanks on the watershed. The alluvium consists of clastic materials ranging from clays and silts to well-cemented boulder conglomerates with little continuity of bedding. This alluvial fill material is more than 400 m deep in places and serves as a huge ground water reservoir. Depth to ground water varies greatly in the watershed ranging from 50 m at the lower end to 145 m in the central parts of the watershed (Libby et al., 1970). Topographic expression of the alluvium is that of low undulating hills dissected by present stream channels whose routes are controlled by geologic structures. Upland slopes can be as great as 65% while slopes in the lower lying areas can be as small as 2 to 3%. Major channel slopes average about 1% with smaller tributary channels averaging 2 to 3%.

The remaining mountainous portion of the watershed consists of rock types ranging in age from pre-Cambrian to Quaternary, with rather complete geologic sections. Rock types range from ridge-forming limestone to weathered granite intrusions. The geologic structural picture of the mountainous area is complex, with much folding and faulting. This folding and faulting, along with igneous intrusions has resulted in large areas of shattered rock, which influence the watershed hydrology.

The watershed hydrology is, in places, controlled by past geologic events and structures. Intrusive igneous dikes in the Tombstone Hills influence ground water movement, as well as change the surface drainage. The Schieffelin granodiorite alters the course of the Walnut Gulch main stream, acts as a probable ground water barrier between the ground water in the Tombstone Hills and the deep alluvial basin, and has caused numerous small perched water tables along its perimeter. Highly compacted conglomerate beds greatly alter the path of stream channels and, in places, divert streams at more than right angles. High angle faults form new paths for streamflow, making channels arrow-straight in some places and causing diversions in others.

Soils

Soils on the Walnut Gulch Experimental Watershed reflect the geologic parent material from which they developed. The limestone influenced alluvial fill parent material is dominate on the watershed. The soils that developed from this material are generally well drained, calcareous, gravelly loams with large percentages of rock and gravel at the soil surface (Gelderman, 1970). Soil surface rock fragment cover (erosion pavement) can range from nearly 0% on shallow slopes to over 70% on the very steep slopes (Simanton et al. in press). The major soil series presently defined on this area are Bernardino (fine, mixed, thermic *Ustollic haplargid*), Cave (loamy, mixed, thermic, shallow *Typic paleorthid*), Hathaway (loamy-skeletal, mixed, thermic *Aridic calciustoll*), and Rillito (coarse-loamy, mixed, hyperthermic *Typic calciorthid*). The uppermost 10 cm of the soil profiles contain up to 60% gravel, and the underlying horizons usually contain less than 40% gravel. The remaining soils developed from igneous intrusive materials and are generally cobbly, fine textured, shallow soils.

Vegetation

Although historical records indicate that most of the watershed was grassland approximately 95 years ago; now shrubs dominate the lower two-thirds of the watershed (Hastings and Turner, 1965). Major watershed vegetation includes the shrub species of creosote bush (*Larrea tridentata*), white-thorn (*Acacia constricta*), tarbush (*Flourensia cernua*), snakeweed (*Gutierrezia sarothrae*), and burroweed (*Aplopappus tenuisectus*); and grass species of black grama (*Bouteloua eriopoda*), blue grama (*B. gracilis*), sideoats grama (*B. curtipendula*), bush muhly (*Muhlenbergia porteri*), and Lehmann lovegrass (*Eragrostis lehmanniana*). Shrub canopy cover ranges from 30 to 40% and grass canopy cover ranges from 10 to 80%. Average annual herbaceous forage production is approximately 1200 kg/ha.

Instrumentation

The initial rainfall and runoff instrumentation on Walnut Gulch was installed in 1954-55. The initial network of 20 precipitation recording gages was expanded in the early 1960's to the 85 gage network currently in place on the watershed (Osborn and Reynolds, 1963). Five supercritical precalibrated flumes were constructed prior to 1955 to measure runoff from the heavily sediment laden ephemeral streams of Walnut Gulch. All five flumes failed or were badly damaged within two years. They failed for hydrologic, hydraulic, and structural reasons. Following extensive hydraulic model research at the Agricultural Research Service (ARS) Outdoor Hydraulic Structures Laboratory in Stillwater, Oklahoma, the original five flumes were rebuilt using a design known as the Walnut Gulch Supercritical flume (Gwinn, 1970; Smith et al., 1982). Six additional flumes were added later.

Runoff from small (< 40 ha) watersheds is measured using various gauging structures. These structures include broad-crested V-notch weirs, H-flumes, and supercritical flow flumes. Currently 10 small watersheds are monitored. Runoff from watersheds larger than 200 ha is measured with large supercritical flow flumes (Smith et al., 1982). The largest flume, at the outlet of the Walnut Gulch watershed has a flow capacity of 650 m^3s^{-1}. Sediment from small watersheds monitored with V-notch weirs is sampled with automatic pump samplers (Allen et al., 1976) and sediment traps above the weirs (Osborn et al., 1978). Sediment from small watersheds equipped with supercritical flow flumes is sampled with a total-load automatic traversing slot sampler (Renard et al., 1986). Soil moisture within various vegetation/soil complexes throughout the watershed is measured using time domain reflectometry (Zegelin et al., 1989). Permanent vegetation plots and transects have been established to evaluate the impacts of management practices and global change on vegetation.

HYDROLOGY

Climate

The climate of Tombstone, Arizona and the surrounding Walnut Gulch Experimental Watershed is classified using the modified Koppen's method (Trewartha, 1954) and data collected at Tombstone from 1941 - 1970 (Sellers and Hill, 1974). Mean annual temperature at Tombstone is 17.6°C and mean annual precipitation is 324 mm. The climate is classified as arid or desert (BW) if mean annual temperature is less than 18°C and mean annual rainfall is less than 318 mm, and semiarid or steppe (BS) if mean annual rainfall is greater than 318 mm. With a mean annual precipitation of 324 mm, the climate at Tombstone is semiarid or steppe, BS, but close to an arid or desert climate, BW. The BS climates are further distinguished as hot (h) or cold (k). Using the original Koppen's classification, Tombstone is classified as BSk because the mean annual temperature is less than 18°C. Using the modified Koppen's scheme the climate at Tombstone is classified as BSh. Therefore, the climate at Tombstone can be classified as semiarid or steppe, hot, with a dry winter (BSh) but is quite close to being an arid or desert climate and is near the temperature boundary for hot (h) or cold (k).

Precipitation

Precipitation varies considerably from season to season and from year to year on the Walnut Gulch Experimental Watershed. Osborn (1983) reported, based on records from 1956-80, that annual precipitation varied from 170 mm in 1956 to 378 mm in 1977 (Figure 2); summer rainfall varied from 104 mm in 1960 to 290 mm in 1966; and winter precipitation varied from 25 mm in 1966-67 to 233 mm in 1978-79. Approximately two--thirds of the annual precipitation on the Walnut Gulch Watershed occurs as high intensity, convective thunderstorms of limited areal extent. The moisture source for these thunderstorms is primarily the Gulf of Mexico, although Pacific Ocean storms from southwest of Arizona also produce moisture surges that result in convective storms. Winter rains (and occasional snow) are generally low-intensity events associated with slow-moving cold fronts, and are generally of greater areal extent than summer rains. Convective storms can occur during the winter as well. Runoff on the Walnut Gulch Watershed results almost exclusively from convective storms during the summer season.

Precipitation Variability and Implications for Range Management

Summing individual storm events to generate monthly and seasonal values for precipitation illustrates some water supply and forage management problems. The ensemble of individual storm events such as that in Figure 3 for August 27, 1982 resulted in the August isohyetal map shown in Figure 4. The ratio of maximum point precipitation of 90 mm to the minimum of 45 mm (a ratio of 2:1) has been measured with considerable regularity. But more importantly, although these extremes were only 4 km apart, they occurred in the same pasture of one ranch. The maximum rainfall value produced good forage whereas the minimum rainfall produced less than normal forage. Figure 4 illustrates the precipitation variability during the summer season when most forage production occurs in the Walnut Gulch watershed. Again, the variability is appreciable with the amounts of 240 mm and 170 mm being less than 5 km distant.

Transmission Losses

In semiarid areas such as the Walnut Gulch watershed, ranching, wildlife, increasing populations, urbanization, expanding industry, and needs of downstream water users all compete for limited water resources. The increased demand for water resources creates pressure to develop new sources of water and requires better methods of quantifying the water budget; assessing streamflow; and assessing the interaction between streamflow, flooding, infiltration losses in channel beds and banks, evapotranspiration, soil moisture, and ground water recharge.

