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Contents

Integrated watershed management

The goal of watershed management is to implement management systems which provide one or more of the following: preservation, conservation, and sustainable exploitation of the resources of a watershed while being economically beneficial to those concerned. In the past, exploitation of resources, often in an unsustainable manner, has been the driving anthropogenic force on watersheds, while preservation and conservation activities have been instituted in reaction to the results of resource exploitation. Increases in population and economic activity since World War II have led to increased pressure to develop the resources of watersheds, particularly in developing countries (Hufschmidt and Kindler, 1991). However, there is an increasing awareness that for the development to be sustainable, conservation (preservation in some instances) of the resources is essential and must be integrated with economic and social factors in the evaluation, planning, and implementation process.

The history of the development of the United States serves as a good illustration of how preservation, conservation, and exploitation factors have shaped natural resource policies and management. The rise of the US as an economic power was fuelled by the exploitation of its many natural resources. Indeed, it was due to the rapid exploitation that preservation and conservation activities were initially proposed. The concept of preservation is evident in the writings of Emerson, Thoreau, and Muir who proposed that wildness areas were necessary for spiritual renewal, maintaining the American frontier experience, and to protect areas from urbanization. Managed development and conservation was promoted most notably by President Theodore Roosevelt in the late 1800s who, along with others, advocated directed management of natural resources by professional resource specialists (Hays, 1959). In the early twentieth century, conservation took on different meanings depending on the federal agency implementing management systems. To the Forest Service, conservation meant management of forests for sustainable lumber yield (Greely, 1972). To the Bureau of Reclamation, it meant conserving water for use in irrigation, flood control, and hydroelectric power generation (National Resource Council, 1993). To the Soil Conservation Service (SCS), it meant conserving soil and water resources to increase agriculture productivity.

It was not until the early 1960s, however, that the US Water Resources Council formally recognized that environmental and socio-economics objectives should be linked together in water resource planning (US President's Water Resources Council, 1962). By 1980, the US government had adopted these planning principles with the two main objectives of environmental quality and national economic development (US Water Resources Council,

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

1983). The multiobjective approach embedded in the concept of multiple use has been formally adopted for decision making by the US Forest Service in forest management planning (Kent *et al.*, 1991) and recently the SCS has developed a structure for the consideration of such factors as water quality, economics, and wildlife in planning and evaluation of management systems.

Although there are many published methodologies for the evaluation, planning, and implementation of integrated watershed management systems, they generally include the following steps:

1. Problem definition
2. Inventory of available data/collection of required data
3. Selecting decision criteria
4. Selecting management alternatives
5. Ordering, by importance, the decision criteria
6. Using the ordered decision criteria to rank the management systems and recommend the "best management system"
7. Implementing the "best management system"
8. Monitoring to evaluate the "best management system".

The first step, problem definition, is the most critical because the solution to a problem is shaped by how the question is posed. Step two is important to understand the biotic and abiotic characteristics of a watershed, the interactions and feedback mechanisms which occur, and to plan on how best to monitor the watershed. Steps 3 through 6 are the most important for both the decision maker and those affected by the selection of the management system. Decision makers can be assisted in these critical steps by the science of multiobject decision making and the technology of decision support systems. Step 3, selecting decision criteria, involves choosing specific factors which will directly affect those people impacted by a given management system. Examples of decision criteria are net returns to the farmer, nitrate leached to the groundwater, and sediment delivered to a reservoir. Step 4, selecting management alternatives, involves the scientist, sociologist, economist, and extension agent among others in the selection of management systems which are viable alternatives to the conventional system currently in place. Step 5, ordering the decision criteria, is one of the most difficult and contentious steps in that all those concerned have to agree on the relative merits or weights of each of the decision criteria. Step 6, ranking the management alternatives, involves using the ordered or weighted decision criteria to compute a score for each management alternative which is then used to rank the alternatives from best to worst.

In this paper, we will concentrate on Steps 2 through 5 with emphasis on semiarid rangeland watersheds. We will discuss the value of a comprehensive database and its interpretation with regard to abiotic and biotic responses, the need for simulation models to provide values of decision criteria for different management systems, and the need for the incorporation of multiobjective decision theory in the recommendation of management systems for integrated watershed management.

DATA COLLECTION

A comprehensive database is indispensable for sound decision making regardless of the problem. In the context of integrated watershed management in semiarid regions, data are necessary to quantify the temporal and spatial variability of the hydrologic and sediment budgets, characterize the type and extent of soil-vegetation resources, and understand the interaction and feedback of natural versus anthropogenic impacts on watershed resources. Obtaining a data record which represents conditions on the watershed requires a long-term commitment by the data collection agency or organization because of the extreme temporal and spatial variability of processes occurring in semiarid regions. However, even with an institutional commitment to long-term data collection, additional experiments need to be designed and implemented to evaluate the effects of alternative management systems, either existing or newly developed, on watershed resources. In this section, we describe the long-term data collection program at the Walnut Gulch Experimental Watershed in southeastern

Arizona, USA (Figure 1) and rainfall simulator experiments designed for the parameterization and verification of hydrologic and erosion management models.

Walnut Gulch Experimental Watershed

The Walnut Gulch Experimental Watershed was established by the Agricultural Research Service (ARS) in 1954 to examine the effects of upland conservation management systems implemented by ranchers on downstream water supply for irrigation districts. In addition, the Walnut Gulch Experimental Watershed has provided a unique outdoor laboratory for scientists to study the temporal and spatial variability of rainfall, infiltration, runoff, erosion, and sediment yield occurring on semiarid rangeland watersheds.

Description

The Walnut Gulch Watershed encompasses the 150 square kilometres in southeastern Arizona, USA. (Figure 1) that surround 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 1945 m MSL. Cattle grazing is the primary land use with mining, limited urbanization, and recreation making up the remaining uses.

Soils and vegetation

Soils on the Walnut Gulch Watershed 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 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.

Although historical records indicate that most of the watershed was grassland approximately 95 years ago, shrubs now dominate the lower two-thirds of the watershed (Hastings and Turner, 1965) and probably resulted from overgrazing. 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

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 1960s 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 as a result of various hydrologic, hydraulic, and structural reasons. Following extensive hydraulic model research at the 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 10 small (< 40 ha) watersheds is measured using various gauging structures. These structures include broad-crested V-notch weirs, H-flumes, and supercritical flow flumes (Plate 1). Runoff from watersheds larger than 200 ha is measured with large supercritical flow flumes. The largest flume, at the outlet of the Walnut Gulch Watershed has a flow capacity of 650 m^3s^{-1} (Plate 2). 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 climate change on vegetation and livestock production.

