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Past, Present and Future Water Resources Research in Arid and Semiarid Areas of the Southwestern United States

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1 INTRODUCTION

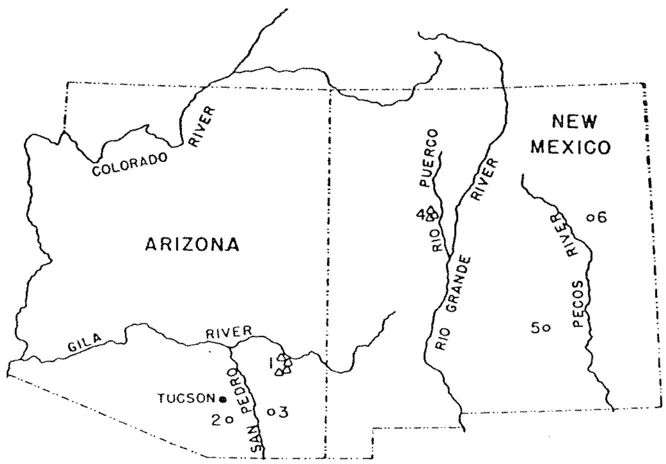
Rapid strides have been made in water resources research in the past several decades, especially in semiarid/arid areas. Much of this progress has been connected with the rapid developments in computer technology, which have enabled the handling and analysis of the large mass of data required to solve water resource problems. Analytic capabilities have progressed, in fact, to the point where we have fallen behind in our ability to obtain field verification for the rather complicated models, which are being used to define various processes in the hydrologic cycle. Thus, future endeavors will necessarily involve improvements in our field experimentation.

Today, despite our technological advances we are still collecting our water resource data with mechanical equipment developed in the late 1930's. Spin-offs from the space technology are only now becoming common in water resource technology. For example, low cost solar panels provide the energy so often needed by the more sophisticated electronic transducers, which provide the computer compatible digital data needed for model development and verification. A common time scale has been an especially important problem in our work on the Walnut Gulch Experimental Watershed in Southeastern Arizona. We have over 100 individual time-pieces at this site, and attempts to resolve timing differences within short-duration thunderstorms is totally impractical with the individual time bases. However, improved electronic technology is making it feasible to have a central data collection point with inputs from all hydrologic recorders.

In the following sections, several major elements of the hydrologic cycle are discussed. The past, present, and future efforts in each of these sections are illustrated primarily in terms of the work of the Southwest Watershed Research Center Staff.

2 PRECIPITATION

An appreciable part of the progress toward understanding the hydrologic response in arid/semiarid watersheds in the southwestern United States has involved definition of the thunderstorms which dominate the area. The two precipitation networks maintained by the staff of the Southwest Watershed Research Center, on Walnut Gulch and Alamogordo Creek, have been immeasurably valuable in this respect. Figure 1 shows locations of experimental areas; Figures 2 and 3 illustrate storm and annual totals on Walnut Gulch and Alamogordo Creek. The precipitation is variable not only within an individual storm but also on an annual basis, with the minimum annual precipitation depth recorded on the network being generally one-half the maximum value. Although not the case in the 1967 example shown, this generalization is true of many years' data. Thus, the 95 recording raingages on Walnut Gulch and the 65 pages on Alamogordo Creek provide good estimates of the total precipitation on both individual storm and annual bases. Over 1400 gages on the 150 km^2 Walnut Gulch Watershed would be needed to provide a simple correlation coefficient of 0.9 between adjacent gages, a network requiring access roads which would appreciably affect the hydrologic response of the area (Osborn, Lane, and Hundley, 1972).



1. SAFFORD, ARIZONA (ARS LOC. No. 45.000)
2. SANTA RITA nr TUCSON, ARIZONA (ARS LOC. No. 76.000)
3. WALNUT GULCH nr TOMBSTONE, ARIZONA (ARS LOC. No 63.000)
4. ALBUQUERQUE, NEW MEXICO (ARS LOC. No. 47.000)
5. FORT STANTON, NEW MEXICO (ARS LOC. No. 73.000)
6. ALAMOGORDO CREEK nr SANTA ROSA, NEW MEXICO (ARS LOC. No. 64.000)

o ACTIVE LOCATIONS
Δ INACTIVE LOCATIONS

Figure 1 Location of ARS Experimental Watersheds in Arizona and New Mexico, U.S.A.

Three elements are needed for an analytic dexcription of thunderstorm rainfall: (1) distribution of rainfall events, (2) distribution of rainfall depths at a point, and (3) areal distribution patterns. Because of the complexity and incomplete knowledge of the physical basis of precipitation processes, hydrologists generally use probabilistic descriptions of a local variable to predict the statistical properties of future precipitation for input to hydrologic models. The work at the

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LIST OF ERRATA

PAGE	COL.	PARA*	LINE	DELETE	INSERT
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2	2	(middle)	7	assumer	assumed
2	2	partial*	9	37I	37^{o}
3	2	1	1	extention	extension
7	1	(middle)	19	aliminate	eliminate
11	1	watershed*	3	indicated	indicates
15	1	Although*	Sub para b	levles	levels
15	2	While*	11	responsiblity	responsible
15	2	Much*	2	wastern	western
16	1	(last)	(last)	$S = C_1$	$S \pm C_1$
16	2	(middle)	9	surbulent	turbulent
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FOOTNOTES

* Asterisk indicates first word of paragraph containing error.

Southwest Watershed Research Center is no exception to this practice.

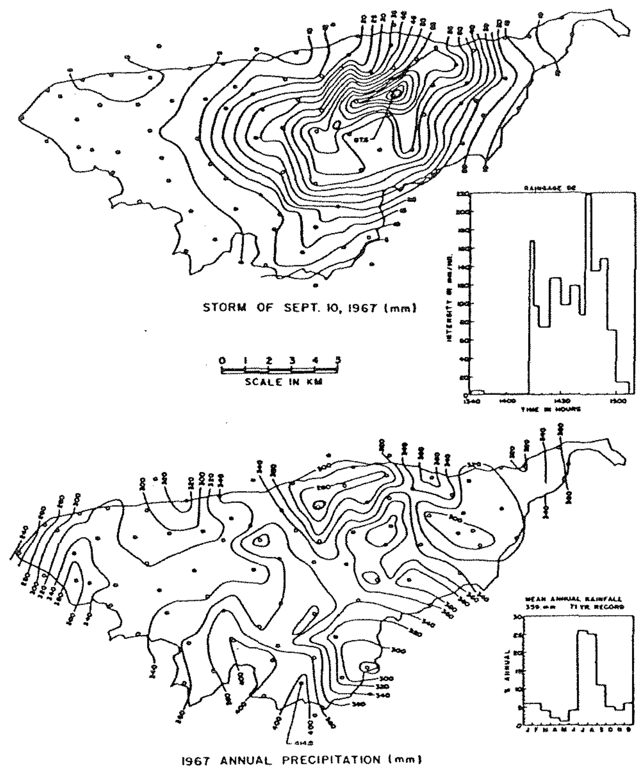

Figure 2 Isohyetal map of the Sept. 10, 1967 storm on the Walnut Gulch Experimental Watershed and the 1967 annual precipitation

