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Water Resources of Small Impoundments in Dry Regions

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SUMMARY

Reservoirs and impoundments in dry regions are dramatically affected by hydrologic factors and events on upstream watersheds. In the southwestern United States, extreme temporal and spatial variability in precipitation often results in erratic runoff/water yield patterns. Runoff in ephemeral streams is subjected to large infiltration losses in the channel alluvium and decreased peak discharge with increasing drainage area. As a result of the hot and dry conditions, there are high evapotranspiration rates and sparse vegetation. The limited vegetation, along with steep gradients in some areas, contributes to low infiltration and high erosion rates. Shallow soil profiles and high sediment yields also characterize arid areas. Ranching economics in these areas cannot justify land management and conservation efforts that require capital expenditures. Because many of these characteristics of arid regions are difficult to measure over extensive areas, water resource modeling has become important in planning small impoundments. One such model, SPUR (Simulation of Production and Utilization of Rangelands) considers climate, hydrology, plants, animals, and economics to aid resource managers and researchers in decision making.

Introduction

There is a lovely road that runs from Ixopo into the hills. These hills are grass-covered and rolling, and they are lovely beyond any singing of it. . . .

> The grass is rich and matted, you cannot see the soil. It holds the rain and the mist, and they seep into the ground, feeding the streams in every kloof. It is well-tended, and not many cattle feed upon it; not too many fires burn it, laying bare the soil. Stand unshod upon it, for the ground is holy, being even as it came from the Creator. Keep it, guard it, care for it, for it keeps men, guards men, cares for men. Destroy it and man is destroyed.
>
> Where you stand the grass is rich and matted you cannot see the soil. But the rich green hills break down. They fall to the valley below, and falling, change their nature. For they grow red and bare; they cannot hold the rain and mist, and the streams are dry in the kloofs. Too many cattle feed upon the grass, and too many fires have burned it. Stand shod upon it, for it is coarse and sharp, and the stones cut under the feet. It is not kept, guarded, or cared for, it no longer keeps men, guards men, cares for men. The tithoya does not cry here any more.
>
> The great red hills stand desolate and the earth has torn away like flesh. The lightning flashes over them, the clouds pour down upon them, the dead streams come to life, full of the red flood of the earth. Down in the valleys women scratch the soil that is left, and the maise hardly reaches the heights of a man. They are valleys of old men and women, or mothers and children. The men are away, the young men and girls are away. The soil cannot keep them anymore (Paton, 1948).

Although the quote from Paton's *Cry, the Beloved Country* was written about conditions in southern Africa, the condition is being repeated all too frequently worldwide. The quote seems especially appropriate to a consideration of small water impoundments. As ecologists, environmentalists, and/or conservationists, we are all aware that what happens on the watershed can have dramatic consequences on the dynamics of what happens in the reservoir or impoundment.

The hydrology/water resources of headwater basins in much of the southwestern United States are dominated by:

(1) Extreme variability in precipitation
  (a) temporally and
  (b) spatially.
(2) Runoff produced in ephemeral streams, which are dry most of the time,
  (a) as runoff traverses the dry streambed, transmission losses reduce the flow;

(b) water yield per unit area decreases with increasing drainage area;
(c) peak discharge per unit area is large near the center of a thunderstorm.

(3) Arid and semiarid conditions, which predominate result in
(a) high potential evapotranspiration and
(b) sparse vegetation.

(4) Physiographic and soil conditions, which result in
(a) low infiltration and
(b) high erosion rates because of steep gradients and sparse vegetation.
(c) steep streams and large alluvial supplies leading to high sediment yield.

(5) Ranching economics that lead to
(a) minimal use of agricultural chemicals;
(b) minimal efforts for land modification;
(c) minimal incentive for conservation programs, and
(d) minimal incentive for range improvement/rehabilitation

PRECIPITATION

Hershfield (1962) considered annual precipitation totals for a large number of gages around the conterminous U.S. and showed that the maximum coefficient of variation is in the Southwest, with the highest values in southern Arizona and southern California (Fig. 1.1). Thus, in addition to the aridity of this same area (except for high-elevation mountains), the highly variable annual rainfall can result in an even more erratic runoff/water yield pattern.

In southeastern Arizona, about ⅔ of the annual rainfall occurs as thunderstorms during the July-September period. These thunderstorms are typically of short duration (1 to 2 hours), high intensity (up to 10 in/hr or 250 mm/hr for 5 minutes is common), and limited areal extent. The intensity pattern within a given storm is also highly variable, as indicated in Figure 1.2 where 4 raingages on the Walnut Gulch Experimental Watershed, with large amounts in a short period, were compared. Hyetograph differences for these storms are even more dramatic when presented as dimensionless distribution graphs.