Climate

The climate of Tombstone, Arizona and the surrounding Walnut Gulch Watershed has been 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. Thus, 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 on the Walnut Gulch Watershed varies considerably from season to season and from year to year. Osborn (1983) reported, based on records from 1956-80, that annual precipitation varied from 170 mm in 1956 to 378 mm in 1977; 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

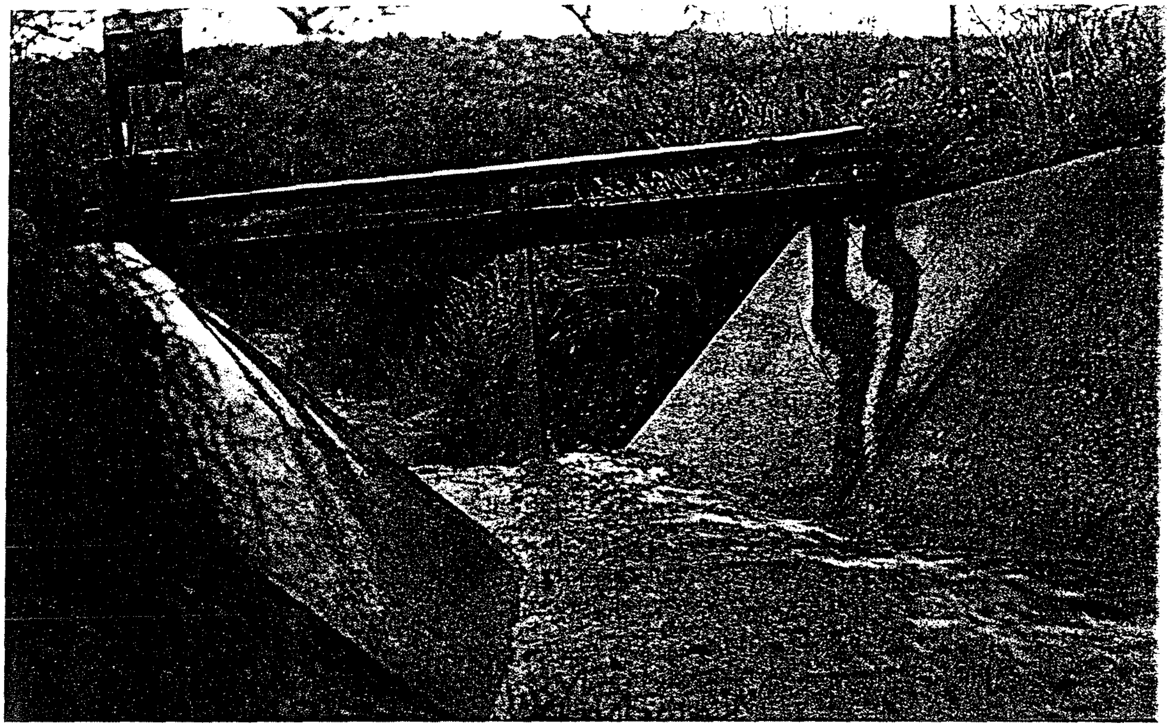


PLATE 1 A 2 m^3/s supercritical flume (Smith *et al.*, 1982) and water quality sampler (Renard *et al.*, 1986). View looking downstream showing sampler in a small flow.

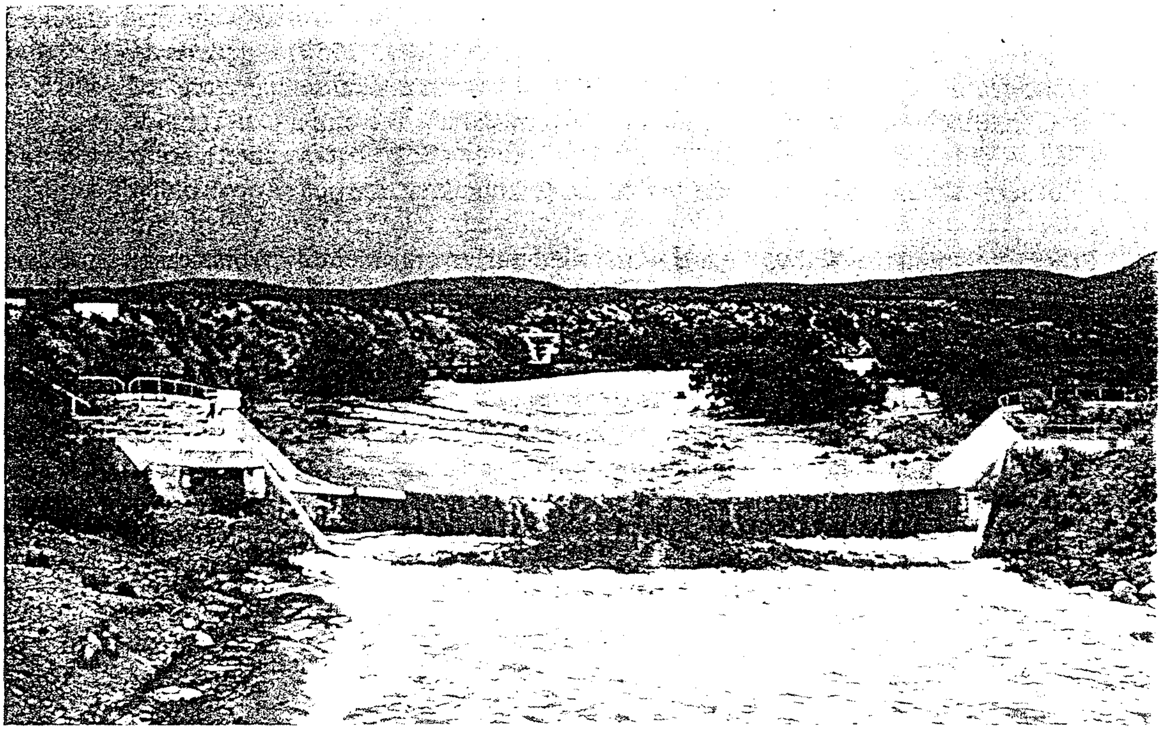


PLATE 2 A view looking upstream of the 650 m^3/s supercritical flume (Gwinn, 1970) at the outlet of the Walnut Gulch Experimental Watershed with a discharge of approximately 30 m^3/s. Note that the lower portion of the structure is an energy dissipator.

storm events such as that in Plate 3 and Figure 2 for August 27, 1982 resulted in the August isohyetal map shown in Figure 3. The ratio of maximum point precipitation of 90 mm to the minimum of 45 mm (a ratio of 2:1 in an individual month where thunderstorms dominate) 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.