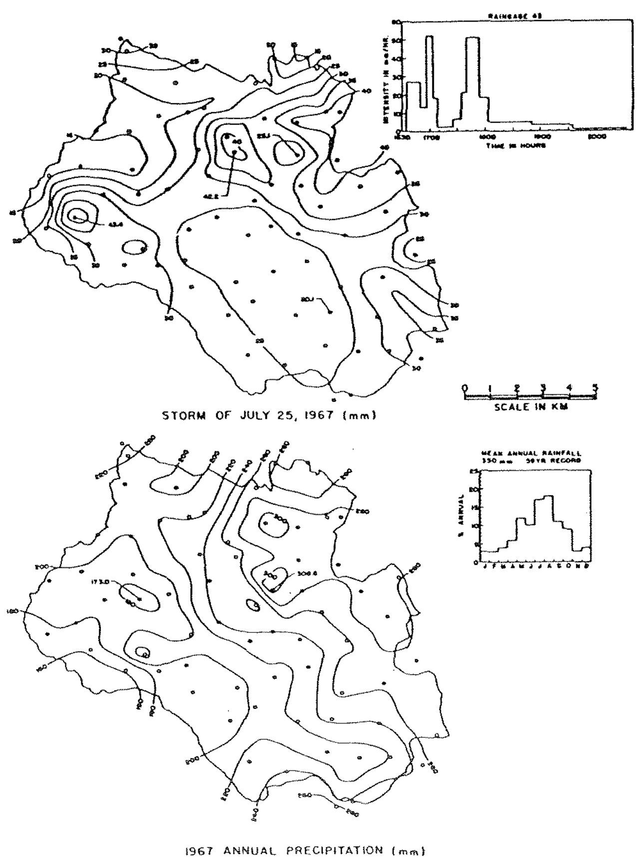

Figure 3 Isohyetal map of the July 25, 1967 storm on the Alamogordo Creek Experimental Watershed, and the 1967 annual totals

(a) Distribution of Rainfall Events.

Precipitation in the southwestern United States occurs with varying characteristics depending upon its moisture source. The annual rainfall in the area is distributed between two seasons. The pronounced summer peak results from moisture originating in the Gulk of Mexico or from tropical storms off Baja, California (Sellers, 1960; Osborn and Davis, 1977). These summer storms are characterized by high-intensity, short-duration, limited areal extent, air-mass thunderstorms, or slow-moving cold fronts. Winter storms result from Pacific Ocean storm systems moving inland over several major mountain ranges before reaching Arizona and New Mexico, where they produce low-intensity, long-duration, large areal-extent storms. These winter storms often produce snow at higher elevations, but seldom produce appreciable runoff from the intermountain rangeland areas.

A simulation flow chart used to describe the occurrence of summer storms is shown in Figure 4. National Weather Service weather maps and climatological data from point locations were used to determine the frequency of occurrence for each of the six possible outcomes from the flow diagram. Osborn and Davis (1977) indicated that although there is little chance of a frontal southwest thunderstorm occurring on Alamogordo Creek, there is a good chance of frontal activity. However, for Walnut Gulch there is little chance of frontal activity but a good chance of moisture from the southwest.

Multiple regression analysis was used to correlate physical characteristics (longitude, latitude, and elevation) with precipitation frequency patterns in Arizona and New Mexico. The results (mean correlation coefficient of 0.76) indicated a significant correlation (at the 5% level) if the variables are assumer to be normally distributed.

Partial results of such work indicate that the probability of occurrence of southwest rainfall on day n is:

$$P_{SW}(n) = 0.08 + 0.00001h + 0.01(31-\ell_a) - 0.01(114-\ell_o) \qquad (1)$$

where

$P_{SW}(n) \geq 0$

h = elevation in feet

ℓ_o = longitude in degrees ($103^o < \ell_o < 114^o$)

ℓ_a = latitude in degrees ($31^o < \ell_a < 37^I$)

Once SW rainfall occurs, there is a much greater chance of rainfall the next day. This persistence was observed to be highly correlated to elevation. The chance of rain on day n+1 is:

$$P_{SW}(n+1) = P_{SW}(n) \frac{h}{1000} \qquad (2)$$

where $P_{SW}(n+1) \leq 0.65$

They also showed that the average number of events in a season (N) could be expressed by the relation

$$E(N) = 333 + 0.00467h - 3.11\ \ell_a - 1.97\ \ell_o \qquad (3)$$

with $R^2 = 0.98$ and SEE = 1.90

This equation applies to the stations in Arizona, except those in the Little Colorado River Basin (northeast portion of the State). Comparison

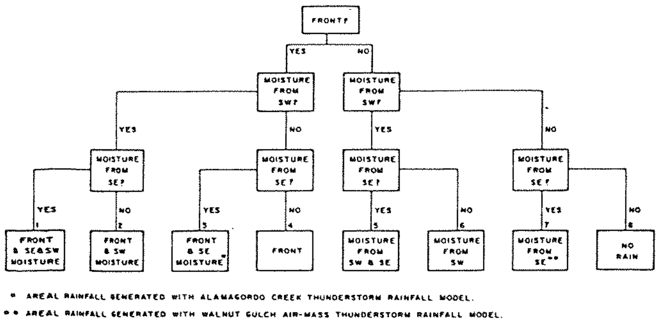

Figure 4 A particular scheme for the occurrence phase of a summer rainfall model for Arizona and New Mexico (Osborn and Davis, 1977)

of Eq. 3 with one developed by Duckstein, Fogel, and Thames (1973) for records in the Catalina Mountains near Tucson (after adjusting for using a shorter record) showed close agreement. Thus, the number of seasonal thunderstorm occurrences from Eq. 3 can be tested against results within the rainfall occurrence model (for example from Eq. 1 and others like it for each storm type). Development of this empirical storm occurrence model is continuing.

In a parallel analysis, Smith and Schreiber (1973), like other investigators (Weiss, 1964; Hershfield, 1970), showed that a Markov chain better described air-mass thunderstorm rainfall than did a Bernoulli model (Fig. 5). They showed that in addition to describing the beginning of the summer "monsoon" season, the Markov model gave a better fit to the cumulative distribution of wet days per season for raingages in southeastern Arizona. The markov model with segmented non-homogeneity was obtained by partitioning the wet and dry probabilities during the season, which improved the fit to the historical data as compared with using the average wet and dry probability throughout the season.

(b) Distribution of Rainfall Depths

Much work has been done to describe the rainfall depths measured at a sampling point (raingage). Renard and Brakensiek (1976) reported at least 14 different depth simulation techniques, several of which were developed for the thunderstorm conditions encountered in the southwestern U.S.

The fact that hydrologic variables are not normally distributed, is no surprise to most hydrologists. Reich (1969) stated:

> Nature has no back room boy dictating that flood series (or precipitation depths) should follow a particular law... Rather let us visualize...mathematical functions for what they are-merely a continuation of man's efforts at curve fitting.

Recent developments with mixed distributions have been made possible by digital computers eliminating the laborious calculations necessary for accurate solution. The application of mixed distributions will undoubtedly become more common because of the greater ease of describing precipitation resulting from different types of storms (like thunderstorms and snowfall).