An important component of the Walnut Gulch water budget is streamflow abstraction from infiltration in the channel beds and banks. These depletions or abstractions are called transmission losses. An example of transmission losses is presented in Figures 3 and 5. The August 27, 1982 storm, illustrated in Figure 3, was isolated in subwatershed 6 on the upper 95 km^2 of the Walnut Gulch watershed (and not all of that produced runoff). The runoff measured at Flume 6 (Figure 5) amounted to 2.46×10^5 m^3 with a peak discharge of 108 m^3s^{-1}. Runoff traversing 4.2 km of dry streambed between Flume 6 and Flume 2 resulted in significant infiltration losses (Keppel and Renard, 1962; Renard, 1970; Lane, 1983). For example, in the 4.2 km reach the peak discharge was reduced to 72 m^3s^{-1} and 48,870 m^3 of water were absorbed in the channel alluvium. During the course of the 6.66 km from Flume 2 to Flume 1, the peak discharge was further reduced, and 41,930 m^3 of runoff was infiltrated in the channel alluvium.

Transmission losses are important because water infiltrates when flood waves move through the normally dry stream channels, reducing runoff volumes and flood peaks (Babcock and Cushing, 1941; Renard, 1970), and affecting components of the hydrologic cycle, such as soil moisture and ground water recharge. Procedures have been developed to estimate transmission losses for flow events in ephemeral stream channels (Lane, 1982; Lane, 1983; Lane, 1985, Lane, 1990). The differential equation describing transmission losses in a channel reach is based on the assumption that the volume of losses in a reach is proportional to the upstream inflow volume, a constant or steady-state loss rate, and the lateral inflow rate per unit channel length.

Data from 10 gaged channel reaches in Arizona, Kansas, Nebraska, and Texas representing 127 individual event hydrographs were used to calibrate transmission loss prediction equations (Lane, 1983). The effective saturated conductivity of the channel bed, K, represents the steady-state conductivity of the channel bed material under natural conditions of entrapped air and sediment in the flow. It thus can be as much as an order of magnitude less than conductivity estimates made with infiltrometers and clear water. Effective conductivity values were derived by considering total losses from an event divided by the length and width of the channel reach and by the flow duration at the upstream end of the reach. These event estimates were averaged over all flow events for a channel segment to derive an estimate of the mean effective hydraulic conductivity. Values of K for different bed material classes were tabulated by Lane (1982).

The transmission loss estimation procedure (Lane, 1983) accounts for empirically observed dependence of infiltration losses on inflow rate to a channel reach and reproduce reductions in flood peaks and volumes similar to those measured in ephemeral stream channel networks. Estimated flood peaks from observed Walnut Gulch watershed data and from applying a distributed watershed model incorporating the transmission loss estimation procedure are shown in Table 1.

TABLE 1. Comparison of flood peaks derived from observed data and simulation results using a distributed watershed model with the transmission loss procedure adapted from Lane (1990).

Watershed on Walnut Gulch	Record Length (yr)	Area (km^2)	Estimated flood peaks in $m^3s^{-1}km^{-1}$			
			Observed		Simulated	
			2 yr	100 yr	2 yr	100 yr
63.103	17	.0368	6.76	32.3	6.65	41.3
63.104	17	.0453	7.74	56.2	6.87	40.8
63.111	20	.578	6.54	34.8	4.03	24.3
63.011	13	8.24	2.29	27.5	2.51	31.5
63.008	13	15.5	1.31	11.4	1.53	9.2

[1]Log-normal probability distribution used to estimate flood frequencies.

Data in Table 1 provide a partial explanation of observations of decreasing flood peaks with increasing drainage area on the Walnut Gulch watershed (Keppel and Renard, 1962). Simulation model calculations with and without transmission losses suggest the following. For the 2 yr flood on the 0.0368 km^2 watershed 63.103, transmission losses in a single 200 m long channel reach reduced the peak discharge by about 2%. In contrast, the corresponding reduction for the 15.5 km^2 watershed 63.008, with an extensive channel system, was estimated as about 30% in the peak discharge. On watershed 63.008 approximately one-third of the runoff volume from the 2-yr flood becomes transmission losses and thus potential ground water recharge. Finally, the importance of recharge through the Walnut Gulch ephemeral stream channels has been confirmed by ground water mounding (increases in water levels in wells in and adjacent to the main channels) after flood events (Wallace and Renard, 1967).

Water Balance

The Walnut Gulch watershed water balance, although variable from year to year as well as across the area, is obviously controlled by precipitation. Figure 6 illustrates the water balance for average conditions. Given the average 305 mm input precipitation, approximately 254 mm is detained on the surface for subsequent infiltration. Essentially all of the infiltrated moisture is either evaporated or transpired by vegetation back to the atmosphere. Based on data collected from small runoff plots, approximately 51 mm of the incoming precipitation is in excess of that which is intercepted and/or infiltrates. We refer to this as "onsite runoff." As the runoff moves over the land surface and into dry alluvial channels, transmission losses begin. Approximately 45 mm of transmission losses occur and approximately 6 mm of surface runoff are measured at the watershed outlet. The 45 mm of transmission losses result in some ground water recharge and some evaporation and transpiration from vegetation along the stream channels. Figure 6 does not show quantities for ground water recharge and evaporation and transpiration of channel losses, because their quantification is difficult and very site specific. The geology along and beneath the stream channel creates some reaches that are underlain by impervious material, whereas in other locations, the channel extends to regional ground water and permits appreciable recharge. Where the channel is underlain by impermeable material, riparian aquifers connected to the channel support phreatophytes and saturated alluvium following major runoff. Potential evaporation (Class A USWB pan) is approximately 267 cm per year which is approximately 8.7 times the annual precipitation.

RESEARCH PROJECTS

Rainfall Simulation Studies

Rainfall simulation is a valuable tool for evaluating the hydrologic and erosional responses of natural environments (Renard, 1986). Rainfall simulators (infiltrometers), give researchers maximum control over where, when, and how data are collected and results can be easily compared among ecosystems because similar rainfall sequence, intensity, and amount can be applied and antecedent conditions controlled. Early rainfall simulation studies on the Walnut Gulch Experimental Watershed included various types of simulators and a wide range of plot sizes (Kincaid et al., 1964; Tromble et al., 1974; Lane and Shirley, 1982). Current rangeland rainfall simulation studies were begun at Walnut Gulch in 1981 to develop rangeland soil loss factors for erosion prediction models. These studies were conducted using a rotating boom rainfall simulator (Swanson 1965) on 10.7 by 3.05 m plots.

The general procedure included spring and fall rainfall application on at least two replications of three treatments on one or more soil types in each ecosystem studied (Simanton et al., 1986). Treatments were natural cover or no treatment (both grass and shrub), vegetation clipped, and all vegetation and surface cover removed (bare). The clipped treatment, not intended to represent grazing effects, was used to determine vegetation effects on erosion and the bare plot was to define the role of rock fragments (erosion pavement) on soil erosion.

Results from the treatment comparisons of erosion rates separated the effects of various surface and canopy characteristics. A negative exponential relationship was found between erosion pavement (surface rock fragments > 5 mm) and erosion rates (Simanton et al., 1984). The bare soil treatment produced the largest erosion rates which increased with time for about two years before reaching an "equilibrium" with the energy input (Simanton and Renard, 1986). The erosion rate increase for the bare soil treatment closely emulated runoff changes attributed to decreases in soil root and residue material causing reduced soil macropore structure (Dixon and Simanton, 1979).

Emerging and current technology coupled with faster, larger, and more readily available personal computers have focused the need for a process based technology to predict rangeland erosion and sedimentation rates (Lane et al., 1988). The Water Erosion Prediction Project (WEPP), initiated in 1985 to meet this goal, was designed to collect field data from both crop and rangeland soil and vegetation complexes throughout the United States. The WEPP rangeland rainfall simulation field procedures were modifications of the Walnut Gulch procedures (Simanton et al., 1991). Modifications included instantaneous changes in rainfall intensities, additions of overland flow, both large (10.7 by 3.0 m) and small (1.2 by 0.6 m) plots, and above- and below-ground-biomass sampling. These modifications gave soil infiltration and erosion data needed to parameterize model infiltration process and define interrill and rill soil erodibilities. Two of the 20 WEPP rangeland sites were located on the Walnut Gulch Experimental Watershed and were chosen to represent semiarid brush and grass rangeland. Preliminary results from these WEPP field studies include the determination of rangeland rill and interrill soil erodibility value and the development of a crust factor for a Green Ampt infiltration model.

Significant Findings

Ten years of rainfall simulation studies on rangeland erosion plots have produced a large database used to parameterize soil erosion prediction models. These studies, conducted on many rangeland ecosystems, represent a unique database that will be very difficult to duplicate. Rangeland erosion studies are a relatively new research area and our results have only begun to answer basic questions regarding erosion estimating techniques on rangelands. The importance of erosion pavement on the rangeland erosion has been demonstrated and appears to have a more dominant role in this process than vegetation canopy. New algorithms have been developed to reflect rangeland response to the rainfall (R), topography (LS), cover-management (C), and support practice (P) factors of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991). Additional studies, research approaches, and analyses are needed to fully understand rangeland erosion processes.