Transmission losses

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. Transmission losses are important because water infiltrates when flood waves move through the normally dry stream channels (Plate 4), reducing runoff volumes and flood peaks (Renard, 1970), and affecting components of the hydrologic cycle, such as soil moisture and ground water recharge. An example of transmission loss is presented in Figure 4.

The August 27, 1982 storm, illustrated in Figure 2, 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 4) amounted to 2.46×10^5 m^3 with a peak discharge of 108 m^{3}s^{-1}. Runoff traversing 4.2 km of dry streambed between Flume 6 and Flume 2 resulted in significant infiltration losses (Lane, 1983) (Plate 4). For example, in the 4.2 km reach the peak discharge was reduced to 72 m^{3}s^{-1} and 48 900 m^3 of water were absorbed in the channel alluvium. During the course of the 6.7 km from Flume 2 to Flume 1, the peak discharge was further reduced, and 41 900 m^3 of runoff was infiltrated in the channel alluvium.

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 5 illustrates the water balance for average conditions. Given the average 324 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 5 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.

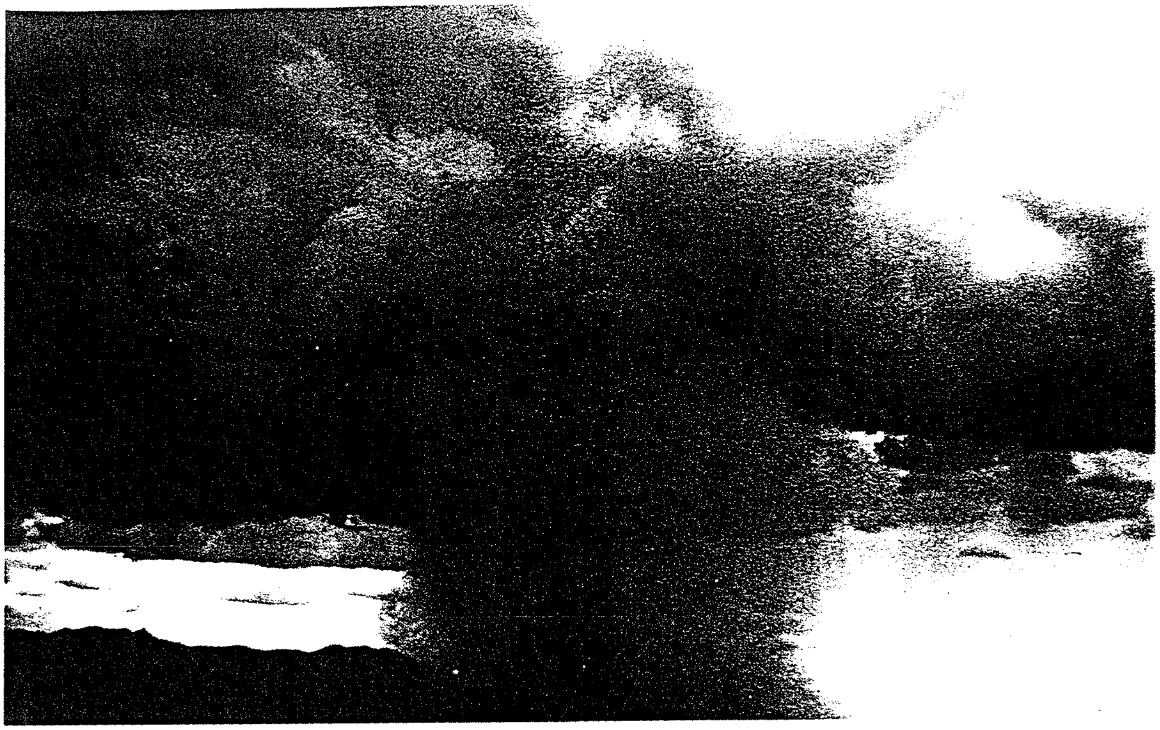


PLATE 3 A picture of an air mass summer thunderstorm with precipitation from the cloud mass typically covering only a portion of the experimental watershed

PLATE 4 An advancing flood wave moving over a normally dry alluvial stream bed such as might result from events as shown in Figure 2 and Plate 3 respectively. Infiltration losses in the streambed during such events are large and affect the water balance.

FIGURE 2
Isohytal map of a storm on 27 August 1982

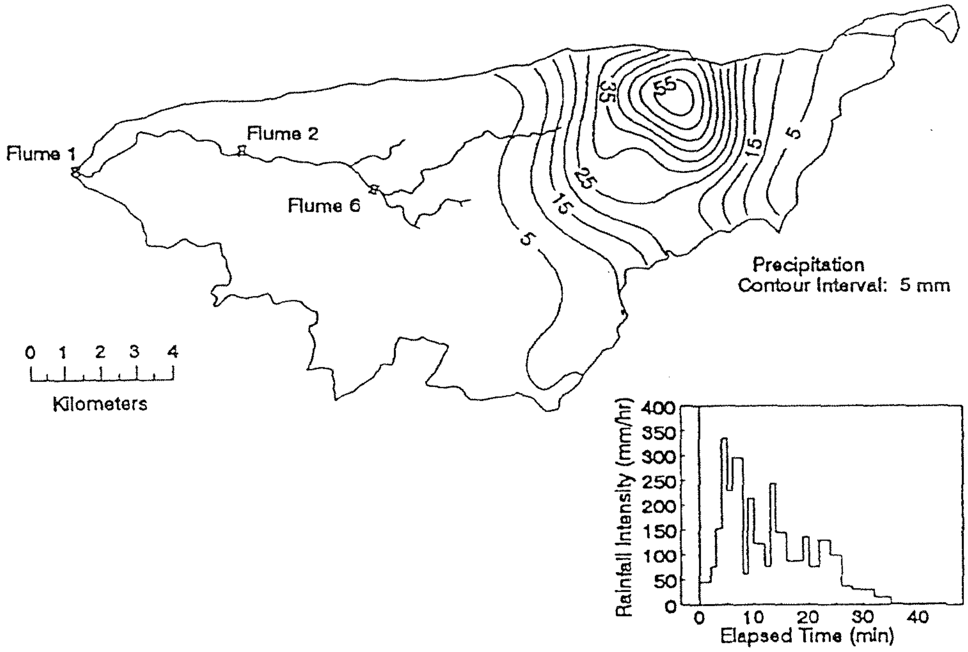


FIGURE 3
Isohyetal map of August 1982 as measured with a precipitation network of 85 recording gauges