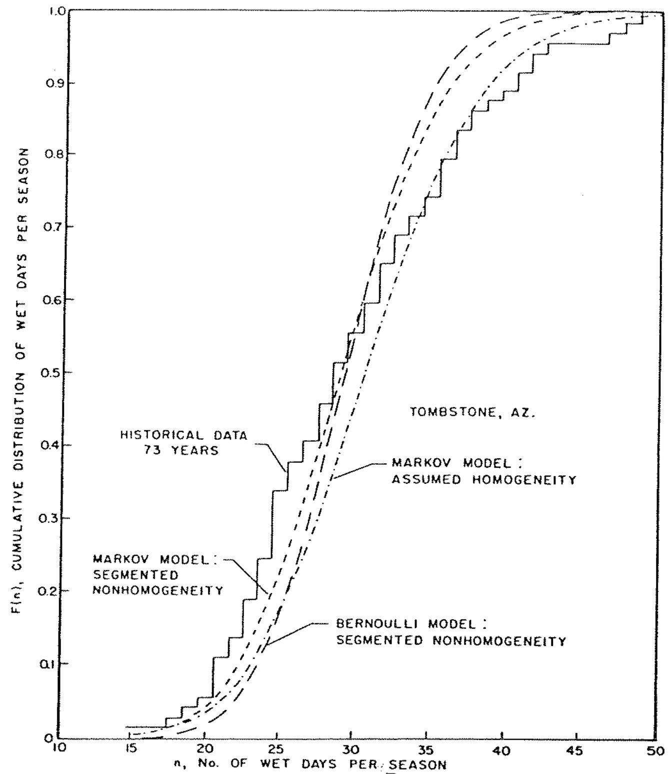

Figure 5 Predicted and observed cumulative distribution of the number of wet days per season at Tombstone, Arizona (Smith and Schreiber, 1973)

As an extention of their work on thunderstorm occurrence, Smith and Schreiber (1974) showed that the seasonal rainfall depth (X) for three gages in southeastern Arizona was describable with a compound or mixed exponential distribution of the form

$$P(X \geq x) = \alpha e^{-\lambda_1 x} + (1-\alpha)e^{-\lambda_2 x} \qquad (4)$$

where α, λ_1 and λ_2 are parameters. The resulting distributions are illustrated in Figure 6.

Each cumulative frequency distribution curve shown in Figure 6 is approximated by two straight line segments joined at some inflection point (x_c). The skew of the density function increases the undertainty of the sample probabilities as rainfall depth increases.

(c) Thunderstorm Depth-Area Patterns

Depth-area relationships for the thunderstorms of the southwestern U. S. can be evaluated with large, dense raingage networks, like those maintained by the Southwest Watershed Research Center. Smith (1974) investigated the areal properties of air-mass thunderstorms and described the storm pattern with a monotonic dimensionless depth-area relationship (Fig. 7). He also expressed the depth-area relationships proposed by three other investigators in dimensionless form, as shown in Figure 7. Assuming the storms are occurring randomly, uniformly distributed in space, the rainfall population at any point may be considered to be composed of samples taken with equal likelihood from any point within the associated storm. Using statistics, which he developed from this assumption, he developed a general relation between normalized storm isohyetal pattern, center depth probability, and point rainfall probability. This general relationship and the dimensionless depth-area relationship could then be

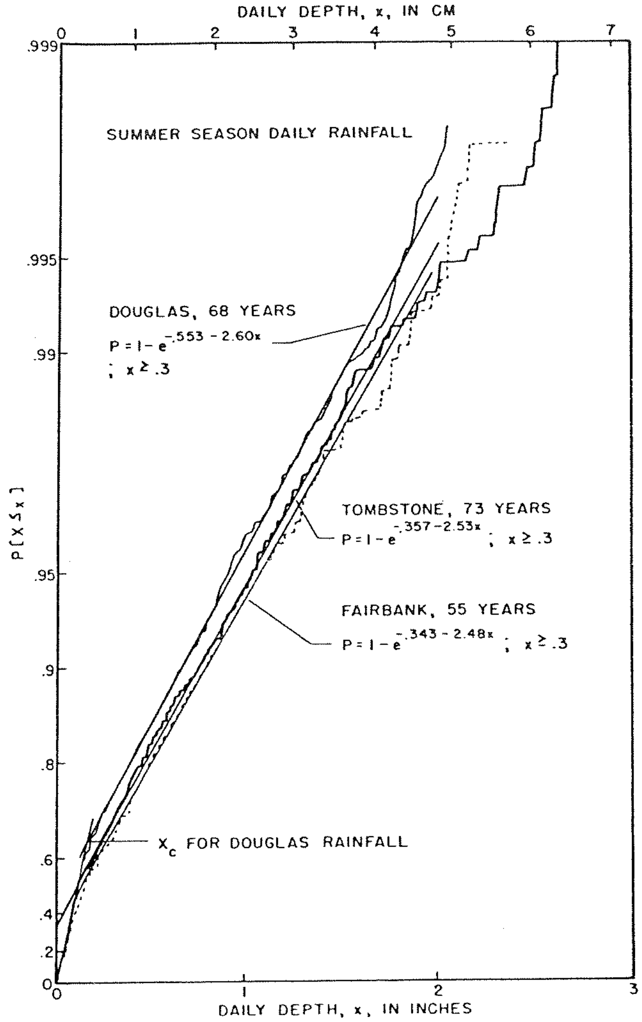

Figure 6 Distributions of summer season daily rainfall depths for three sampling stations in southeastern Arizona (Smith and Schreiber, 1974)

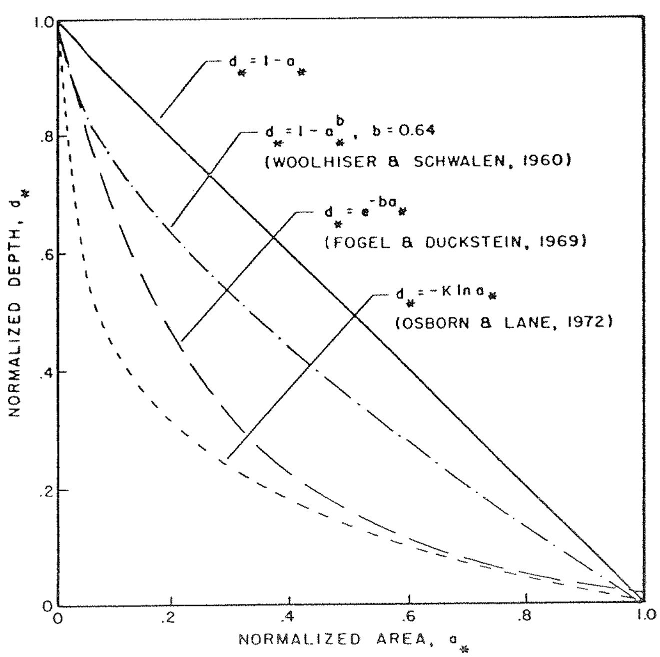

Figure 7 Normalized depth-area relations for air-mass thunderstorms proposed by three investigators (Smith, 1974)

used to simulate the point rainfall depth. Smith's depth-area relationship compared more favorably with the historical record at the Tombstone raingage than did those of other investigators (Fig. 8). Using these developments, it is possible to postulate a depth-area relationship and test it against a historical record.