Natural Resource Simulation Modeling

(1) CREAMS - Chemical, Runoff, and Erosion from Agricultural Management Systems

(a) Introduction

The Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model is a continuous simulation, daily time step, model based on soil moisture storage, modified Soil Conservation Service (SCS) runoff curve number as a function of soil moisture, a leaf area-based evapotranspiration model, storage-based soil water redistribution and seepage model, and a runoff volume-peak discharge equation based on watershed characteristics. Complete model descriptions and parameter estimation techniques for water balance calculations are given by Knisel (1980), SCS (1984), and Lane (1984). The CREAMS hydrologic model (Knisel, 1980) was used to illustrate water balance and flood prediction on small upland Walnut Gulch experimental watersheds.

(b) Example Application

The Lucky Hills intensive study area consists of six small (0.18 to 4.5 ha) watersheds and associated instrumentation for ancillary erosion plot studies and related hydrologic-vegetation studies. Watershed Lucky Hills 103 (also called LH-103 and 63.103) is a 3.7 ha watershed consisting of an upland area (Watershed LH-101, 1.29 ha) and two lateral areas contributing to a main channel reach approximately 150 m long (Osborn and Simaton, 1989). Soils, vegetation, and climate are typical of the brush dominated areas of the Walnut Gulch watershed described earlier. Daily precipitation data from 1965 through 1981 were used with CREAMS to calculate a water balance and flood peaks from LH-103. Parameters were estimated using standard handbook procedures (Lane, 1984) and the baseline, or condition II, runoff curve number was adjusted to match observed mean annual runoff during the 17 year period. No other calibration was done.

Calculated water balance components for LH-103 are shown in Table 2. The 17 year average annual precipitation was 302.9 mm and the measured average annual runoff volume was 19.8 mm with a standard deviation of 16.5 mm. Calculated mean annual runoff (after calibration) was 19.7 mm with a standard deviation of 13.5 mm. Monthly values of calculated runoff are shown in Table 2 and are compared with measured data in Figure 7. At LH-103, runoff has been measured in every month except February and April and the CREAMS model simulated runoff in every month except April. The CREAMS model tended to over predict runoff from October through June and under predict from July through September (Figure 7). The relation between observed mean monthly runoff, Qo, and the CREAMS model estimates, Qe, was Qe = 0.35 + 0.78 Qo with R^2 = 0.93. Estimated annual runoff and maximum annual peak discharge from LH-103 are shown in Table 3. A log-normal probability distribution was used to estimate annual runoff volumes and maximum annual peak discharges.

The relation between estimates of annual runoff volume from the observed data, Qo, and from the CREAMS data, Qe, was Qe = 1.74 + 0.95 Qo with R^2 = 0.95 indicating a very close agreement. The corresponding relation for maximum annual peak discharge was QPe = -2.82 + 0.72 QPo with R^2 = 0.99 indicating a very high correlation, but a bias. The coefficient of 0.72 indicates that the CREAMS model under estimated annual flood peaks by approximately one-third (Table 3). For the upland Watershed LH-101, the corresponding relation between observed and computed maximum annual peak discharges was QPe = -11.4 + 0.92 QPo with R^2 = 0.99 indicating approximately a 37% underprediction for the 2-yr flood and approximately a 14% under prediction for the 100-yr flood. These findings are consistent with earlier applications of the CREAMS model at Walnut Gulch wherein Devaurs et al. (1988) found approximately a 20 - 30% underprediction of maximum annual peak discharges on Watersheds LH-101 and LH-103.

Therefore, data in Tables 2 and 3 suggest that the CREAMS model can be calibrated to produce reasonable estimates of monthly and annual runoff volumes. However, before conclusions on peak discharge predictions can be made, additional tests under semiarid conditions are needed to test the runoff volume-peak discharge algorithm used in the CREAMS model. Finally, notice that the CREAMS model computed an average annual value of 0.2 mm percolation below the root zone. This suggests that there is a potential for ground water recharge in the upland areas of the Walnut Gulch watershed.

(2) RUSLE - Revised Universal Soil Loss Equation

(a) Introduction

Erosion control has been one of the most widely used technologies for conservation in the United States. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) has been the technology used by USDA for these conservation planning efforts. Because of problems with the technology, and because of research conducted after the 1978 handbook release, plans

TABLE 2. Monthly and average annual water balance for watershed LH-103 calculated from the calibrated CREAMS Model using data from 1965 to 1981.

	Annual Averages				
Month	Precipitation mm	Runoff mm	ET mm	Percolation mm	Average Soil Water mm
January	18.0	.58	18.6	.03	22.2
February	14.2	.28	18.0	.17	20.7
March	15.0	.18	21.2	.00	16.1
April	3.8	.00	11.8	.00	6.6
May	5.3	.13	7.4	.00	2.0
June	8.3	.28	8.4	.00	1.3
July	87.9	7.24	62.2	.00	9.8
August	63.3	4.78	63.7	.00	14.9
September	39.1	3.45	34.8	.00	15.7
October	21.0	1.70	16.5	.00	16.0
November	7.7	.05	9.7	.00	16.0
December	19.3	1.02	12.1	.00	18.8
Total	302.9	19.69	284.4	0.20	13.3

were made to revise the technology in 1985 which resulted in the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991).

(b) Model Description

RUSLE retains the six factors of the USLE (A=R K LS C P), where R is the product of storm kinetic energy and maximum 30-min intensity, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover-management factor, and P is

TABLE 3. Frequency analyses of observed and predicted annual runoff volumes and maximum annual peak discharges from Watershed LH-103, 1965 to 1981.

Return Period (yr)	Probability	Observed Data Volume (mm)	Observed Data Peak (mm/h^{-1})	CREAMS Model Volume (mm)	CREAMS Model Peak (mm/h^{-1})
1.25	0.80	6.2	13.9	6.7	5.1
2.0	0.50	13.8	24.4	14.6	14.9
5.0	0.80	21.1	42.9	31.6	27.5
10.0	0.90	47.6	57.6	47.5	37.9
25.0	0.96	74.8	78.9	73.2	53.4
50.0	0.98	99.9	96.5	96.5	66.5
100.0	0.99	131.0	116.0	125.0	81.6

the support practice factor. The R-factor represents the weather input that drives the sheet and rill erosion process. Thus, differences in R-values represent differences in erosivity from climate. One of the most significant improvements in RUSLE is an expanded isoerodent map in the Western United States. Data from more than 1,000 locations were used in preparing this new map. The K-factor is a measure of the inherent erodibility of a given soil with the standard condition of a unit plot (22.1 m by 3.66 m) maintained in continuous fallow. Experimental data suggest that K-factor values vary with season, and are highest in the spring following soil-fluffing freeze-thaw actions and lowest in fall and winter following rainfall soil compaction or when the soil is frozen. Seasonal variability is addressed using relationships relating the short-term erodibility to the annual R-factor and the frost-free period. The short-term estimate of K is weighted in proportion to percent of annual R for bimonthly intervals.

RUSLE uses three separate L-factors for length and S-factors for slope. They include a function of slope steepness, and a function of susceptibility to rill relative to interrill erosion. A slope profile previously represented as a single plane or uniform slope can be a poor topographical representation. Complex slopes can be described readily in RUSLE to provide an improved topographic representation.

The cover-management factor, C, is perhaps the most important RUSLE factor because it represents conditions that can be managed to reduce erosion. Values for C are a weighted average of soil loss ratios (SLRs) that represent the soil loss for a given condition at a given time to that of the unit plot. Thus, SLRs vary during the year as soil and cover conditions change. To compute C, SLRs are weighted according to the erosivity distribution. The C subfactor relation is given by $C = PLU \cdot CC \cdot SC \cdot SR \cdot SM$, where PLU is the prior land-use subfactor, CC is the canopy subfactor, SC is the surface cover subfactor, SR is the surface roughness subfactor, and SM is a soil moisture subfactor used in the Pacific Northwest, USA, small-grain-farming areas.

One reason for the subfactor approach in RUSLE is for applications where SLR values are not available. For example, no experimental erosion data exist for many vegetable and fruit crops. Developing SLR values using the subfactor method is easier with RUSLE and more accurate than making comparisons with values in the 1978 handbook.

P-factor values, the least reliable of the RUSLE factors, represent how surface conditions affect flow paths, flow hydraulics, and thus, erosion. For example, with contouring, tillage marks are credited with directing runoff around the slope at reduced grades. However, slight changes in grade can change runoff erosivity greatly. Small changes in features such as row grade, and their effect on erosion are difficult to document in experimental field studies, leading to appreciable scatter in measured data. Thus, P-factor values represent general effects of such practices as contouring and stripcropping.