Practicing hydrologists are continually plagued in thunderstorm dominated runoff areas (such as the southwestern U.S.) with daily rainfall totals as the only data available for design. Thus, if a reservoir is to be designed and precipitation data are available for a location within a project, the hydrol-

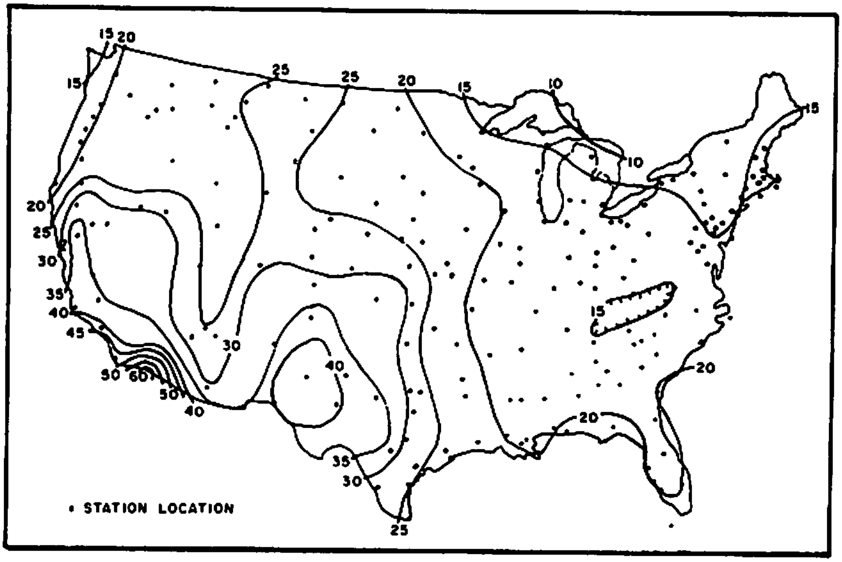

Figure 1.1. Coefficient of variation of annual precipitation in percent (Hershfield, 1962).

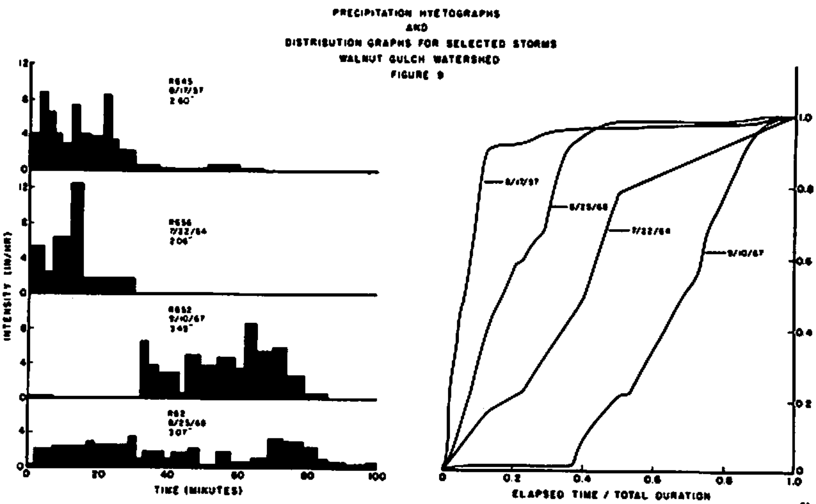

Figure 1.2. Precipitation hyetographs and distribution graphs for selected storms on the Walnut Gulch watershed (Renard, 1970).

ogist must decide how much runoff might be expected from the available rainfall record. Furthermore, to preclude the disaster of the impoundment being overtopped and destroyed, a spillway (principle and emergency) must be designed for some peak discharge and some total runoff volume. For example, if the rainfall record included a maximum of 3 inches (75 mm) on any day in the record, it would make a great deal of difference whether those 3 inches occurred in 1, 2, 6, or 24 hours, because 3 inches in 24 hours might not produce any runoff (depending on the soils and vegetation), whereas the same amount of rainfall in 1 hour might result in a very large runoff.

For this reason, hydrologists such as those at the Southwest Rangeland Watershed Research Center are developing probabilistic models which disaggregate daily rainfall amounts into a hyetograph so that precipitation excess (precipitation minus infiltration) can be computed with the use of a time-dependent infiltration function such as was developed by Rawls, Brakensiek, and Miller (1983).

Spatial precipitation variability associated with air mass thunderstorms represents still another design problem for the hydrologist. Unfortunately, the number of precipitation networks available for quantifying such variability is extremely limited (Osborn, Lane and Hundley, 1972; Hershfield, 1971).

One precipitation network is the U.S. Department of Agriculture's Walnut Gulch Experimental Watershed, in southeastern Arizona, which was established in 1961. The 57.7mi^2 drainage area (150 km^2) has a network of almost 100 recording precipitation gages on, or adjacent to, the study area. The network facilitates the definition of the rainfall on both individual storm events, as well as the aggregate from seasonal and annual totals. Some of this variability is indicated in Figure 1.3 for an event on July 16, 1967 and for the 1967 annual total. Data from networks such as these have been used with considerable success in modeling thunderstorm depth-area relationships (Renard and Brakensiek, 1976) which, in turn, are then used in water resource simulation models for varied climates in the continental U.S.