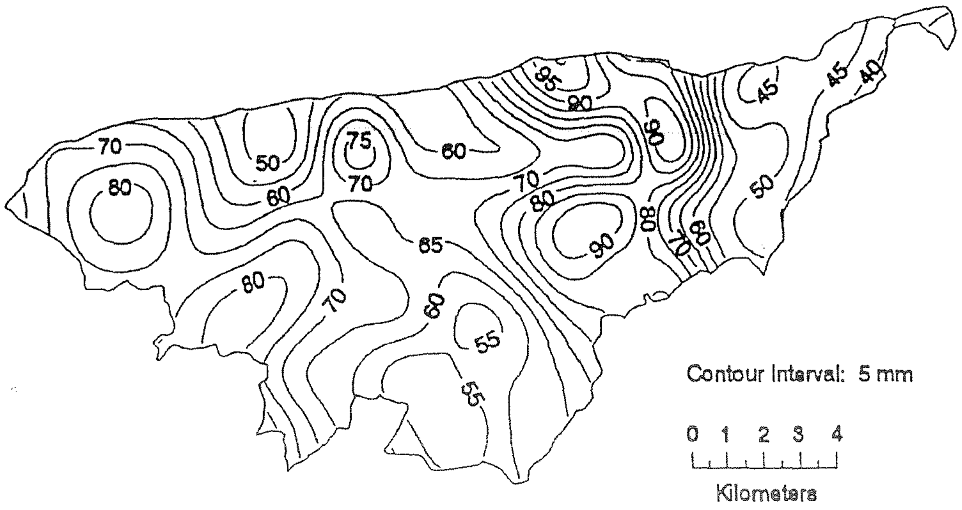


FIGURE 4
Hydrograph resulting from the storm event on 27 August 1982. Transmission losses in the normally dry streambed reduced the volume and peak discharge.

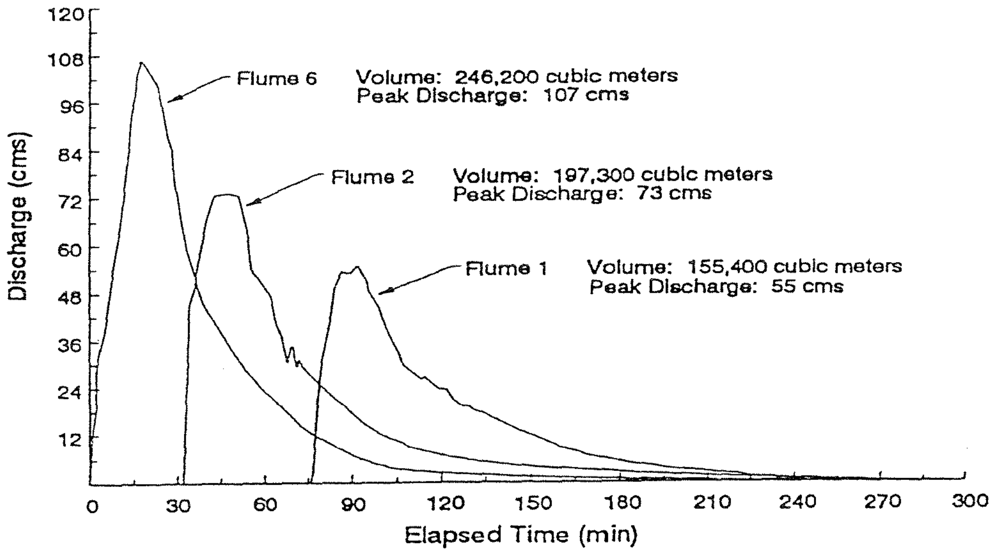
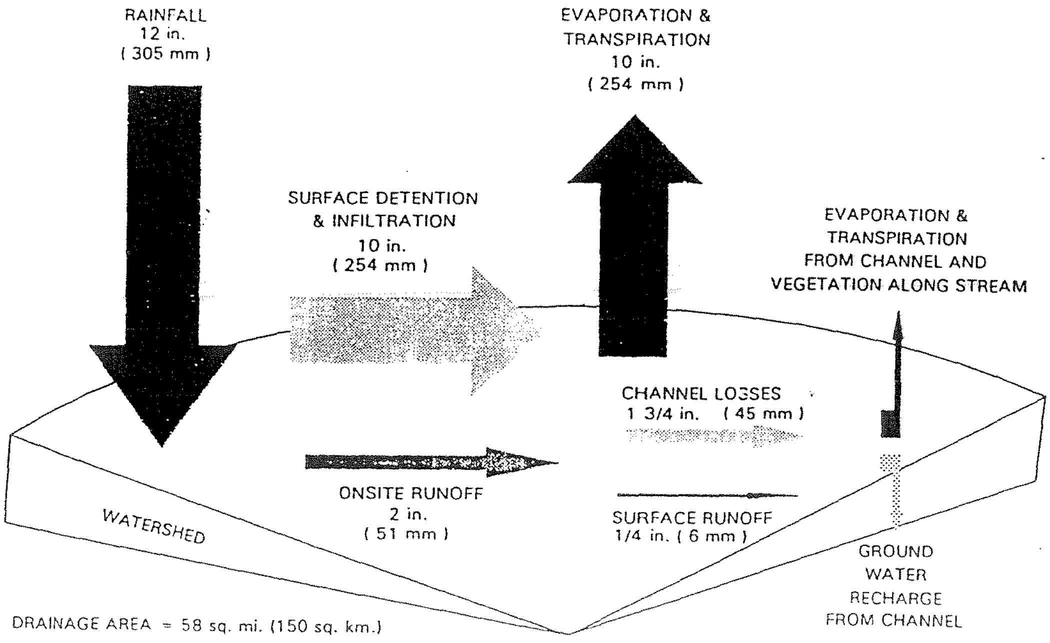


FIGURE 5
Annual water balance for the Walnut Gulch Experimental Watershed



Rainfall simulation studies

Implementing the data collection program described above to evaluate possible management systems is often difficult because of the cost and time involved to collect a representative data set. An indispensable adjunct to a watershed data collection program is rainfall simulation, a valuable tool for evaluating the hydrologic and erosional responses of natural environments (Renard, 1986). Rainfall simulators 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 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 soil). 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. 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 natural resource 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 and Nearing, 1989). 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 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 the Green-Ampt infiltration model.