Soil loss and sediment yield data from Simanton et al. (1980), Renard and Stone (1982), and Simanton et al. (1986) were used with RUSLE simulations as a test of the technology. RUSLE was developed for application on hillslopes and because it is not intended to reflect deposition and channel/gully erosion, Figure 8 was developed to illustrate the difference between RUSLE predicted erosion and measured sediment yield as a function of drainage area. As the drainage area increases, the RUSLE predicted soil loss is less representative of actual conditions because stream energy and gully erosion becomes more important. The illustration was prepared for brush dominated conditions although the largest watershed also had a considerable grass cover. This increase in the difference between measured minus predicted sediment yield and watershed size differs from the concept normally used with sediment delivery ratios (Branson et al., 1981). Sediment delivery ratio's assume increasing deposition with increasing watershed area. Thus the trend of increasing ratios presented in Figure 8 (beyond the scale of this figure) would be expected to decrease with increasing watershed area in a semiarid climate because of spatial precipitation variability and runoff reductions due to transmission losses. Transmission losses reduce the transport potential for sediment movement.

(3) WEPP - Water Erosion Prediction Project (Watershed Model)

(a) Introduction

The USDA Water Erosion Prediction Project (WEPP) watershed version is an extension of the WEPP profile version computer model (Lane and Nearing, 1989). Both models provide erosion prediction technology based on fundamentals of hydrology, soil physics, infiltration theory, plant science, hydraulics, and erosion mechanics. The models have the ability to 1) estimate spatial and temporal distributions of soil loss and sediment yield at any point on a hillslope or within a watershed and 2) account for management affects and land use on the erosion process. The basic concepts guiding the WEPP watershed model development are that watershed sediment yield is the result of detachment, entrainment, transport, and deposition of sediment on overland (rill and interrill) flow areas and channel flow areas. The suspended sediment movement on rill, interrill, and channel flow areas is based on a steady state solution to the sediment continuity equation (Foster and Meyer, 1972). The erosion and deposition calculations are physically based in that the basic equations are derived from the equations of motion and momentum. Empirical relationships and physical process approximations are used to reflect those processes which influence erosion and deposition but are too complex or varied, either spatially or temporally, to be represented by a simple differential equation. Thus, subprocesses that significantly influence erosion and deposition (rainfall, runoff, plant growth, management operations) are represented at a complexity level commensurate with the erosion and deposition calculations. The model simulates the erosion process on two types of landform; hillslopes and channels. Hillslopes are defined as areas on which broad sheet and rill flow occur. Channels are defined as ephemeral gullies, established channels, or concentrated flow areas where backwater occurs.

(b) Management effects on controlling parameters

The controlling parameters affected by management on croplands are those that define infiltration characteristics (saturated conductivity, capillary potential), surface roughness (depression storage and friction factor), and soil erodibility (interrill and rill erodibility and critical shear stress). Rangelands differ from croplands in that soil surface characteristics of rangelands have evolved over time and are generally in quasi-equilibrium with the climate and vegetation regime. The primary management practices affecting erosion and runoff on rangelands are grazing intensity and vegetation manipulation by mechanical means (chaining, root plowing, herbicides) or burning (natural or prescribed). These management practices affect canopy cover, soil surface cover, and bulk density. In the current version of the model (Version 92.2), the management practices simulated are grazing and burning, which are assumed to affect only the infiltration and roughness parameters.

(c) Example

The use of WEPP as a management tool is illustrated using data from Lucky Hills 103 (described above) and two common rangeland management scenarios; cattle grazing with no management and cattle grazing after a brush to grass conversion. Table 4 lists the characteristics of the management practices. The two brush scenarios consist of no herbicide application or grass reseeding and no or moderate grazing of cattle. The three grass scenarios consist of an initial herbicide treatment to remove the brush, reseeding with grass, and three grazing intensities. The heavy grazing management practice necessitates reapplication of the herbicide and reseeding every five years due to heavy grazing impacts.

The climate (precipitation, temperature, and solar radiation) used for the simulation of each

TABLE 4. Five management practice summaries for Lucky Hills 103, Walnut Gulch Experimental Watershed.

Vegetation	Management practice	AMU[1] ha/cow	Utilization[2] (%)	Herbicide	Seeding
Brush	No grazing	0	0	none	none
	Moderate grazing	18	18	none	none
Grass	No grazing	0	0	once	once
	Moderate grazing	12	20	once	once
	Heavy grazing	2	85	every four years	every four years

[1] - animal management units
[2] - percent of area grazed

management practice was a 15 year sequence generated by the CLIGEN model (Nicks and Lane, 1989). Initialization of infiltration parameters was taken from van der Zweep et al. (1991) and hillslope erodibility parameters from Laflen et al. (1991). Channel erodibility parameters were calibrated by adjusting them until the simulated average annual sediment yield matched the observed sediment yield for the present brush conditions.

The simulation results show management scenario trends to be expected; namely that increasing grazing intensity increases the water yield, sediment yields, and the magnitude of the 2-year frequency peak discharge, while conversion from brush to grass has the opposite effect (Table 5).

Increases in both vegetation density and residue amount on the soil surface as a result of converting from brush to grass or as a result of lower grazing intensity increases infiltration (or decreases runoff) and protects soil particles from detachment by raindrop impact. The most significant impact of the management scenarios is on hillslope sediment yield. For example, converting from brush to grass with no grazing results in a hillslope sediment yield decrease of 91%. This decrease, however, does not translate into a similar decrease in watershed sediment yield. Although the wash load entering the channel decreases significantly, runoff amounts and

TABLE 5. Average annual output for watershed runoff volume, two year return period watershed peak discharge, and hillslope and watershed sediment yield for five management practices for Lucky Hills 103, Walnut Gulch Experimental Watershed.

Vegetation	Management alternative	Watershed Runoff volume (mm)	Watershed Peak Discharge (mm/hr^{-1})	Sediment Yield ($t\ ha^{-1}$)	
				Hillslope	Watershed
Brush	No grazing	20	27	0.92	2.27
	Moderate grazing	27	33	1.54	2.84
Grass	No grazing	15	24	0.08	1.70
	Moderate grazing	17	26	0.10	1.74
	Heavy grazing	18	38	0.16	2.13

discharge rates do not, and thus channel sediment transport capacity also does not decrease significantly. The resulting watershed sediment yield decreases only 25%. The major implication is that measuring the off-site response (in this case watershed sediment yield) may not provide an accurate evaluation of an on-site management practice. This example illustrated the use of a natural resource simulation model in evaluating alternative management practices based solely on the physical responses (runoff amount, sediment yield). However, a major concern to the rancher will be the economics of recommended management practices. A methodology for including economics within a decision making framework that considers conflicting management objectives is presented in the Decision Support System section.

(4) KINEROS

(a) Introduction and Model Description

KINEROS (Woolhiser et al., 1990b) is an event-oriented, physically-based, distributed rainfall-runoff and erosion model developed by current and former staff members of the Southwest Watershed Research Center and associated graduate students. It simulates the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. Steady and unsteady state flow dynamics of overland and channel flow are modeled using the kinematic wave approximation of the full dynamic wave equations (Wooding, 1965; Woolhiser and Liggett, 1967). The partial differential equations describing flow and erosion and sediment transport are solved by finite difference techniques. Within this model watershed geometry is represented as a cascade of planes and channels and the Smith-Parlange infiltration model (Smith and Parlange, 1978) is used in an interactive manner at each computational node to determine surface runoff rates. The model can accommodate spatial variability of rainfall input as well as infiltration, runoff, and erosion parameters. KINEROS may be used to determine the impacts on flood hydrographs and sediment yield of various artificial features such as urban developments, small detention reservoirs, or lined channels and various surface management practices. A detailed description of this model is contained in Woolhiser et al. (1990b).

(b) Example Application

Model application and performance for runoff estimation was demonstrated on the Lucky Hills-106 (LH-106) subwatershed of the Walnut Gulch Experimental Watershed. This watershed is located in a brush dominated region of Walnut Gulch and has an area of 0.36 ha with records available from 1965.