RUNOFF

In most dry regions, the water table is considerably below the stream channel invert, especially in the headwater areas. The result is that the streams are influent rather than effluent. As such, the stream channels contain water only during unusual precipitation/storm events, and then

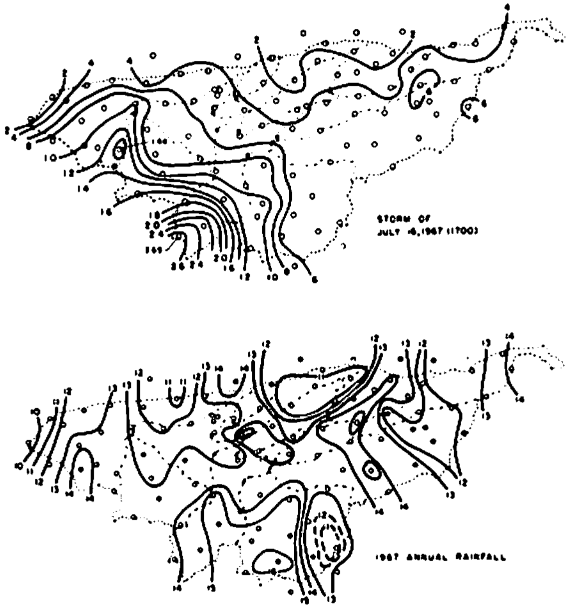

Figure 1.3. Isohyetal maps of the July 16, 1967 storm and the annual precipitation (in) for 1967 (Renard and Brakensiek, 1976).

generally for only short periods of time. Thus, the channels on a basin such as the Walnut Gulch Experimental Watershed are dry 99 percent of the time.

The isohyetal map for a typical air-mass thunderstorm with the hydrographs at consecutive streamflow stations on Walnut Gulch are shown in Figures 1.4a and 1.4b. Most of the heaviest part of the storm was concentrated on the 8.24 km^2 (2035 acre) subwatershed 11. Although there was some precipitation on the intervening area between subwatershed 11 and watershed 8, it was probably minimal relative to the amount from watershed 11. From flume 11 to flume 8, there are 6.6 km (4.1 miles) of channel, with a mean width of 11.6 m (38 feet). The 1000 cfs (cubic feet per second) (28.3 m^3/sec) peak flow with 49 acre-feet (AF)(60,400 m^3) of runoff measured at flume 11 was reduced by infiltration in the channel alluvium to slightly less than 700 cfs (19.8 m^3/sec) peak flow and 34 AF (46,800 m^3) of runoff at flume 8. For this flow, like many other storms on the upper portion of the watershed, most of the runoff was lost in the channels before

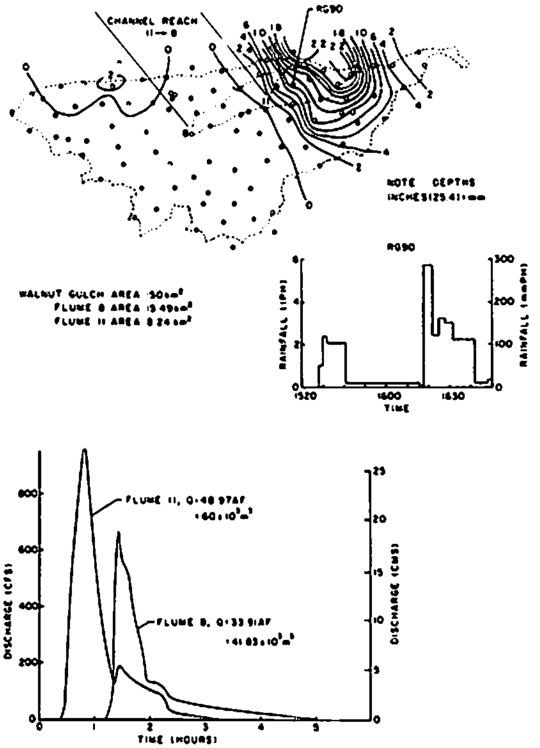

Figure 1.4a. Storm of July 30, 1966 centered on subwatershed 11. Isohyetal lines represent rainfall depths in 0.2 in increments.

Figure 1.4b. Observed hydrographs at subwatersheds 11 and 8 for the July 30, 1966 storm.

reaching the lowest station of Walnut Gulch. However, when storms occur near the outlet or when the channel alluvium is already wet, discharge at the outlet is greater.

Hydrologists unfamiliar with storm characteristics in the thunderstorm areas of the Southwest are usually surprised at the large peak discharges encountered in such streams. For example, on numerous occasions, peak discharges of 1500 cfs/mi^2 (16.3 m^3/sec/km^2) have been measured in those portions of the experimental area where a particularly intense thunderstorm was centered. Because of the spatial variability of the precipitation (leading to partial area runoff), and because of transmission loss, peak discharge per unit area decreases with increasing drainage area.