Ten years of rainfall simulation studies on rangeland erosion plots have produced a large database used to parameterize hydrologic and soil erosion prediction models. These studies, conducted on many rangeland ecosystems, represent a unique database that would 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 erosivity (R), soil erodibility (K), 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.

DECISION SUPPORT SYSTEMS

As implied in the introduction, preservation, conservation, and exploitation of watershed resources have conflicting objectives which need to be resolved to implement a sustainable management system. Given that, we need to make recommendations of which management system to use. The most efficient method to present the user with decision alternatives, both in terms of cost and time, is through a combination of data bases, simulation modelling, sound judgement by the resource analyst, decision theory, and decision support systems. Multiobjective decision theory allows the evaluation of alternative management practices given that some objectives will be in conflict. The methodology involves ranking in order of importance or utility, the objectives for different scenarios. An objective criterion is used to evaluate which scenario yields the optimum or best ranking of the objectives. This is not a new concept in natural resource management; the USDA Forest Service has been using similar methodology in their forest management planning (Kent *et al.*, 1991).

Technology which incorporates all aspects of the decision making process is termed a decision support system (DSS). In a broad sense of the definition, an SCS soil conservationist with Agriculture Handbook 537 (Wischmeier and Smith, 1978), which describes the USLE, is an example of a DSS for erosion evaluation. In DSS applications on computers, the three most important components of a DSS are a database, a simulation model, and a decision model.

In the first part of this section, we describe several simulation models developed by the ARS for the evaluation of management systems on one or more of the following: hydrology, erosion, water quality, vegetation, and domestic animal production. These models were developed to be applied in support of the evaluation of management systems, inventory of agricultural resources, and planning of national agricultural policy. In the second part, we describe a prototype decision support system under development which has the objective of integrating multiobjective decision theory with simulation modelling to recommend a "best management system" from a suite of viable alternative management systems.

ARS simulation models

Although data are a necessary component of integrated watershed planning, few, if any, watersheds are as heavily instrumented as the Walnut Gulch Watershed described above. Establishment and maintenance of data collection programs is expensive and requires an

TABLE 1
Selected ARS models used for evaluation of management systems

Model name	Simulation mode/ time step	Purpose
	Plot scale	
IRS Stone *et al.* 1992	event/minutes	Parameterize infiltration and runoff modes from rainfall simulator data
	Field scale	
CREAMS Knisel, 1980 GLEAMS Leonard *et al.* 1987	continuous/daily	Predict nutrient and pesticide losses in surface water and sediment, leachate below the root zone, and erosion and sediment yield
EPIC Williams *et al.* 1983	continuous/daily	Predict erosion impact caused by farming systems on soil productivity
	Watershed scale	
WEPP Lane and Nearing 1989	continuous/ minutes, daily	Predict the spatial and temporal variability of erosion and sediment yield as impacted by agricultural management systems
SPUR Wight and Skiles 1987	continuous/daily	Predict the impact of rangeland management systems on the utilization and productivity of rangelands
SWRRB Williams *et al.* 1985	continuous/daily	Resource assessment of hydrologic unit sized areas
KINEROS Woolhiser *et al.* 1990	event/minutes	Predict the runoff hydrograph and erosion and sediment transport from small agricultural and urban watersheds.
AGNPS Young *et al.* 1987	event/daily	Predict the impacts of farming systems on water quality from large agricultural watersheds

infrastructure of trained scientists and technicians as well as long-term financial support. As a result, our understanding of natural processes based on instrumented watersheds is incorporated into simulation models for application on similar watersheds. Simulation models are frequently used to plan, evaluate, and select management systems. Numerous such models have been developed by the ARS. The models can all be described as mathematical (Woolhiser and Brakensiek, 1982) with a mixture of empirical and theoretical components or relationships. Most use regression or empirical relationships to quantify the parameters used in the model. They are robust if the data from which parameters were determined represent a global set of conditions. Listed in Table 1 are selected ARS hydrologic, erosion, and water quality models which are or have been used in the programs of various groups both inside and outside the USA. Note that this list is by no means all inclusive.

Considerable research in support of any hydrologic model involves efforts to parameterize the algorithms used. For example, most watershed management models have problems with parameter robustness when data from limited geographic, climatic and land use was used to develop the model. Thus, users of watershed management models need to be cautious as they use such models in areas different from those where the calibration data were collected.

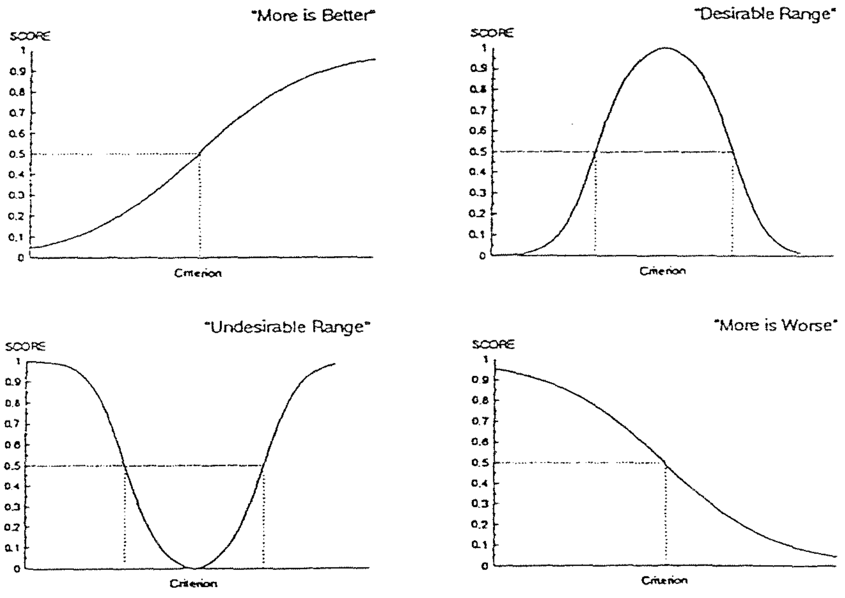
In the past, one of the primary difficulties in the application of process based models was the lack of input precipitation data in general and rainfall time-intensity data in particular. In order to extend the applicability of simulation models for management evaluation while taking advantage of a process based approach, several climate generator models have been developed. The three climate generators used in conjunction with some of the simulation models listed above are the WGEN model (Weather Generator) (Richardson and Wright, 1984), the CLIGEN model (Climate Generator) (Nicks and Lane, 1989), and the USCLIMAT model (Woolhiser *et al.*, 1988). All three models use Markov-chain wet-dry probabilities for generating daily precipitation. WGEN describes the precipitation depth using a gamma distribution; CLIGEN uses a skewed normal distribution; and USCLIMAT uses a mixed exponential distribution. All generate wind, radiation, and temperature. CLIGEN is used in EPIC, SWRRB, and WEPP (Table 1): WGEN is used in SPUR; and USCLIMAT is used in KINEROS. The CLIGEN model has been parameterized for the entire U.S. and is in the process of being parameterized for other countries.