A period of record with homogenous runoff conditions (1973-80) was selected to obtain 10 calibration and 30 verification rainfall-runoff events with runoff volumes greater than 0.254 mm. Sensitivity analysis was then carried out over a range of event sizes (based on observed runoff volume) to identify model calibration parameters. Parameter parsimony was obtained by using multipliers which linearly scale distributed field estimated parameters. This method assumes that the relative values of initial parameter estimates are correct. The sensitivity analysis justified the selection of two overall watershed parameter multipliers. The two multipliers were selected to scale the distributed model parameters Ks (saturated hydraulic conductivity), and n (Manning's roughness). Optimization techniques were used to provide the best fit to the 10 calibration events. The Nash-Sutcliffe (Nash and Sutcliffe, 1970) efficiency criterion, E, was used as the objective function. The coefficient of efficiency was selected for model evaluation because it is dimensionless and easily interpreted. If the model predicts observed runoff with perfection, $E = 1$. If $E < 0$, the model's predictive power is worse than simply using the average of observed values Qo_i (observed runoff). An efficiency value of 0.92 for runoff volume was achieved for the optimization set. For the set of 30 verification events, an efficiency of 0.93 for volume was obtained. Scatter plots of simulated runoff volumes versus observed values for the optimization set and the verification runoff events at LH-106 are shown in Figures 9a and 9b. The computed versus observed points cluster very close to the 1:1 line for the optimization set but the model has a tendency to overpredict the verification set volume. However, model performance is generally very good. Additional analysis on other Walnut Gulch subwatersheds over a basin scale range using a research version of KINEROS (Goodrich, 1990) also demonstrated a high level of model performance, especially when compared to other physically-based modeling studies conducted in Walnut Gulch (Hughes and Beater, 1989). The study by Goodrich (1990) also demonstrated internal model accuracy using nested subwatersheds.

(b) Application of KINEROS to Detect Hydrologic Effects of Brush to Grass Conversion

With some level of model confidence established, KINEROS was then evaluated to assess whether it could be used to detect hydrologic response to artificially induced vegetation changes from brush to grass on a small semiarid watershed (Woolhiser et al., 1990a). Typically a paired watershed approach is used for this type of analysis. Mathematical models such as KINEROS provide an alternative method where model parameters are estimated from pretreatment period data. After treatment, the observed variables are compared with model predictions to determine the effects of the change.

Lucky Hills Watershed 102 (LH-102) has an area of 1.46 ha and is adjacent to LH-106 and was used as a paired watershed to LH-106. The LH-106 1973-80 data set employed in the calibration and verification (discussed earlier) was obtained from a pretreatment period of stable-watershed-cover conditions. In February 1981 LH-106 was treated with a herbicide to kill the woody plants. A 1984 evaluation of LH-106 and LH-102 for canopy cover showed that nearly all the woody plants had been killed on LH-106 and that the canopy cover was 12% compared with 46% for LH-102.

In June 1984 both watersheds were seeded to a grass and forb mixture with a land imprinter (Dixon and Simanton, 1980). In 1986 total canopy cover was found to be 30% (19% grass) and 36% (2% grass) for LH-106 and LH-102, respectively. A much earlier and better grass stand was established on LH-106 and it has persisted longer than on LH-102. Neither watershed has been grazed by livestock since 1965 but rabbits have grazed both watersheds heavily since seeding and have largely contributed to the near depletion of the grass on LH-102.

(c) Data Analysis

Summary rainfall and runoff statistics for watersheds LH-106 and LH-102 are shown in Table 6. These statistics indicate a low mean and the large year to year variability of annual runoff from these semiarid rangelands. In the subsequent analysis, only storms with runoff greater than 0.254 mm were used. These storms accounted for total runoff of 92% and 89% for watersheds LH-106 and LH-102, respectively.

The KINEROS model was used to estimate runoff hydrographs for the 1981-83 herbicide period when LH-106 was nearly devoid of living vegetation and for the 1984-87 period when grass become established. The pretreatment model parameters were used for all periods so the model results could be interpreted as runoff estimates that would have occurred without treatment. Some evidence indicates that vegetation changes in this rainfall zone will result in

TABLE 6. Annual Precipitation and Runoff Statistics for LH-106 and LH-102.

Year	Annual Rainfall (mm)	Runoff LH-106 (mm)	Runoff LH-102 (mm)
Entire period (1973-87)			
mean	299.0	24.6	24.9
std. dev.	90.7	20.1	19.6
Pretreatment period (1973-80)			
mean	299.7	22.9	23.4
std. dev.	100.1	23.6	22.9
Herbicide treatment (1981-83)			
mean	311.4	30.0	21.3
std. dev.	108.7	1.8	1.5
Grass/imprint (1984-87)			
mean	288.0	24.6	30.5
std. dev.	82.3	22.9	22.1

very small (Simanton et al., 1977) or undetectable changes in runoff (Bosch and Hewlett, 1982). From physical reasoning we might expect a runoff increase during the 1981-83 period followed by a runoff decrease during the 1984-87 period as a result of land imprinting effects and better cover. These are typically transient changes but in our analysis we will assume that the changes occur in a stepwise manner.

Simulation results for the 1981-83 period indicated more simulated events are above the line of equality than below so it might be inferred that runoff decreased during this period. For the period 1984-87 a substantial runoff volumes decrease was indicated. However, if the paired runoff measurements at LH-106 and LH-102 are examined, a different interpretation is plausible. A double mass plot of annual runoff from LH-106 and LH-102 is presented in Figure 10. This figure suggests that runoff increased on LH-106 relative to LH-102 during 1981-83 and then decreased during 1984-87. Regression relationships between runoff volumes from LH-106 during the pretreatment period and concurrent runoff volumes for LH–102 were calculated with a 95% confidence region for the true regression line for all three periods. The equality hypothesis of runoff between the two watersheds could not be rejected for the pretreatment period and for the 1984-87 period which is consistent with the double mass plot. Therefore, the question arises "Why do the model results differ from the results inferred from paired watershed analysis?"

To address this question examine Figure 9b and note that the model overestimates runoff for the verification set. This overestimation is especially pronounced for the runoff events with volume less than 12.7 mm. Model estimates are expected to be biased high even if the watershed had not been treated because the 1981-83 events were in the low range. Even with an actual runoff increase from LH-106 during 1981-83, the model might still show an overprediction, if the increase was small. To examine this factor more closely LH-102 was modeled with KINEROS in the same fashion as LH-106. Errors of estimation Qs_i - Qo_i for LH-106 versus the errors for LH-102 for each period are plotted in Figures 11a-11c and in each plot the errors are highly correlated. During the herbicide treatment period the points appear to shift downward, and shift upward during 1984-87 grass establishment period. These shifts indicate a runoff increase for LH-106 relative to LH-102 for the 1981-83 period and a decrease in the following period once the model bias is removed.

(d) Discussion and Conclusions

The analysis indicated that if the runoff changes are small, model predictions can be misleading if the parameters are estimated from a small subset of the pretreatment data. The apparent inconsistency between model results and data disappears when model errors for the treated watershed were compared with those for an adjacent watershed. However, the availability of paired watershed data was the only way this insight could be gained.

Part of the modeling error is due to optimization event selection and the fact that the two largest events were not included in this set to test model extrapolation ability. These conclusions agree with those of Langford and McGuinness (1976) who found that the standard error of estimate for paired watersheds is less than that for a model. The results are also consistent with Simanton et al. (1977) who suggested runoff decreases due to brush-to-grass conversion as well as the conclusions of Hibbert (1983) that brush-to-grass conversion should result in no significant increases in water yield from semidesert shrublands.

Decision Support System

As part of the USDA-ARS Water Quality Initiative, the Southwest Watershed Research Center is developing a prototype decision support system (PDSS) to evaluate the effects of alternative management practices on economic and surface and ground water quality criteria. While modifications of the PDSS components for rangeland applications is a topic of future research, the decision model can already be used as an aid in evaluating management practices on rangeland. To illustrate the components of the decision model consider the WEPP example discussed above. The alternative management practices and the decision variables considered are those given in Table 5. In addition, we consider the economic consequences of each alternative.

TABLE 7. Score matrix for management practices.

	Vegetation and Extent of Grazing				
Grazing:	Brush No	Brush Moderate	Grass No	Grass Moderate	Grass Heavy
Runoff:					
Volume	0.74	0.5	0.86	0.81	0.79
Peak	0.69	0.5	0.77	0.72	0.34
Sediment yield:					
Hillslope	0.85	0.5	1.00	1.00	1.00
Watershed	0.69	0.5	0.84	0.83	0.74
Net returns	0.00	0.5	0.00	0.00	0.00

Using standard costs for ranching in southern Arizona (personal communication, Dan Robinette, Soil Conservation Service, Tucson, AZ, June 1992), estimates were made of the income streams for each of the five management alternatives. The income streams were discounted with a discount rate of 9% to their present values to account for the fact that the cost of brush-to-grass conversion is incurred in the current year for the sake of benefits in future years. The results tabulated for 20 years yielded the following net returns per hectare: brush with no grazing, $0.00; brush with moderate grazing, $55.00; grass conversion with no grazing, -$74.00; with moderate grazing, -$28.00; with heavy grazing, -$17.00.

Scores (unitless values from 0 to 1) were obtained based on scoring functions parameterized by the simulation results (Yakowitz et al, 1992). Brush with moderate grazing was selected as the conventional practice of ranchers in the area and this practice determined the baseline values of the decision variables which score 0.5 by definition. The score for each alternative practice is determined by evaluating the scoring function for each decision variable at the predicted values from the simulation run. Table 7 contains the resulting scores. Note that the conventional practice scores 0.5 for all criteria. From this "score matrix" the alternatives grass with no grazing and the alternative grass with moderate grazing dominate (do as well in all criteria and exceed in at least one) the alternatives brush with no grazing and grass with heavy grazing. In addition the alternative grass with no grazing dominates grass with moderate grazing.