As with peak discharge, water yield generally decreases with increasing drainage area (Figure 1.5). By contrast, in more humid areas, water yield per unit area may increase with increasing drainage areas for example, Coshocton, Ohio in Figure 1.5. In other regions (Riesel, Texas), the water yield appears to be independent of drainage area.

The hydrologic balance of a watershed such as Walnut Gulch includes a rather large component for transmission losses (Figure 1.6). In fact, the hydrologic balance of Walnut Gulch contains almost 15 percent of the total water input (precipitation) as transmission losses, or a total of 6.7×10^6 m^3 for this 150 km^2 basin.

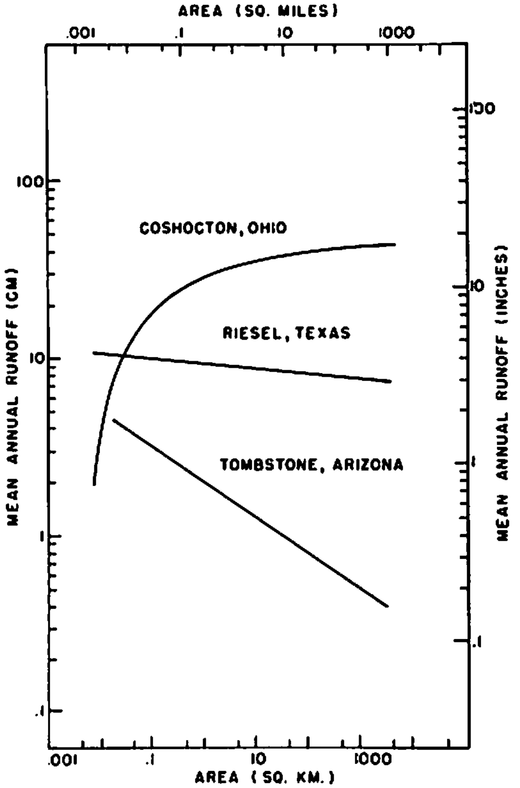

Figure 1.5. Mean annual runoff versus size of drainage area for several vicinities (Glymph and Holtan, 1969).

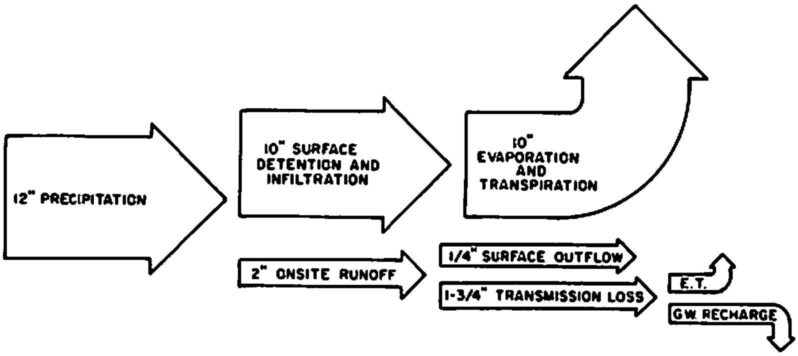

Figure 1.6. Water balance of Walnut Gulch Watershed (Renard, 1970) (1 in = 25.4 mm).

OTHER CHARACTERISTICS OF DRY REGIONS

Arid and semi-arid areas are characterized by moisture deficiencies, but more importantly, the potential for evapotranspiration is much greater than the annual or seasonal precipitation. For example, in southeastern Arizona, pan evaporation of more than 100 inches (2.54 m) is about 7 to 8 times the annual rainfall, enabling only vegetation capable of using the limited soil moisture rapidly and efficiently to grow.

In most dry regions, the watershed vegetation is composed of mixtures of plant communities (grasses, brush, forbs, cacti). Because of limited moisture, the percentage of the total land area covered by foliage of live plants is generally very low (on Walnut Gulch, for example, generally less than 10 percent, and often as low as 2 percent). Many of the bare areas between plants contain roots which affect the soil moisture beneath and between plants, and in turn, contribute to the soil structure-erosion problem. Most warm-season grasses are classified as C_4 plants, which are more efficient water users than the C_3 brush plants (most grass plants use about ⅓ the water of a brush plant per equal amount of biomass product). Thus, in soil moisture modeling, which is essential for runoff prediction, not only must the plant density be considered, but also the composition of the plants using the soil moisture.

PHYSIOGRAPHIC AND SOIL CONDITIONS

In most dry regions of the southwestern U.S., the topography is dominated by rolling hills or outwash from major mountain systems. Generally, land gradients are steep; slopes of over 50 percent are common.

Soils formations in most dry regions reflect the absence of moisture. In fact, because of the steep gradients, there is often an absence of an appreciable A horizon. A soil morphologist accustomed to conditions in more humid areas might be inclined to state that the western soils (except those of major irrigated valleys) are often really only partially weathered geologic material deposited as outwash from mountain systems.