Prototype decision support system for water quality

The ARS is developing a Prototype Decision Support System (PDSS) to evaluate the impact of farm management systems on water quality and farm profitability. The objectives of the system are to (i) illustrate the use of multiobjective decision theory with imbedded simulation models and (ii) provide a framework for an operational DSS. The major components of the PDSS are a system driver, a user interface, a limited database, a simulation model, and a decision model. The system runs on a workstation platform using the UNIX operating system under the X-Window graphical interface environment. The user interface conforms to the SCS graphical interface standards (SCS, 1990) for all their software development. Limited databases have been constructed to provide parameter values for both the simulation model and the decision model. The simulation model is a modified version of the GLEAMS model (Leonard *et al.*, 1987). The modifications include the addition of the CREAMS (Knisel, 1980.) nitrogen component and the EPIC (Williams *et al.*, 1983) dynamic crop growth component. A farm accounting program, Cost and Returns Estimator (CARE) (Midwest Agricultural Associates, 1988), is used to compute net income as a function of the profit from crop yield and the cost of implementing and maintaining a management system.

The decision model is based on multiobjective decision theory which incorporates dimensionless scoring functions (Wymore, 1988) as modified by Yakowitz *et al.* (1992). Scoring functions are a means of scaling between 0 and 1, decision criteria (i.e. runoff, sediment, nitrogen concentration, economics) which have different units and magnitudes. The values for the decision criteria can be parameterized by simulation models, databases, or expert opinion. The choice of which decision criteria to use will depend on the problem. For example, runoff, sediment, and chemicals and nutrients in both the surface runoff and the leachate, and the economics of the management systems are potential decision criteria which could be considered for a water quality problem. The scoring functions are chosen from the four generic types, more is better, more is worse, desirable range, and undesirable range, (Figure 6). Examples of decision criteria which would be associated with the two most commonly used function types are net returns with more is better and pollutants with more is worse. The functions are constructed such that the average annual value of a conventional management system scores .5 for each of the decision criteria selected. The slope of the

FIGURE 6
Generic scoring function types



function at the score of .5 is determined by the annual minimum value and the average annual value of the decision criteria. The scores for the decision criteria for alternative management practices are computed in relation to the conventional practice. The importance order of the decision criteria can be specified by the user or computed by the normalized slope of the function. This latter method assigns more value to those decision criteria for which small differences in the values of the alternative criteria make a large difference in the score. After an importance order has been determined, a best and worst composite score is computed by a simple linear program for each alternative. Contained in the best and worst score are all possible weighting vectors for the given importance order of the decision criteria. This approach developed by Yakowitz *et al.* (1992) eliminates some of the subjectivity associated with assigning weights to decision criteria typical in multiobjective decision methodologies. The alternatives are ranked according to the average of the best and worst scores. The "best" alternative is the one with the highest average score.

EXAMPLES

As examples we use the WEPP simulation model and the multiobjective decision model described briefly above to evaluate rangeland management grazing systems. For the first example, the WEPP model is used alone to generate runoff and erosion values for the different grazing systems and an evaluation of the impact of grazing on watershed sediment

TABLE 2
Five management system summaries for Lucky Hills 103, Walnut Gulch Experimental Watershed

Vegetation	Management System	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 4 years	every 4 years

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

TABLE 3
WEPP simulated average annual runoff volume, two-year return period peak discharge, and hillslope and watershed sediment yield for five management systems for Lucky Hills 103, Walnut Gulch Experimental Watershed

Vegetation	Management System	Watershed runoff volume (mm)	Watershed peak discharge (mm/hr)	Sediment yield (t/ha)	
				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

yield is discussed. For the second example, the same runoff and erosion values along with net profits are used as decision criteria to rank the grazing systems using the multiobjective decision model described above.

Simulation model without a decision model

The use of WEPP for the evaluation of management systems is illustrated using data from Walnut Gulch sub-watershed Lucky Hills 103 (LH-103) and two common rangeland management scenarios; cattle grazing with no management and cattle grazing after a brush to grass conversion. Watershed LH-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 170 m long. Soils, vegetation, and climate are typical of the brush dominated areas of the Walnut Gulch watershed described earlier. The characteristics of the grazing management systems are listed in Table 2. The two brush scenarios consist of neither 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 four years due to heavy grazing impacts.

The climate (precipitation, temperature, and solar radiation) used for the simulation of each management practice was a 15 year sequence generated by the CLIGEN model (Nicks and Lane, 1989). Infiltration parameters were estimated using data from LH-103 and erodibility parameters estimated from rainfall simulator experiments. 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 the expected management scenario trends; 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 3). 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 or upland 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 or lateral sediment input entering the channel decreases significantly, runoff amounts and discharge rates do not, and thus channel sediment transport capacity also does not decrease significantly so that 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. To further decrease the watershed sediment yield and protect the channel from degradation, some sort of erosion control would have to be installed in the channel.

This example illustrates the use of a natural resource simulation model in evaluating alternative management practices based solely on the physical responses (runoff amount, sediment yield). By examining the raw data values in Table 3, one would conclude that the grass, no grazing and the grass, moderate grazing would be acceptable management systems to reduce both hillslope and watershed sediment yield. However, a major concern to the rancher, who ultimately selects the management practice, will be the economics of recommended management practices.

Simulation model with a decision model

The alternative management practices and the decision criteria listed in Table 3 were used with the decision model described above. Two evaluations were done, one without considering the economics of the management systems and one considering the economics. Estimates were made of the income streams for each of the five management alternatives using standard costs for ranching in southern Arizona. 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 annual 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.

The score function types and associated decision criteria used were more is better for net returns and runoff volume (Figure 6) and more is worse for hillslope and watershed sediment yield and peak discharge. The more is better function type was chosen for runoff volume because the ranchers use runoff water to fill stock tanks to provide water for cattle.