The next step is to rank the decision variables in order of importance. The prototype DSS allows the importance or priority order to be specified explicitly by the decision maker. In the absence of a preferred order of importance, for example when policy or specific environmental problems are unknown, the importance order is determined by default in the decision module. Ranking the decision variables by the normalized value of the slopes of the scoring functions at the baseline values results in the importance order:

1) net returns,
2) watershed peak discharge
3) hillslope sediment yield
4) runoff volume, and
5) watershed sediment yield.

The default method of ordering the criteria ranks highest for that criterion which has the potential for the greatest change in score when a small change in the variable near the conventional practice value is observed; the decision variable which is the most vulnerable is considered most important.

Based on the established importance order of the decision variables, best and worst composite scores are determined for each of the alternatives by solving the linear programs given in Yakowitz et al. (1992). The solutions to these linear programs are the most optimistic and pessimistic composite scores (weighted averages) consistent with the importance order given above.

Figure 12 illustrates the result of the analysis if the economic decision variable is not considered and Figure 13 illustrates the economic returns having the highest priority. The bars indicate the sensitivity of the total score to the weights (consistent with the importance order) assigned to the decision variables. Note that the best and worst composite scores for the conventional practice are both 0.5 by design. Ranking the practices in descending order of the average of the best and worst composite scores preserves the dominance relations discussed above. For this example, without considering the economics, the practices are ranked:

1) grass with no grazing,
2) grass with moderate grazing,
3) brush with no grazing,
4) grass with heavy grazing, and
5) brush with moderate grazing.

When economic considerations are taken into account (Figure 13), the conventional ranching practice, brush with moderate grazing, takes over the first position. The benefits of converting to grass are outweighed by the increased costs. A major trend in national natural resource management is in the direction of developing decision support technology. The prototype decision support system which we have discussed here can aid the decision maker with the complexity of evaluating alternative practices when more than a single objective is involved.

Global Change Program

(1) Introduction

The ARS is the nation's and the world's largest single source of scientific expertise and research in agriculture (ARS-GCWRA, 1992) and the Walnut Gulch Experimental Watershed is one of three watershed research centers with regional and national research responsibilities. Two of these watershed research centers (with research and administrative programs located at Tucson, Arizona and Boise, Idaho) have lead responsibility for watershed-based global change research. The global change research program at Walnut Gulch is designed to contribute to ARS programs addressing problems of national concern related to water and energy in managed ecosystems (cultivated farmland and rangelands). Components of these problems include issues of atmospheric warming, water supplies, and food security.

(2) Description of Research Program

Research at the Southwest Watershed Research Center at Tucson and the Walnut Gulch Experimental Watershed addresses six major objectives of the national ARS program. They are as follows:

1) Analyze and interpret scale effects of hydrologic and atmospheric processes;
2) Utilize new technologies for parameter estimation and system evaluation of hydrologic and atmospheric models;
3) Develop and modify components of hydrologic and atmospheric models to improve the evaluation of land-atmosphere processes and interactions;
4) Determine the spatial variability of precipitation and temperature on a watershed scale, its temporal characteristics, and its relationship to atmospheric and topographic influences;
5) Integrate spatial dependence, non-stationarity, natural and anthropogenic climatic

variability and orographic effects into existing weather generating computer programs; and

6) Use interactive models as a basis for developing mitigation and adaptive strategies for global change on managed ecosystems within the global environment.

The Walnut Gulch Experimental Watershed is a key experimental facility in the national ARS program. It brings an important database and an essential field data collection element to the program.

Examples of Cooperative Projects

The high quality, current and historical hydrologic database and network existing at the Walnut Gulch watershed as well as the associated knowledge base have made it an ideal location to conduct large scale interdisciplinary research intended to understand both the water and energy balance using remotely sensed as well as conventional ground based data. Monsoon'90 was one such experiment that was recently completed (Kustas et al., 1991). The objects of the ARS-NASA sponsored experiment were to 1) couple remotely sensed data with energy and water balance models to provide large area flux estimates in semiarid rangelands, and 2) to infer changes in surface-atmospheric interactions at different length scales. This ground, multiple aircraft, and satellite campaign was an interdisciplinary effort that included investigators from the Institute for Radioengineering and Electronics (IRE) of the Russian Academy of Sciences, University of Arizona, additional ARS locations, U.S. Dept. of Energy, U.S. Geological Survey, University of Maryland, Utah State University, Jet Propulsion Laboratory, and several groups from France. Remotely-sensed, ground-based meteorological/flux, soil moisture, atmospheric boundary layer profile and vegetation data were collected during a dry, baseline condition, prior to the monsoon season when vegetation was senescent and during the monsoon season which is characterized by vigorous vegetation growth and widely varying soil moisture conditions. Experimental timing enabled very good pre- and post-storm watershed characterization.

Another on-going interdisciplinary research effort, focusing on Walnut Gulch, is being carried out as part of a NASA Earth Observing System (EOS) investigation. This study, entitled Utilization of EOS data in Quantifying the Processes Controlling the Hydrologic Cycle in Arid/Semi-Arid Regions (Kerr and Sorooshian, 1990) is being conducted with the University of Arizona, Laboratoire d'Etudes et de Research en Teledetection Spatiale (Tolouse, France), and other investigators. This team is using pre-EOS, and will utilize post-EOS launch, remote sensing data in an attempt to identify the key factors that control and dominate the hydrologic cycle at basin and climatic scales. From the Walnut Gulch watershed scale, the study will proceed to scale up to regional scales within Arizona. Another important objective involves the cross validation of the methodology acquired in Walnut Gulch and southern Arizona with findings of the LERTS group in the semi-arid regions of Africa.

FUTURE AND SUMMARY

Emphasis in the future regarding water use in arid and semiarid areas will of necessity focus on improved efficiency for utilization and conservation. Population growth and the increasing demand for food, fiber, and amenities for life will require technology development for resources in water deficient climates that ensures environmental enhancements. The advent and rapid advances in computer technology and associated modeling capability have enhanced society's ability to explore alternatives to the sustained use of arid and semiarid areas. Multiobjective decision making, geographic information systems, digital elevation databases, expert systems, remote sensing, and other new electronic technologies are exciting tools that have promise for natural resource management.

At the same time, climate change, pollution, and other increasing demands on natural resource utilization continue to pose new problems. For example, our analytical capabilities are advancing at a more rapid pace than our ability to collect prototype data with which to test hypotheses and further refine our knowledge of natural resource processes. For example, our databases are still generally collected using sensors developed decades ago, although new sensors have been developed in connection with space-age technology. Thus, there is an acute need for funds to upgrade instrumentation on experimental watersheds to permit "real time" data acquisition for model development, calibration, and validation from experimental watersheds so that the technology can be rapidly applied to the millions of hectares of semiarid and arid areas.

We have reviewed the past and current research activities on the Walnut Gulch Experimental Watershed and attempted to illustrate the many causal actions controlling the hydrologic cycle in watersheds with a semiarid and arid environment. The temporal and spatial variability of processes affecting the response of such watersheds are difficult to quantify but certainly necessary to understand. Highlights of the Walnut Gulch Experimental Watershed case study have included:

1) Precipitation variability controlling runoff, erosion, forage production, and water quality;
2) Advances in measurement of streamflow and sediment yield;
3) The role of transmission losses in the water balance of semiarid watersheds;
4) The impact of ephemeral streams in sedimentation and ground water recharge;
5) The use of experimental watersheds and rainfall simulation experiments in database development for natural resource model building;
6) The impact of possible climate change in water and soil resource utilization in arid areas;
7) The need for technology development involving remote sensing, geographic information systems and technology to permit sustainable use of natural resources with special emphasis on water; and

8) Development and testing of natural resource models has progressed. Models such as CREAMS, WEPP, RUSLE, and KINEROS are reported along with decision support systems and show considerable promise for quantifying management impacts on the hydrologic cycle.