The rate and amount of infiltration in dry-regions are often low. Low infiltration amounts are due to the short duration of the thunderstorms, shallow soil depth which limits the soil reservoir, the presence of impervious layers like caliche (Figure 1.7), and/or the presence of impeding layers at the soil surface due to such biological activity as algal crusts or cryptogams.

Erosion from dry regions is more of a problem than is generally thought. The amount of eroded material passing a given point on a stream system is known as sediment yield. In the sparsely vegetated areas of mixed brush-grass cover, where thunderstorms dominate and overland flow (Hortonian flow) is common, the sediment yield may well be at the maximum reported by Langbein and Schumm (1958) (Figure 1.8). The figure illustrates the importance of erosion/sedimentation processes in dry regions. Furthermore, these high sediment yield values help to explain the presence of shallow soil profiles, and often account for the absence of an A horizon. The most desirable type of soil, containing organic matter and nutrients, is often non-existent, because erosion removes it as fast as soil is developed from the parent geologic material. Erosion also explains the so-called erosion pavements (coarse material > 10 mm) dominating the soil surface in many sparsely vegetated areas (Figure 1.9).

In many larger streams, a large alluvial supply, high stream gradients (resulting in extraordinary velocities), and high peak runoff per unit area create large sediment yields. Two contrasting morphologic tendencies are apparent in an ephemeral stream channel: the channel profile tends (1) to be convex due to transmission losses in the normally dry channel alluvium, and (2) to be concave due to more flow downstream because of tributary inflow. Thus, the stream behavior is often difficult to predict. Sediment transport varies in ephemeral as well as perennial streams; in addition, the temporal and spatial variability in precipitation (where thunderstorms dominate runoff), combined with transmission losses, further complicate

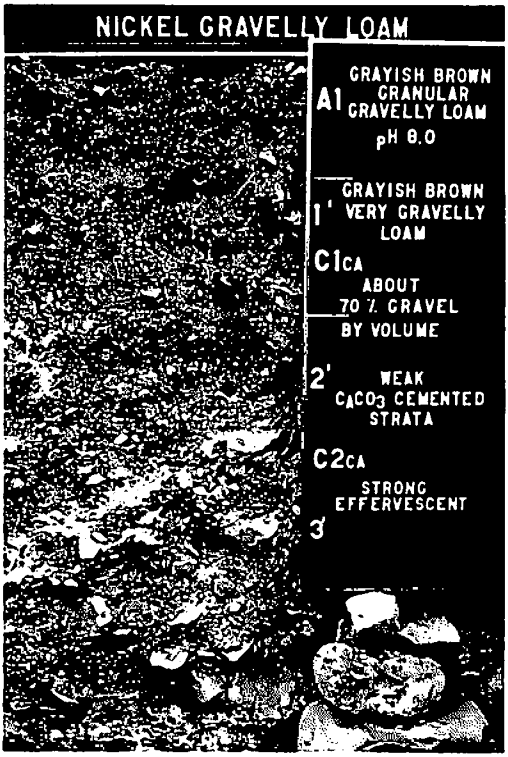

Figure 1.7. A typical soil profile in the semi-arid areas of southeastern Arizona. The profile, which is often 70 percent gravel by volume, generally has a caliche layer at depths up to 1 m, which restricts moisture movement and root development.

the prediction of stream behavior. On most of the larger channels of Walnut Gulch, the channel profile is nearly constant, varying only slightly from the 1 percent mean value. Thus, detailed modeling of water yield, sediment yield and the transport of chemical pollutants from dry land watersheds is complex.

However, Renard and Laursen (1975) have developed a conceptual model to describe ephemeral stream phenomena mentioned above. It includes a stochastic runoff model (Diskin and Lane, 1976; Lane and Renard, 1972), the Manning equation, and the Laursen (1958) sediment transport