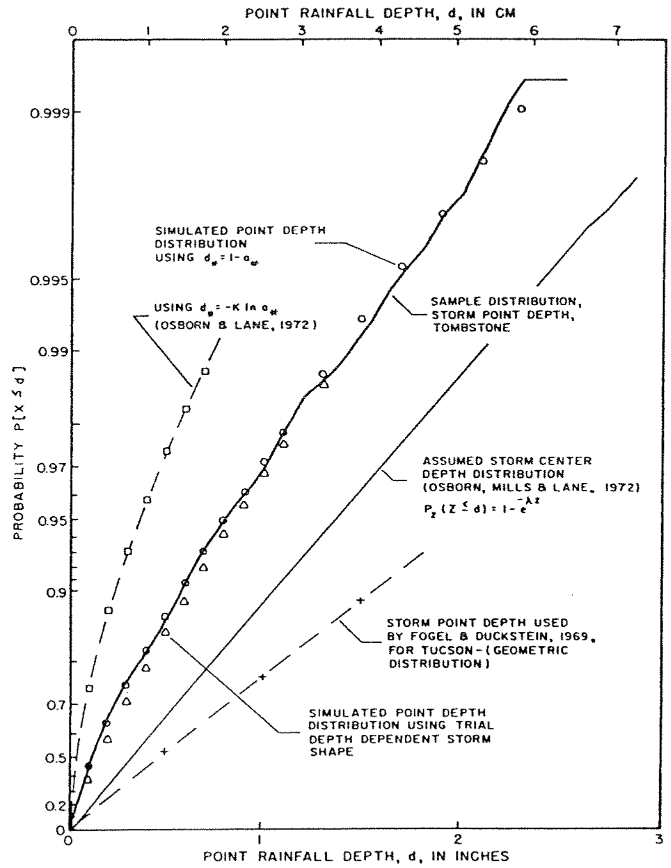

Figure 8 Storm center-depth distribution and several point-depth distributions, including measured data for Tombstone, Arizona, and simulated distributions (Smith, 1974)

To illustrate the differences among thunderstorm depth-area relationships encountered in various parts of the U.S., Osborn and Renard (1977) developed Figure 9 for an assumed storm center depth of 50.8mm (2 in). The storms covering the least area are pure air-mass thunderstorms, whereas the wide-area storms are those encountered in the mid-continent area of the U.S. In other areas where summer thunderstorms are often associated with frontal activity, the distribution will undoubtedly be somewhere between the two extremes.

(d) Future Precipitation Efforts

Several problems have hampered progress in precipitation quantification in basin and range provinces as well as in mountainous areas. Generally, long term climatological stations have been established in valleys where towns are located Such locations do not afford the opportunity to

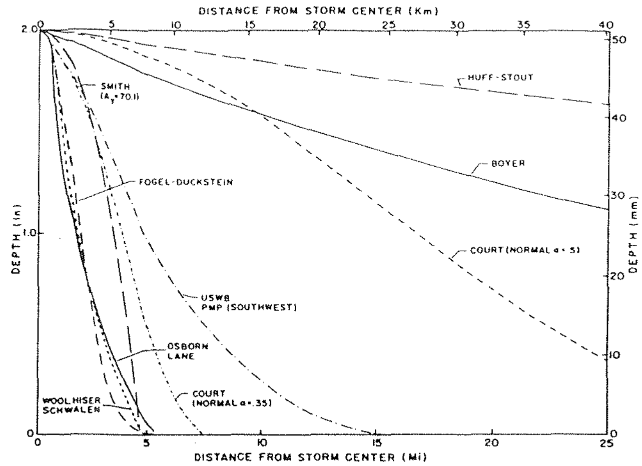

Figure 9 Thunderstorm distribution patterns, symmetrical around storm center (Osborn and Renard, 1977)

sample orographic precipitation effects (the valleys often have not only less rainfall, but fewer events). Obviously, the 1400 raingage network for a 150 km^2 area, as discussed by Osborn, H.B., Lane, L.J., and Hundley, J.F. (1972) is not realistic. What is really needed are some portable precipitation networks (with sufficient gages to define the thunderstorms), which can be moved into an area for a short period, to quantify the distributions of storm occurrence, rainfall depth, and areal patterns before being moved to another area.

The mobile network needs to be automated so that the record from each gage location is centrally recorded in computer-compatible format. Such a system would eliminate the timing problems that perplex clock-driven-raingage networks, like those on Walnut Gulch and Alamogordo Creek. Imagine asking 100 people what time they have on their watch. There will be a large range of answers. Thus, it is difficult, if not impossible, to measure the temporal and spatial build-up and dissipation of a thunderstorm and to verify postulations about thunderstorm physics at ground level based on the timing of about 100 raingages.

Information is also needed about drop size distribution in high-intensity storms because of their importance to water quality work, and on the frequency of hail storms (although the frequency is low, they can be very damaging), which have very damaging effects on plants, animals, and man-made facilities. The conventional 8-in funnel weighing or tipping-bucket raingage does not record such an event accurately. For example, in 1961, a hail storm on Alamogordo Creek (Osborn and Reynolds, 1963) produced hail drifts that made travel impossible for over 24 hours. The weighing gages did not record the true storm amount or duration, except in a few instances where the cone was dislodged from the receiver funnel. Usually the time and rate at which the hail melted in the cone and dropped into the bucket was the only record of the storm.

Analytically, most future development will involve regionalization techniques, like those reported by Osborn, Lane, and Kagan (1974), and verification of simulations on areas other than those for which the model was developed.

3 INFILTRATION

Several Australian hydrologists have made noteworthy contributions on the topic of infiltration. Two recent ones documenting the state-of-the-art of infiltration in watersheds were the work of Fleming and Smiles (1975) and Dunin (1976). Thus I am somewhat hesitant to spend appreciable time on the topic.

Work at our Center has been in two general areas of infiltration: (1) the use of infiltration theory (equations) to compute precipitation excess in runoff simulation work, and (2) infiltration measurement and control through soil surface management.

(a) Modeling Precipitation Excess

Much progress has been made in soil physics and porous media flow for theoretically describing unsaturated soil water movement, with much of this progress due to the work in Australia. Some of this recent progress has been associated with rapid developments in digital computers which has facilitated numerical solutions of the partial differential equations. Smith (1972) described a numerical model of unsaturated, unsteady one-phase soil moisture flow to predict infiltration from rainfall to a ponded upper boundary condition. Figure 10 illustrates the graphical presentation of infiltration obtained from numerical solution of the differential equations describing unsaturated flow in porous media. The first curve represents infiltration decay from initial sudden ponding at the soil surface, while the remaining curves are identified by the uniform rainfall rate (R) at the surface. Infiltration continues at the rainfall rate until a time of ponding (t_p) when the soil potential at the surface is zero and the infiltration rate decreases with time as an exhaustion phenomenon. Using dimensionless variables for rainfall rate, infiltration rate, and time, leads to unification of the decays. The three pertinent relationships for the solution are:

$$f'_* = (1 - \alpha)\,(Q'_* - Q_{0*})^{-\alpha/(1-\alpha)} \qquad (5)$$

$$Q'_{p*} = B(r_* - 1)^{1-\beta} \qquad (6)$$

$$T_0 = D(\theta_0 - \theta_i) \qquad (7)$$

where $f'_* = f_* - 1$ and $f_* = \frac{f}{f_\infty}$

f_∞ = infiltration rate at $t = \infty$

α = exponent parameter in infiltration equation

Q'_* = dimensionless accumulated soil water in excess of $(f_{\infty *} t_*)$

Q_{0*} = dimensionless reference volume

B = parameter in functional relation between Q_{p*} and r_*

$Q_{p*} = Q_*$ at $t = t_p{}^* (r_* - 1)$

$r_* = R/f_\infty$ = dimensionless rainfall rate

T_0 = normalizing time

β = exponent parameter, in functional relation between Q'_{p*} and r_*

θ = percent water content by volume, L^3/L^3

θ_i = percent initial water content

$\theta_0 = \theta$ at $\psi = 0$

D = parameter for normalizing time $T_0 = D(\theta_0 - \theta_i)$

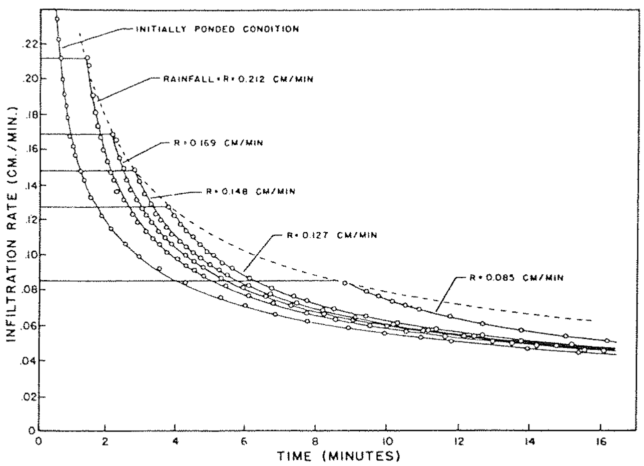

Figure 10. A family of infiltration curves for a range of precipitation rates produced by the numerical model (Smith,1972)

The loci of points (t_p,R) form a curve which Smith called the "infiltration envelope", which is similar in shape to a Kostiakov infiltration function from a ponded upper boundary condition. Under real world conditions, t_p is spatially highly variable reflecting the corresponding variability in infiltration for a given rainfall rate.

Smith and Chery (1973) showed how the several parameters of Eqs. 5, 6, and 7 in their computer Soil Equivalent Model (SEQM) can be estimated from infiltrometer records. They compared model results with measured data from a 1.83- x 3.66- m (6- x 12- ft) runoff plot, and with results from the infiltration subroutine of the watershed model (USDAHL-70) developed by Holtan and Lopez (1971). Results for one simulation are shown in Figure 11. One important point illustrated in this example is the inadequacy of integrating raingages for measuring rainfall rates for subsequent small-area runoff prediction. The precipitation record indicated that the second rainfall intensity burst was greater than the first, yet recorded runoff was lower on the second peak. Since this could occur only if infiltration rate somehow increased rather than decayed, we can conclude that differentiations of the cumulating raingage or runoff gage, or both, are not accurately assessing the rate patterns. This precipitation excess model has been used subsequently in other efforts by the Center staff.

(b) Measurement and Control

Infiltration control work in our group is being pursued as a means for controlling water movement into soils to improve forage production and to reduce erosion. Basic to our understanding of this work is an understanding of the air interface (AEI) concept (Dixon, 1975a) that *interfacial roughness and openness control the rates and routes of water infiltration by governing the flow of air and water in underlying macropore and micropore systems.* Roughness refers to the microrelief that produces depression storage, whereas openness refers to the macroporosity that is visible at the soil surface. Essential features of the work are shown in Figures 12 and 13.

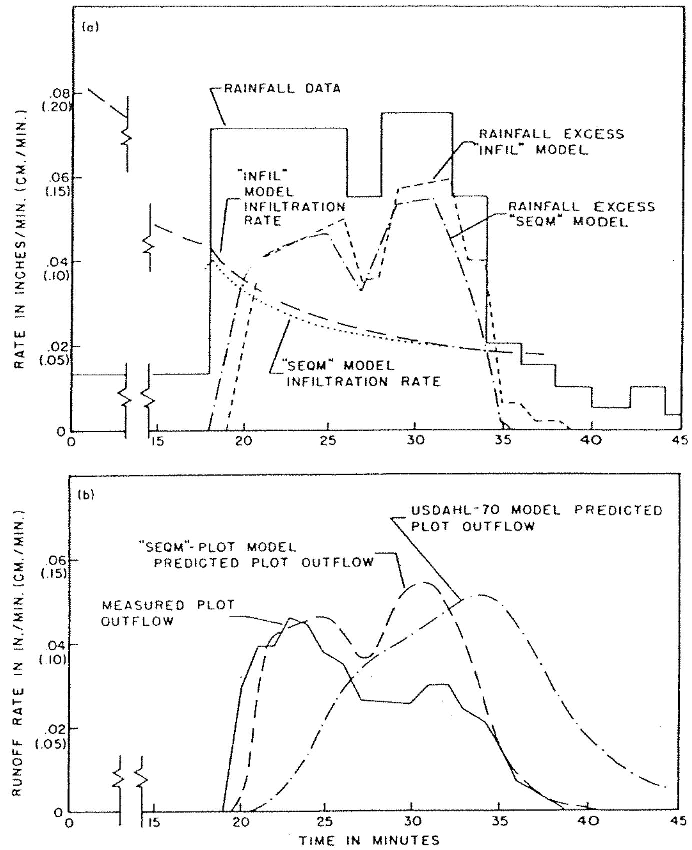

Figure 11 Measured and predicted rainfall excess and plot runoff for the Sept. 10, 1967 event on experimental plot (Smith and Chery, 1973)

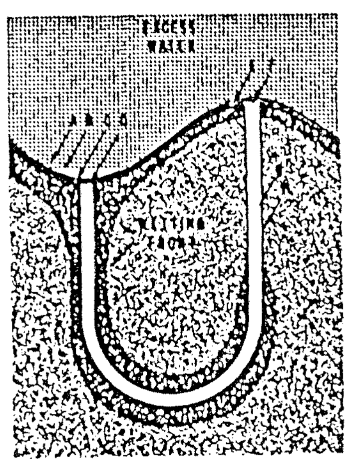

Figure 12 Soil model containing a micropore system. A - plant residue cover on air-earth interface; B - free water surface; C - microdepression in air-earth interface; D - water intake port of macropore; E - microelevation in air-earth interface; F - soil air exhause port of macropore; G - macropore space; H - macropore wall; and I - macropore space (Dixon and Peterson, 1971)

A detailed discussion of the method was given recently by Dixon (1975a). Essential characteristics of the system (Fig. 13), which may be ranked RO>RP=SO>RC=SP>SC are: air and water continuity between the air-earth interface and macropores; border area between the two pore systems wetted with high pressure water; water infiltration, percolation, and interflow rate;

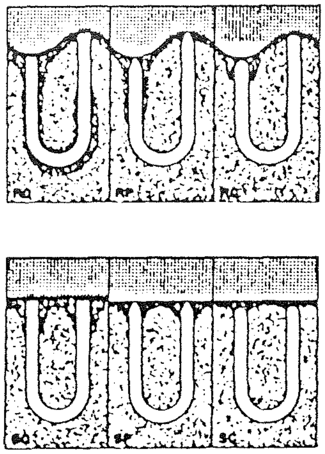

Figure 13 Air-earth interface models and associated u-shaped macropore for water infiltration into soils. Models RP and RC represent rough interfaces containing open, partly open (unstable) and closed macropores respectively; models SO, SP and SC represent smooth interfaces containing open, partly open (unstable) and closed macropores. (Dixon and Peterson, 1971)