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FIGURE 1. Location map, Walnut Gulch Experimental Watershed in southeastern Arizona, USA

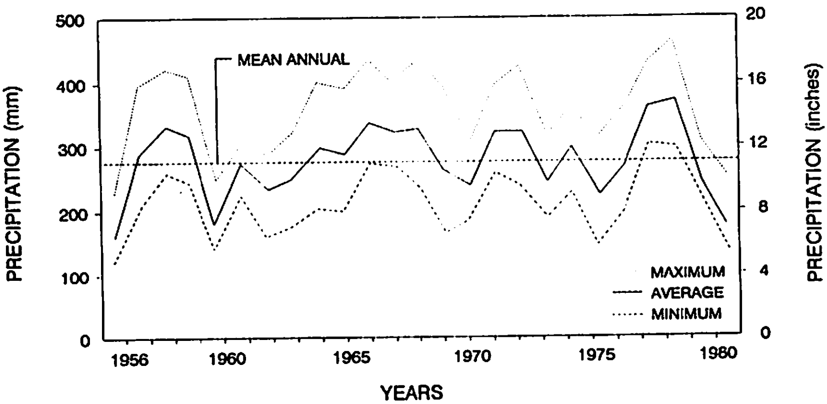


FIGURE 2. **Watershed average and maximum and minimum annual point precipitation (from an individual raingage) for Walnut Gulch (Source: Osborn, 1983).**

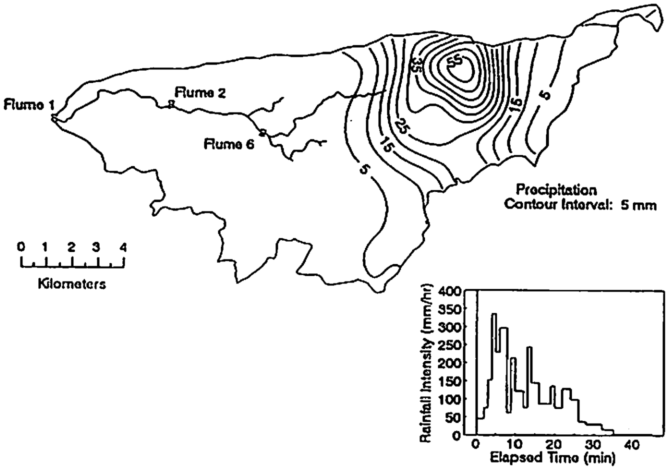
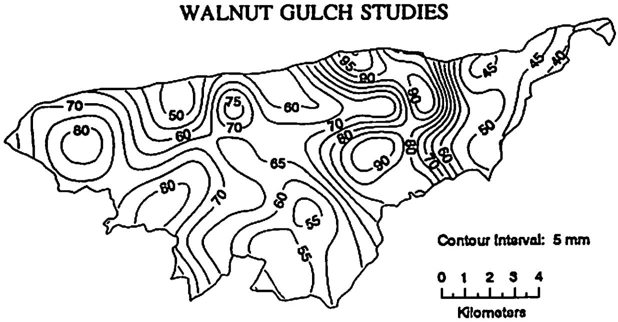
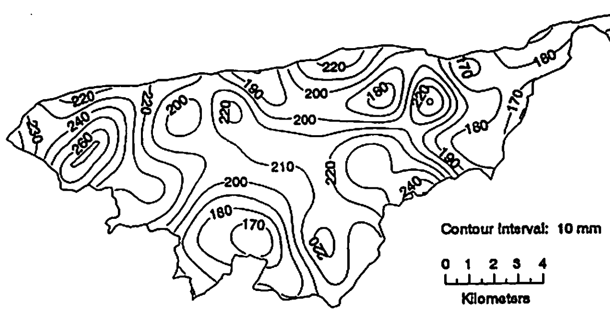


FIGURE 3. Isohyetal map of a storm on August 27, 1982.



August 1982 Isohyets for Walnut Gulch



July - September 1982 Isohyets for Walnut Gulch

FIGURE 4. Isohyetal maps for August 1982 (upper) and the July-September 1982 values (lower) as measured with a precipitation network of 85 recording gauges.

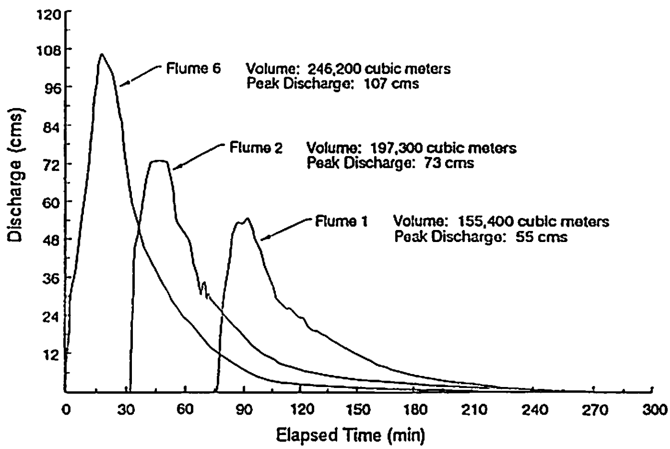


FIGURE 5. **Hydrograph resulting from the storm event on August 27, 1982. Transmission losses in the normally dry streambed reduced the volume and peak discharge.**

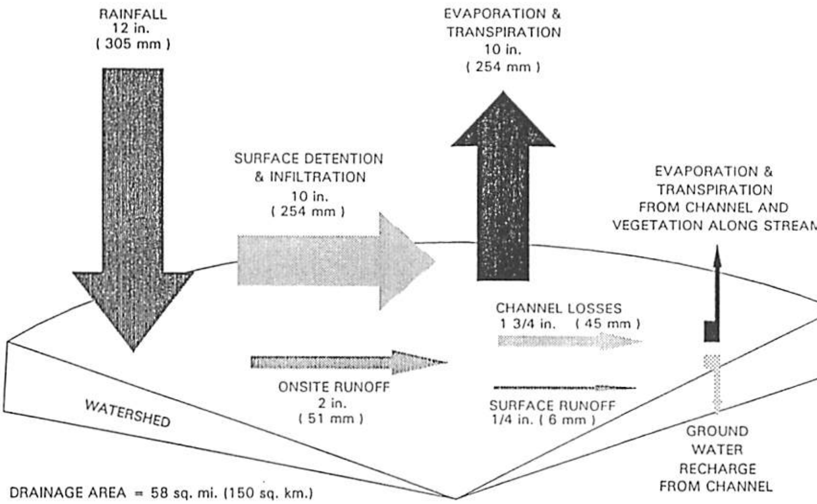


FIGURE 6. Annual water balance for the Walnut Gulch Experimental Watershed.

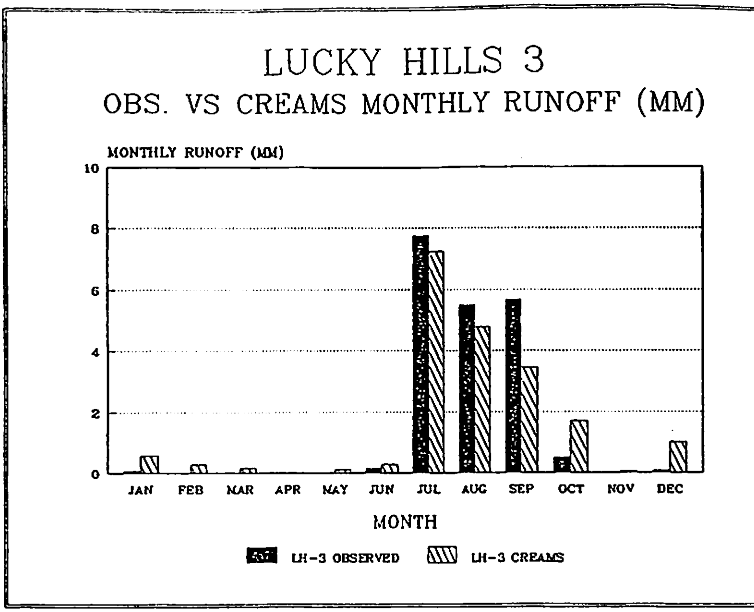


FIGURE 7. Observed and CREAMS simulated runoff for watershed LH-3 (LH-103).

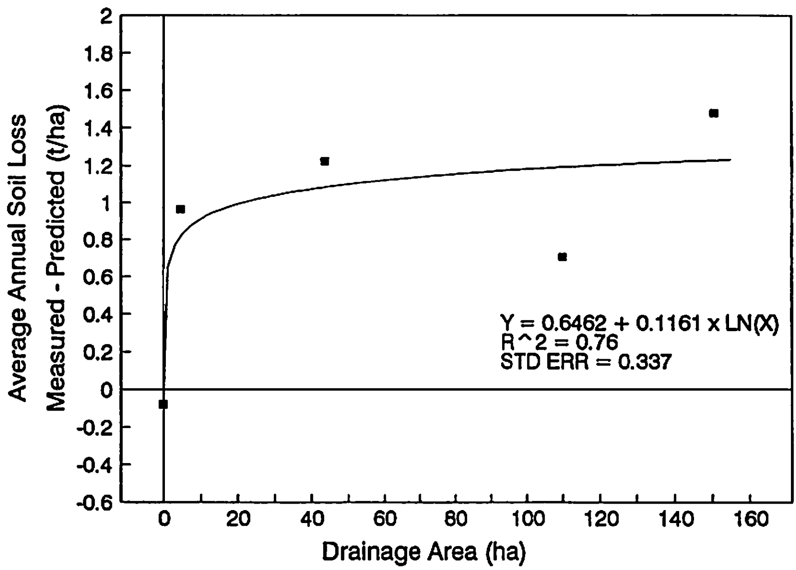


FIGURE 8. **Measured minus the RUSLE Average Annual Soil Loss predicted versus watershed drainage area.**