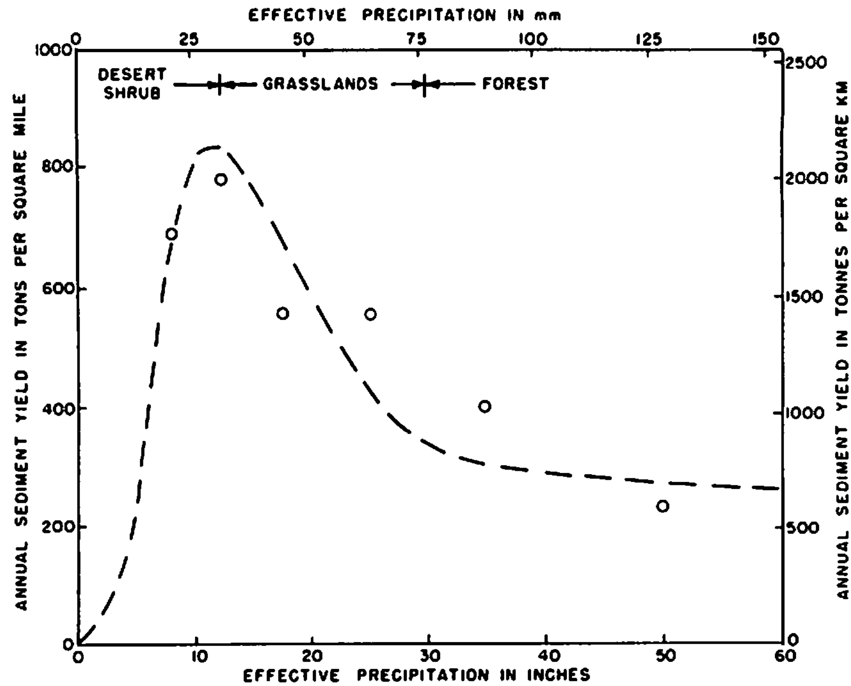

Figure 1.8. Effect of rainfall variation on sediment yield determined from records at sediment sampling stations (modified from Langbein and Schumm, 1958).

relation. The model was used to simulate the relationship between average runoff, sediment yield and drainage area (Figure 1.10). As expected with the large transmission losses, the model predicts decreasing sediment yield with increasing watershed area. To illustrate the sensitivity of the model to changing runoff, the bed material size was kept constant, and the generated runoff events increased and decreased for a 226-ha (560-ac) watershed (Figure 1.10). The variability in sediment yield corresponding to the runoff variability produced was appreciable, and larger than the runoff variability. To further illustrate the model's sensitivity, the mean grain size was altered in the model to reflect observed sediment-size distribution changes in the prototype channel. The resulting sediment yield variability is shown and labeled "range" for a 9,510-ha (23,500-ac) drainage area in the lower portion of the figure. Under prototypical conditions, the sediment transport probably adjusts in some selective process with particle

Figure 1.9. The erosion pavement in this photograph is the residual coarse material following erosion of the fine fractions from soil profile such as that in Figure 7.

shear changes associated with runoff variability. The bed composition at any time, therefore, responds to the rate at which material is being supplied to the channel from sediment sources during various hydrologic events and the rate at which material is being removed from a stream reach.

RANCHING ECONOMICS AND LAND MANAGEMENT

In the dry regions of the western United States, economics of the ranching industry are such that land management and conservation efforts requiring capital expenditures are often too costly to be undertaken. Similarly, because of the expense, the use of agricultural chemicals, such as nutrients for forage production, herbicides for brush control, and insecticides for insect control are generally minimal. Thus, nonpoint chemical pollution is generally not a problem in dry areas, although geologic weathering and natural chemical cycling does occur. There are, however,

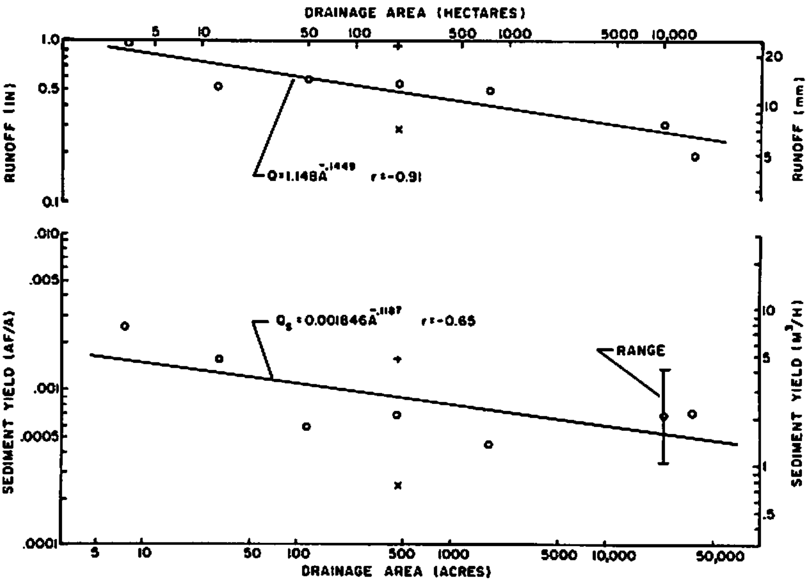

Figure 1.10. Average annual runoff and sediment yield as functions of drainage area for watersheds in southeastern Arizona based on Walnut Gulch simulation data. Equations are for English units (Renard, 1977).

frequent problems with biological contamination of streams and water impoundments.

The chemical aspects of water quality from rangelands have been investigated on Walnut Gulch by sampling at the watershed outlet and from three small interior subwatersheds with varied soils, vegetation, and land use. Schreiber and Renard (1978) observed high early-season nitrate concentrations (as high as 1 ppm) in runoff, which they felt reflected microbial activity in the soil and low plant uptake (plants still dormant). Phosphate relationships were different from those of nitrate, with each area contributing a relatively constant amount per event (one disturbed area had a consistently higher P concentration). The sum of the cations from all areas was relatively low (1 to 1.5 meq/l or milliequivalent per liter) with the highest values from the largest heterogenous area. The chemical constituents examined and reported in this work were within acceptable ranges for most uses, assuming prior removal of sediment found to be excessive in all water supplies.