TABLE 4
Score matrix for decision model example

Decision criteria	Vegetation and extent of grazing				
	Brush none	Brush moderate	Grass none	Grass moderate	Grass heavy
Watershed runoff					
Volume	0.21	0.5	0.09	0.12	0.26
Peak	0.67	0.5	0.73	0.69	0.34
Sediment yield					
Hillslope	0.84	0.0	1.00	1.00	0.99
Watershed	0.69	0.0	0.84	0.83	0.73
Net returns	0.00	0.5	0.00	0.00	0.00

TABLE 5
Importance ordering of decision criteria for decision model example

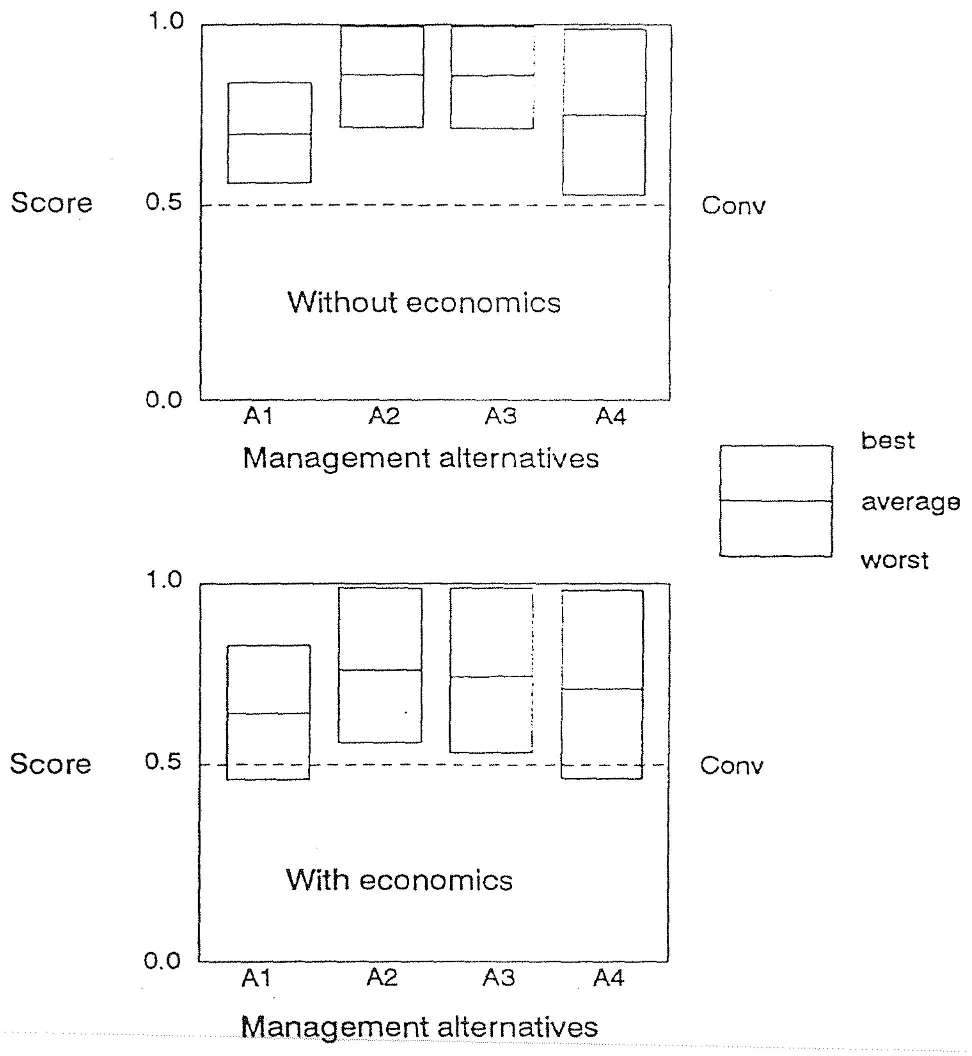
Default ordering	Imposed ordering 1	Imposed ordering 2
Hillslope sediment yield	Net returns	Runnoff volume
Peak discharge	Runoff volume	Hillslope sediment yield
Runoff volume	Watershed sediment yield	Net returns
Watershed sediment yield	Hillslope sediment yield	Watershed sediment yield
Net returns	Peak discharge	Peak discharge

In choosing this type of function, maximizing runoff volume is in conflict with minimizing sediment yield and peak discharge. Scores were obtained based on scoring functions parameterized by the simulation results. 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 criteria which score 0.5 by definition. The score for each alternative practice was determined by evaluating the scoring function for each decision criteria at the predicted values from the simulation run (Table 4). Note that neither the conventional nor any of the alternatives dominated each other. That is, none of the management systems scored higher in all decision criteria.

The next step was to rank the decision criteria in order of importance. The PDSS computes an importance order of the decision criteria or allows the importance order to be specified explicitly by the decision maker. Ranking the decision criteria by the normalized value of the slopes of the scoring functions at the baseline values results in the default importance order listed in Table 5. The default method of ordering the criteria ranks highest that criterion which has the potential for the greatest change in score when a small change in the criteria near the conventional practice value is observed. Based on the established importance order of the decision criteria, best and worst composite scores are determined for each of the alternatives by solving the linear programs given in Yakowitz *et al.* (1992).

Figure 7 illustrates the best and worst scores with and without economics given the default ordering of decision criteria listed in Table 5 and the ranking of the alternatives given in Table 6. Note that when economics is not considered, all the management alternatives dominate the conventional grazing system while, when economics is considered, only two management alternatives dominate the conventional. The height of the bars in Figure 7 indicate the sensitivity of the total score to the weights (consistent with the importance order)

FIGURE 7
Best and worst scores when economics are not included (top) and are included (bottom). Conv = conventional management system, A1-A4 = alternative management systems 1-4.



assigned to the decision criteria. All possible weighting vectors are contained within the best and worst scores represented by the height of the bars. One can readily see that including economics as a decision criterion makes the outcome more sensitive to a given weighting vector.