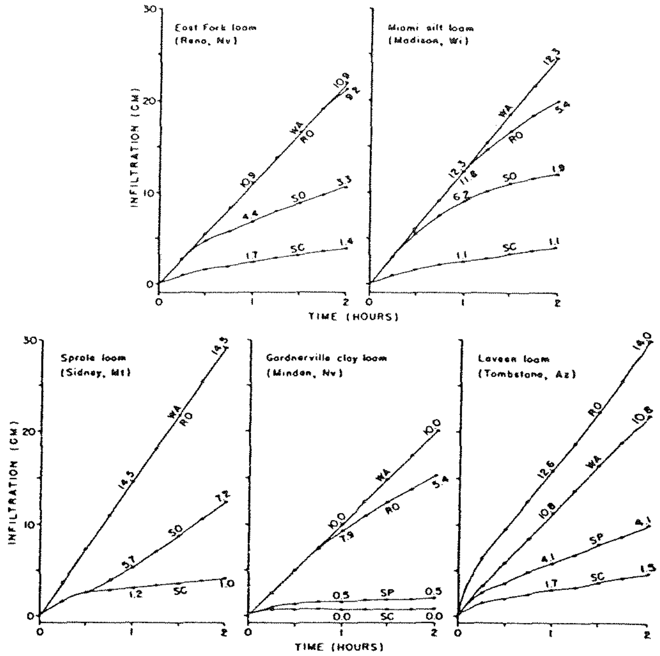

Figure 14 Sprinkled-water infiltration under imposed air-earth interfaces RO and SC and naturally occurring interface either SO or SP. The curve labeled WA gives the total water applied by the infiltrometer spray nozzle. Numbers near curves at 1- and 2-hours times denote infiltration rates (cm/hr) for these times (Dixon, 1975a)

mean vertical and horizontal hydraulic conductivity and gradient; soil-water content and pressure; air permeability of soil surface and exhaustion rate of displaced air; entrapped air pressure; and internal soil erosion.

In developing his concept, Dixon has conducted field experiments at several locations involving a wide diversity of climates, soils, and vegetation. These infiltration tests indicated that standard air-earth interfaces can be imposed to control infiltration of a given soil within a range often exceeding an order of magnitude (Fig. 14). The range widens with time after interfaces are imposed, since the infiltration capacity of the macropore rough open (RO) system increases while the capacity of the small closed (SC) system decreases (Table 1). Earthworm activity under the RO interface not only improves the surface continuity of the macropore system but also increases its extent. Cultural practices which maximize biotic activity at the soil surface create open interfaces (RO and smooth open (SO)) while practices that aliminate such biotic activity lead to closed interfaces (rough closed (RC) and SC).

Progress toward quantifying the AEI concept assumes that the infiltration role of soil surface roughness and openness is adequately represented by a single hydraulic parameter. The parameter, referred to as effective surface head (h_s), combines the effects of surface water head and soil air pressure on the performance of the U-shaped water-intake, air-exhaust circuits of the macropore system. The parameter is defined as the difference between surface water head (h_w) and soil air pressure head (h_a) and usually has a narrow range of only a few centimeters of water surrounding the reference zero (ambient atmospheric pressure). The effective surface head is commonly less than zero where a large surface area becomes saturated, like during an intense rain or during basin and border irrigation.

To quantify the effects of effective surface head required development of special closed-top infiltrometers (Dixon, 1975b). This equipment allows simulation of negative as well as positive h_s values in a narrow range around zero. Data from the closed-top infiltrometer indicated that infiltration is highly dependent on h_s (Figs 15 and 16). In these figures, the effect of the magnitude of effective surface head on cumulative infiltration is presented in the form of coefficients used in the Kostiakov equation for infiltration. The important point is that there is a marked change in the infiltration rate for the various effective surface heads for this East Fork loam soil found near Reno, Nevada.

Further refinement of the AEI concept will involve improving the method for characterizing surface roughness and openness. This task will be formidable because of the dynamic nature of the physical and biotic structure-forming processes at the AEI. Further refinement will also entail: evaluating natural effective surface heads under diverse soil surface and water source conditions; evaluating the effects of various biotic activities on soil openness (like the tremendous termite activity encountered in much of the southwestern U. S.); and developing and testing new and improved cultural practices based on the AEI concept.

(c) Future Infiltration Work

Hydrologists are repeatedly asked to estimate streamflow from precipitation data. To accomplish this, they must be able to compute precipitation excess, i.e. subtract infiltration from precipitation. In the rangelands of the southwestern U. S., the problem of computing precipitation excess is compounded not only by the precipitation variability but also by infiltration variability. A typical soil profile varies appreciable from ridgetop to the channel bottom,

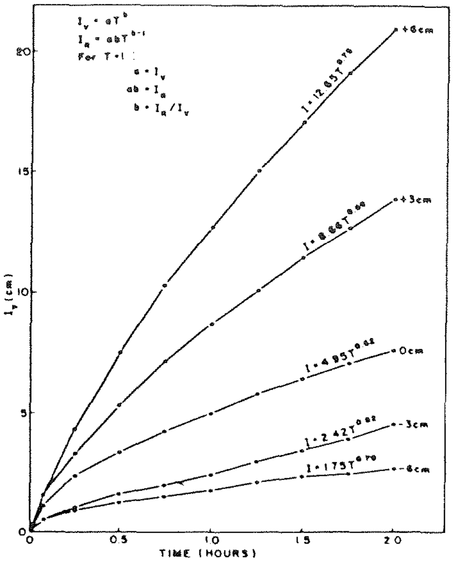

Figure 15 Infiltration volume (depth), I_v, as a function of time and effective surface head in the range -6 to +6 cm water and the equations resulting from the least square fit of Kostiakov's equation to the experimental data (Dixon, 1975a)

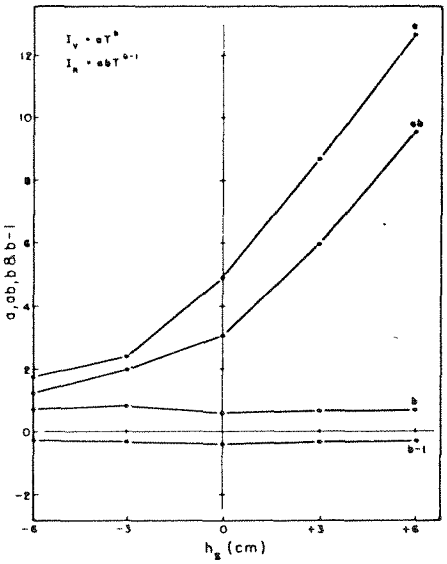

Figure 16 Parameters a, ab, b, and b-1 of Kostiakov's equation and its derivative forms, as functions of the effective surface head, h_s (Dixon, 1975a)

with corresponding changes in its infiltration capacities. Dixon has observed that a vegetative cover can increase infiltration by a factor of 10. An objective method is needed to estimate (or measure) this variability for given soils and vegetation. Such variability must be accommodated, for example, in the planes selected, in a kinematic cascade model. In the case of a lumped model, this variability must be considered in determining the precipitation excess of the watershed. An objective procedure to account for this variability is not presently available but will be required as hydrologists in the future will be asked to include erosion/sediment transport and chemical transport in hydrologic models.