Stephenson and Street (1978) found that typical rangeland cattle operations, such as are encountered in southwestern Idaho, will probably result in coliform bacterial pollution along various reaches of streams draining rangeland; however, these bacterial concentrations will vary according to the number of cattle and their access to streams, as well as according to physical and hydrologic characteristics of the flow regime and to climatic conditions. Continuous monitoring of streams under these conditions will probably show fecal coliform counts frequently in excess of water quality standards. This is even more likely for runoff samples taken in pastures used during winter months for feeding operations.

Stephenson and Street (1978) also reported that runoff from rainstorms increased both total and fecal coliform concentrations. The increase was observed on streams draining from summer grazing ranges with limited management and in streams adjacent to winter pastures; runoff from snowmelt had little effect. Total coliform counts varied more with change in streamflow than did fecal coliform counts. In fenced summer range allotments under deferred grazing management, the effects were the same, except that bacterial counts were not as high or persistent. The decrease in bacterial concentrations at several downstream sampling sites indicated that certain stream segments were self-purifying. The presence or absence of livestock along the streams overshadow any effect variations in chemical concentration of the water might have on bacterial concentrations.

In an extension of the earlier work, Stephenson and Rychert (1982) suggested that the elevated fecal coliform indicator counts observed in streams result primarily from a suspension of stream bottom sediment and organic matter, rather than from sources extraneous to the stream at the time of increased runoff. They suggest that the organic matter content of the sediment may have a critical influence on the survival and/or multiplication of the bacteria. Their results show *Escherichia coli* concentrations of bottom sediments to be from 2 to 760 times greater than from the overlying water. *Escherichia coli* concentrations of bottom sediment were found to be resuspended following disturbance simulation and a rainstorm event, contributing to pollution of the overlying waters. They suggested that microbial analysis of bottom sediments should be done as a part of any water-quality evaluation for rangeland streams. Depending upon the ultimate use of the small impoundment being evaluated, microbial analysis may be critical to the development plan.

Rangeland managers are frequently concerned with revegetation on deteriorated rangelands (Cox et al., 1983). Root plowing (pulling a knife beneath the soil surface to sever roots of woody plants) and reseeding were performed on a 42.5 ha (105-ac) subwatershed in Walnut Gulch in 1970 to measure the consequence of such a program on runoff and erosion/sediment yield. Although there was a period of several years following the treatment (Simanton, Osborn and Renard, 1977) where the runoff, as a function of precipitation, was ill-defined, the post-treatment and pre-treatment runoff characteristics are very similar. The sediment yield, following treatment (grass dominated), has been only about ½ of that for the pre-treatment (brush-dominated) area. However, the cattle grazing capacity of the improved condition, although about 10 times that for the brush, was still not sufficient to justify the treatment cost.

Although there have been numerous evaluations of grazing practice effects on infiltration (see Gifford and Hawkins, 1979), the results have often been inconclusive, or, at best, weakly defined regarding grazing and infiltration consequences. Thus, although research on range renovation efforts continues, currently the most viable alternative for range improvement/conservation is some system of grazing rotation. The method most prominent in the literature is the Savory system (Heitschmidt and Walker, 1983) developed in Africa. Like many other grazing efforts, this system needs to be evaluated in terms of effect on the soil-plant environment.

WATER RESOURCE MODELING FOR SMALL IMPOUNDMENTS

The development of water resource models has closely paralleled the development of digital computers. As recently as four decades ago, design work in hydrology was restricted to the use of nomographs and simple empirical equations. The current trend is toward elaborate digital computer programs capable of describing phenomena that are difficult to measure under field conditions.

Although many have recently written on modeling water resource systems (Branson et al., 1981; Haan, Johnson and Brakensiek, 1982; Dooge, 1973; Singh, 1982a, b, c, d), a brief overview of some of the techniques involved is in order. Figure 1.11 illustrates one way of conceptually classifying water resource models. In many instances, when a process (such as rainfall-runoff) is so complicated as to be ill-defined or when the variability involved is extreme, the modeler may resort to a stochastic model (shown diagramatically as a die). This type of model follows probabilistic laws, while the process develops sequentially in time, unlike purely probabilistic models that are not time-dependent. Mystery models (also called magic or black box models) utilize a given input to produce an output through a mathematical transformation or function (the function may or may not have physical significance). An analytical component model (often called causal model) uses the physics of the process(es) to produce an output. Although causal models are often the most expensive to develop and operate in a prediction mode (more algorithms involved, greater computer cost, and