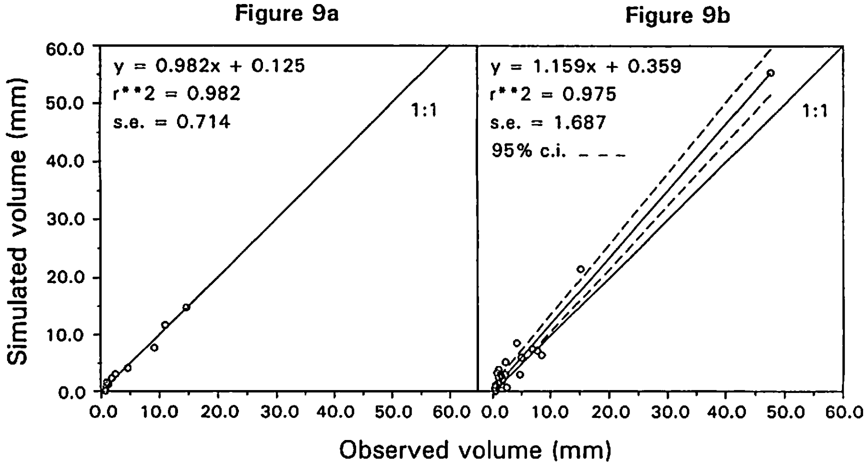


FIGURE 9. Simulated versus observed runoff volumes for Lucky Hills - 106 pretreatment period (1973-1980); a) optimization event set b) verification event set.

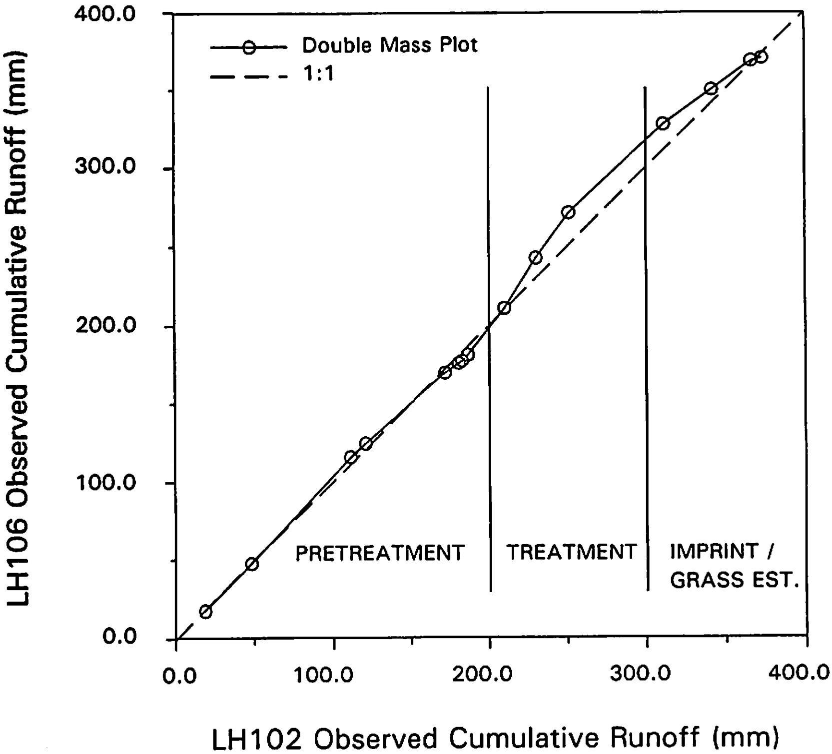


FIGURE 10. Observed double mass plot of accumulated annual runoff volume from LH-102 (untreated) and LH-106 (treated).

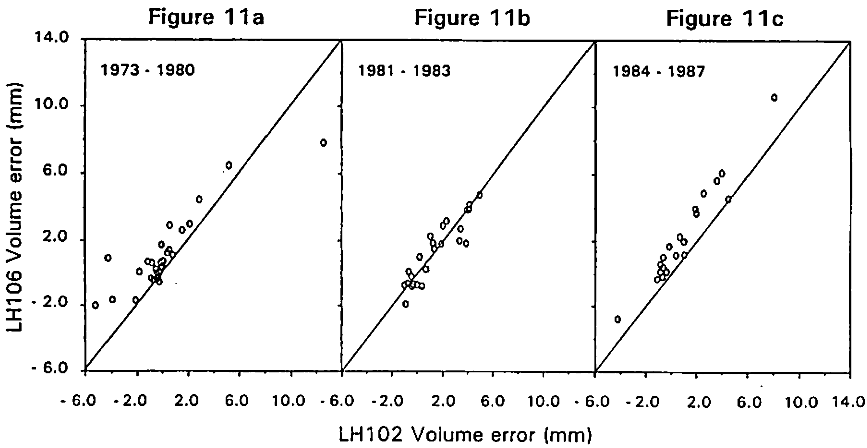


FIGURE 11. **Runoff volume simulation errors on LH-106 versus LH-102 for the a) pretreatment period (1973-1980) b) herbicide treatment period (1981-1983) and c) imprint/grass Est. period (1984-1987).**

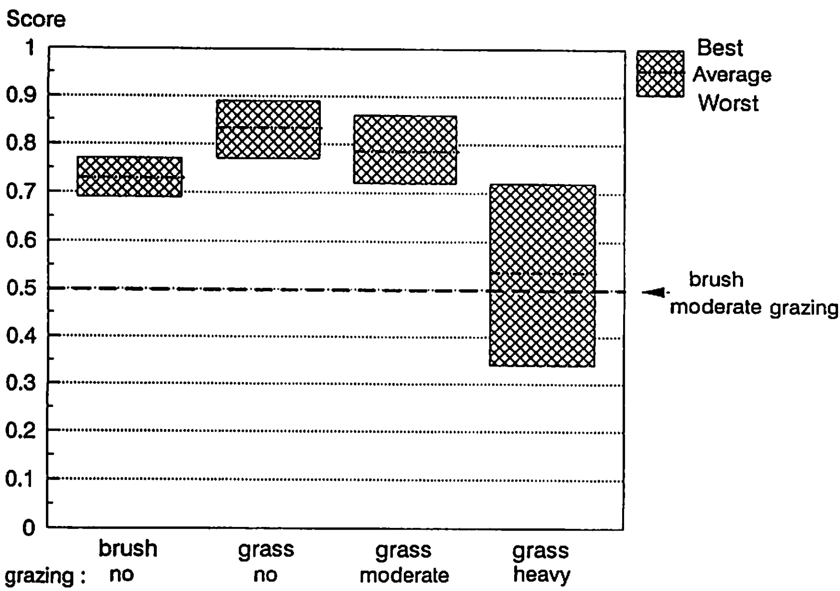


FIGURE 12. Range of total scores from best to worst without economic decision variable.

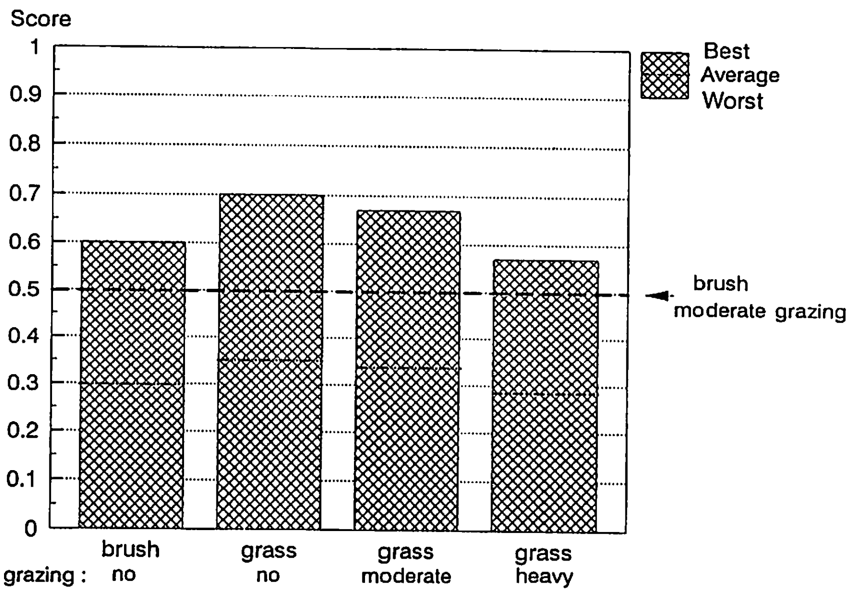


FIGURE 13. Range of total scores from best to worst including economic variable.