There is also a unique opportunity for hydrologists to work with soil and range scientists

TABLE I

TWO-HOUR INFILTRATION FOR AN EAST FORK LOAM SOIL (NEAR RENO, NEVADA) UNDER THE AIR-EARTH INTERFACES RO AND SC AND THE NATURAL INTERFACE SO WHERE INTERFACES RO AND SC WERE IMPOSED IN 1969 AND THEN MAINTAINED UNTIL 1972 (DIXON 1975a)

Air-Earth Interface*	Observation Year	Infiltration Total Absolute (cm)	Infiltration Total Relative** (1)	Infiltration Rate Absolute (cm)	Infiltration Rate Relative** (1)
RO	1969	13.0	1.6	3.6	1.5
RO	1970	39.2	5.0	10.0	4.2
RO	1971	74.6	8.6	20.4	8.9
RO	1972	115.6	11.6	36.6	13.1
SO	1969	8.0	1	2.4	1
SO	1970	7.9	1	2.4	1
SO	1971	8.7	1	2.3	1
SO	1972	10.0	1	2.8	1
SC	1969	6.1	0.8	1.6	0.6
SC	1970	5.3	0.7	1.5	0.6
SC	1971	3.7	0.4	0.6	0.3
SC	1972	5.3	0.5	1.4	0.5

* *RO* = rough open, *SO* = smooth open and *SC* = smooth closed.

** Relative values are expressed as a fraction of the infiltration occurring under the natural interface *SO* for the specific year.

in relating the soil water resource to their various range forage improvement programs. For example, Schreiber and Sutter (1972) showed that the time distribution of available soil water is highly variable (Fig. 17) and that rangeland seeding might be more successful if delayed until the summer "monsoon" season has begun. The season was defined as starting when rainfall provided sufficient soil water to satisfy evapotranspiration for 4 consecutive days. The figure shows the cumulative frequency of years with the monsoon season start on or before a given date (A), the conventional or unconditional probability of wet soil during the season based on the 73-year precipitation record (B), and the conditional probability of wet soil throughout the season (C), given that the season had started. Mathematically, curve (C) is the total number of wet days per day of the season, divided by the number of years when the season has begun on or before that day. With 20% of the monsoon seasons having started by July 5, the frequency line (C) shows that from July 5 to August 10, chances of having available water for seed germination are about 2 out of 3 years. In late August, the chances are 1 in 2 years, and by late September the chances of having available soil

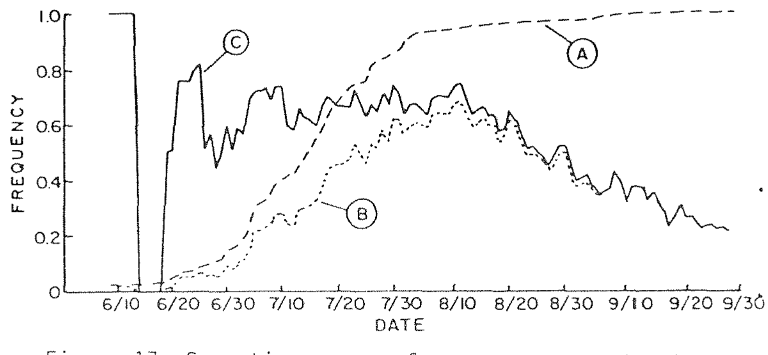

Figure 17 Summation curve of monsoon season beginning (A) and probability of having a wet soil based on a 73-year historical record (B) or the conditional probability of wet soil, given that by the fully wet option, the season has started (C) for the Tombstone raingage in southeastern Arizona (Schreiber and Sutter, 1972)

moisture have decreased to 1 in 5 years. An analysis like this could be used to aid in range reseeding to enable the seeding to coincide with maximum soil moisture. For example, seeding warm season grasses before June will allow germination of some of the seed, which will subsequently die because of inadequate moisture for the plant establishment, thus wasting a significant amount of the seed.

Water harvesting (Schreiber and Frasier, 1977) using wax as a soil sealer has caused more than five-fold increases in forage yields from treated areas on Walnut Gulch. The water harvesting concept is not new -- many examples of such work were reported at the 1974 Water Harvesting Symposium in Phoenix, Arizona (Frazier, 1974, editor). The results of the recent catchment waxing project indicated that this process is applicable to semi-arid rangelands where the harsh summers and long dry periods make forage production difficult. However, the practice is not presently economical because of the high cost of paraffin wax.

There is a tremendous opportunity in rangeland watersheds for developing the AEI (air-earth interface) concept for maximum water use efficiency for both on- and off-site water users. With such an approach, it should be possible to produce maximum forage in some instances, to harvest water for downstream water use in others, or to do both within a watershed. Equipment development has begun to facilitate infiltration control using a mated pair of rollers to imprint the soil surface, remove the brush by chopping (using a shredder or flailer) to provide a surface mulch and reseeding into the depressions of the roller. Figure 18 depicts the paired rollers (1 m wide and 1 m in diameter) being used to provide the surface geometry. The mated pair of rollers have complementary functions; one is designed to enhance runoff and the other is designed to enhance infiltration. Thus, with various roller configurations, a water-harvested area (smooth roller is used to provide an SC area, Fig. 13) is constructed adjacent to a run-in area (the roller with the angle iron ridges creates an RO surface). In water deficient areas, such a scheme could greatly increase the soil water available for forage production.

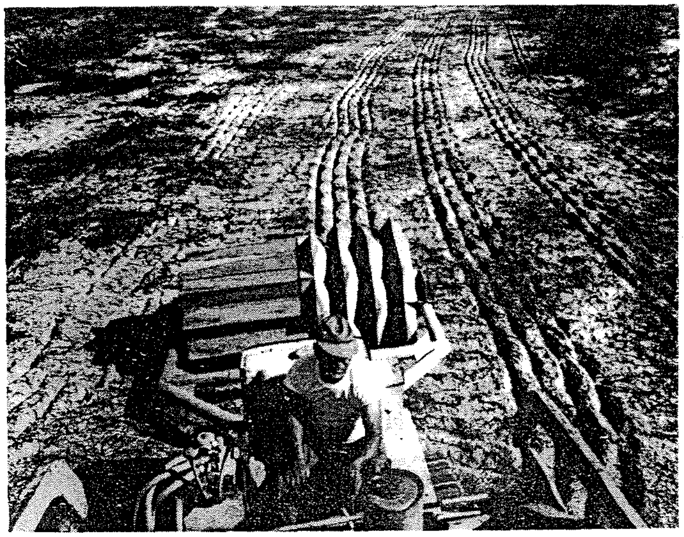

Figure 18 The land rollers used to imprint various infiltration control conditions in the air-earth interface. The treated areas in the center of the photograph contrast with the brush areas on either side. The 1-m wide and 1-m diameter rollers coupled side by side create a harvest area (left) and an enhanced infiltration area (right)

4 RUNOFF

The ephemeral streams of the semiarid southwestern U.S. present many unique problems to hydrologists. Sampling and measurement of the infrequent runoff events have been difficult, requiring innovative equipment designs. Mathematical modeling of watershed runoff has become a useful hydrologic tool, since computer technology advancements have eliminated the problem of the laborious mathematical calculations inherent in such projects. Transmission losses, which abstract a large portion of the runoff in the Southwest, are also being quantified and modeled.