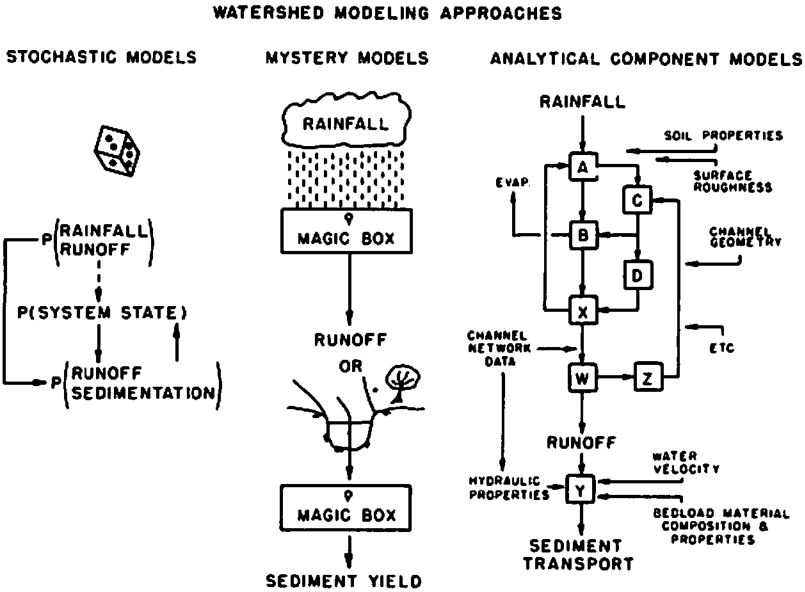

Figure 1.11. Approaches to sediment modeling from watersheds (Renard, 1977).

often more field data required), they generally provide more reliable results, especially when management alternatives are involved. In actual practice, a model for a specific problem may, in fact, include combinations of the three classifications.

A model developed recently by Agricultural Research Service (ARS) engineers and scientists for use on rangelands should be of special merit for a conference on "Small Water Impoundments in Dry Regions." The model, called SPUR (*S*imulation of *P*roduction and *U*tilization of *R*angelands) consists of five basic components: (1) climate, (2) hydrology, (3) plant, (4) animal, and (5) economics. Input data requirements and model outputs are described in a U.S. Department of Agriculture pubication edited by Wight (1983).

SPUR is a physically based rangeland simulation model designed to aid both resource managers and researchers. It can be applied to a wide range of conditions with a minimum of "tuning" or "fitting." It provides a basis for management decisions by predicting herbage yields, livestock production, runoff, and erosion. As a research tool, it helps identify research needs, improves the organization and transfer of information, and provides a focus for ARS range research programs. Individual model components for the

SPUR model were developed by specialists in each area. The individual components were merged under the leadership of the project coordinator, Dr. Ross Wight, in Boise, Idaho. A diagram of the model is given in Figure 1.12. Further development, testing, and documentation of the model are underway. The reader is referred to the SPUR manuscript for further details (Wight, 1983).

SUMMARY

Water resources in dry regions are, by definition, in short supply; thus, competition for them is often dramatic. We must learn to use these limited resources wisely.

The hydrology/water resources of the dry regions of the southwestern United States are characterized by:

(1) extreme temporal and spatial variability;
(2) ephemeral runoff, which often results in large infiltration losses in the channel alluvium;
(3) sparse vegetation and high potential evapotranspiration;
(4) low infiltration in shallow soils with high erosion and sediment yields;
(5) minimal chemical water pollution and minimal capital for conservation/range rehabilitation efforts.

Mathematical modeling offers an objective way to analyze the hetero-

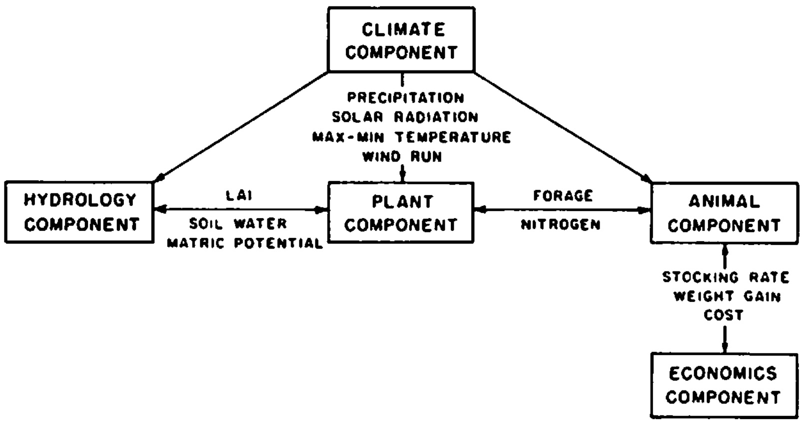

Figure 1.12. Interaction between various components of SPUR (Wight, 1983).

geneous conditions encountered in most dry regions. To better utilize the water resources of small impoundments, the designer must be able to assess the impact of various land use/management alternatives upon the water yield and water quality of the inflow to an impoundment. Sediment is the major water quality consideration for an impoundment, because unless there are major irrigated areas in the watershed contributing to the impoundments, only geologic chemical transport levels are likely to be encountered, and in general, these are low.

The SPUR (*S*imulation of *P*roduction and *U*tilization of *R*angelands) model, recently developed in the Agricultural Research Service of USDA, has been suggested as one model for predicting the inflow to a small impoundment.

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