The default ordering with economics listed in Table 5 may not reflect a rancher's concerns and is a debatable ordering for a land use manager. To illustrate the flexibility of the PDSS, we impose an importance order more consistent with the needs of these two different constituencies. For the rancher, net returns is the most important criteria for obvious

TABLE 6
Ranking of rangeland management alternatives for LH-103 using the WEPP model to parameterize the decision variables of the DSS, decision model example

Management alternatives		Rank			
		without economics	with economics		
		do[1]	do	io 1[2]	io 2[3]
Conventional	Brush, mg[4]	5	4	1	1
Alternative 1	Brush, ng[5]	4	5	5	3
Alternative 2	Grass, ng	1	1	2	5
Alternative 3	Grass, mg	2	2	3	4
Alternative 4	Grass, hg[6]	3	3	4	2

[1] do = default ordering of decision criteria
[2] io 1 = imposed order 1 of decision criteria
[3] io 2 = imposed order 2 of decision criteria
[4] mg = medium grazing
[5] ng = no grazing
[6] hg = heavy grazing

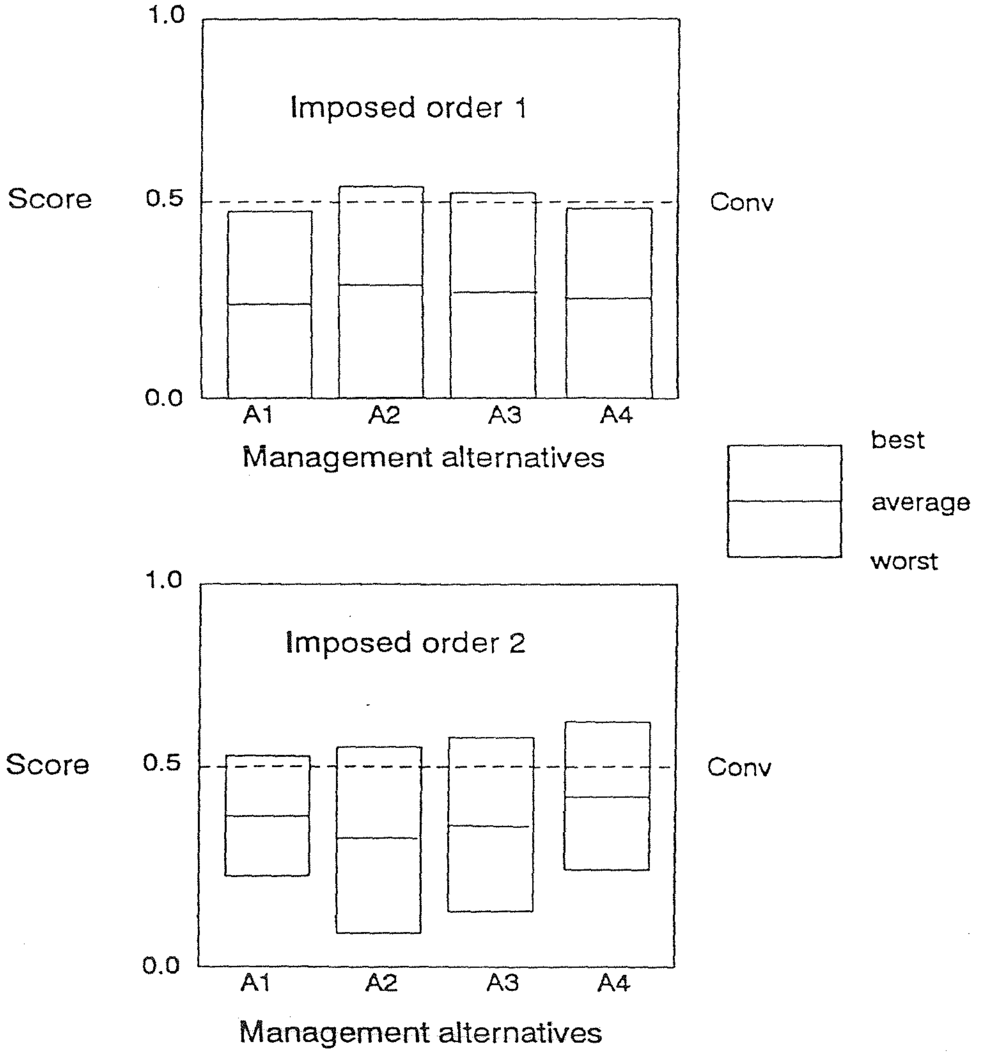
reasons, runoff volume is next because of the need of water supply for livestock, and watershed sediment yield is after runoff volume because of siltation of stock tanks. The rancher is generally not too concerned with the remaining two criteria. For the land use manager, runoff volume is the most important because of its impact on downstream users, hillslope sediment yield is next because it serves as a surrogate for the watershed productivity, and net returns are next because of economic and political constraints. The remaining two criteria would be the least important. These imposed ordering (i.o.) of decision criteria are listed in Table 6 as i.o. 1 for the rancher and i.o. 2 for the land use manager. The resulting best and worst scores are illustrated in Figure 8. In contrast to the ranking given by the default ordering shown in Figure 7, the imposed ordering results in the conventional management system as being the "best" system. Both the results for imposed order 1 (a typical rancher's choice) and imposed order 2 (a land use manager's choice) are consistent with the management systems ranchers in the area are applying to the watersheds.

These results suggest that the management system on the watershed at the present time is a realistic decision given the economic constraints of vegetation manipulation. It is obvious that, if a grass conversion management system were to be recommended, economic incentives to the rancher would have to be instituted in order for that system to be voluntarily adopted.

SUMMARY

- In order for the development of a watershed management system to be sustainable, preservation and conservation of biotic and abiotic factors have to be integrated with economic and social factors in the evaluation, planning, and implementation process.
- Implementation of integrated watershed management systems generally include 1) problem definition, 2) data inventory and collection, 3) selecting decision criteria, 4) selecting management alternatives, 5) importance ordering decision criteria, 6) using ordered decision criteria to rank management alternatives, and 7) recommending the "best" management system.

FIGURE 8
Best and worst scores for imposed order 1 (top) and imposed order 2 (bottom). Conv = conventional management system, A1-A4 = alternative management systems 1-4.



- A comprehensive database is indispensable for sound decision making. The Walnut Gulch Experimental Watershed provides an excellent example of temporal and spatial variability of watershed processes representative of semiarid regions. The intensively instrumented area and the resulting databases are invaluable for hypothesis building and testing, developing fundamental knowledge regarding hydrologic and erosion/sedimentation processes, and developing decision support systems for semiarid rangeland watershed management. Significant results of the collection and analysis of data from Walnut Gulch include the characterization of 1. precipitation variability, 2. the water balance, and 3. transmission losses.

- Rainfall simulator experiments are a quick and inexpensive method to evaluate the effect of alternative management systems and to provide infiltration and erosion parameter values in physically based rangeland natural resource simulation models.

- A means of integrating data collection, simulation modelling, and decision theory for the purpose of evaluating management alternatives is the decision support system. The incorporation of multiobjective decision theory in such a system gives decision makers a scientifically defensible, objective methodology to aid in decision making.

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