(a) Measurement

Much of the success of the work in runoff quantification results from the laboratory work, which produced the precalibrated measuring flume known as the Walnut Gulch supercritical flume (Gwinn, 1970). The unique aspect of this flume is that the flow is accelerated in the entrance transition section (Fig. 19) where the flow passes through critical depth. The acceleration continues throughout the flume length (the 3% slope along the center line exceeds the 1% slope encountered in most channel reaches) with the depth measurement made midway through the straight section. Subsequent experience with the flumes has revealed that the flow at low discharges was sensitive to the position of the thalweg, which varied during, as well as between, flows (Smith and Lane, 1971). Thus, in some instances, a standing wave developed over the head-measuring section, which caused an erratic depth-discharge rating. The problem was rectified by inserting porous training fences in the channel section immediately above the flume (Smith and Chery, 1974), as illustrated in Figure 20. Ten of these large measuring flumes (maximum capacity 570 m^3/sec (20000 cfs)) have been constructed on Walnut Gulch, and a smaller version (2.8 m^3/sec (<100 cfs)) has now been developed to use with some non-point pollution work.

(b) Modeling

Runoff modeling efforts have been varied and have included the classical instantaneous unit hydrograph (IUH) approach, a stochastic approach, and the more physically-based kinematic cascade of planes and channels. Each of these efforts has been directed toward event models without effort to account for changes in the model state caused by evapotranspiration between events. Evapotranspiration measurements on arid and semiarid rangelands dominated by brush or grass are sparse in the southwestern U.S., although the Research Center staff is now constructing some cubic-meter load-cell lysimeters to accomplish this need.

(i) IUH approach

Diskin and McCarthy (1972) presented a conceptual model (Fig. 21) which produces, with certain combinations of its parameters, double-peaked instantaneous unit hydrographs. Each cascade is composed of identical reservoirs, but the number of reservoirs and their time constants are different for the two cascades.

In more recent work, Diskin, M.H., Ince, S., and Oben Nyarko, K. (1977) showed that this scheme worked well for the urban watershed where runoff partitioning between the two cascades can be made proportional to the impervious area (roads, rooftops, etc.) and the pervious area. The outputs of the two cascades are combined to form the output of the model.

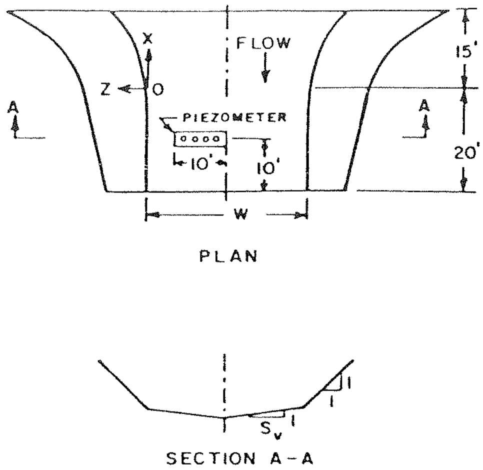

Figure 19a Walnut Gulch supercritical flume geometry and critical measuring details (Gwinn, 1970)

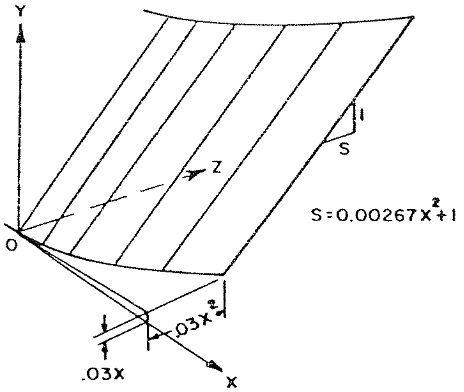

Figure 19b Walnut Gulch flume entrance section cylindroid surface (Gwinn, 1970)

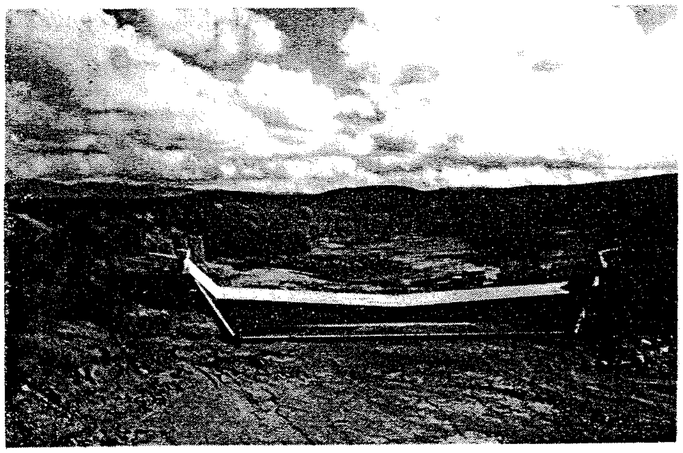

Figure 20a A view of the Walnut Gulch supercritical measuring flume and energy dissipator at the outlet of the experimental area. The vehicle affords an estimate of the size of the structure

The equation of the IUH for this model is given as:

$$U_{(t)} = \frac{A}{K_1(N_1-1)!}\left[\frac{t}{K_1}\right]^{N_1-1} e^{-t/K_1} +$$

$$\frac{B}{K_2(N_2-1)!}\left[\frac{t}{K_2}\right]^{N_2-1} e^{-t/K_2} \qquad (8)$$

where $U_{(t)}$ = instantaneous unit hydrograph ordinate at time t

A and B = parameters expressing relative input to the two cascades of reservoirs

K_1 and K_2 = time parameter of a single linear reservoir in the subscripted cascade

N_1 and N_2 = number of linear reservoirs in the subscripted cascade

e = base of natural logarithms.

The equation contains six parameters, five of which are independent (A+B=1). A single cascade of linear reservoirs as proposed by Nash (1957) is then the special case of Eq. 8 obtained either by the conditions N_1=N_2 and K_1=K_2, or A or B = 1.0. Adopting the time to the centroid (L) of the IUH curve as a basis for expressing the hydrograph in dimensionless quantities, the time base can be expressed as the ratio t/L and the ordinate of the curve by the product (U·L). The time to centroid is also equal to the time lag between the centroids of the rainfall excess hyetograph and the direct surface runoff hydrograph. Figure 22 illustrates the results of dimensionless unit hydrographs obtained by having various ratios of the division of input between the parallel cascades. Diskin and McCarthy (1972) obtained considerably better agreements to measured hydrographs from a 227-ha (684-ac) watershed near Safford, Arizona with the parallel cascade model, a result not surprising in view of the additional parameters. Such a model does have unique advantages of demonstrating the effect on a watershed of changing urban density. As the amount of impervious area increases (A increases in size in Figs. 21 and 22), the hydrograph time distribution would be expected to change appreciably (Diskin, M.H., Ince, S., and Oben Nyarko, K. 1977).

Runoff from small watersheds in semiarid areas is generally accompanied by substantial infiltration losses in the stream channels. This fact and the steep channel slopes tend to produce peaked hydrographs. The characteristic hydrograph shape consists of a fairly narrow triangular peak, followed by a fairly long recession to zero flow. For this reason, Diskin and Lane (1976) fitted double triangle unit hydrographs, basing their computations on the assumption that the entire

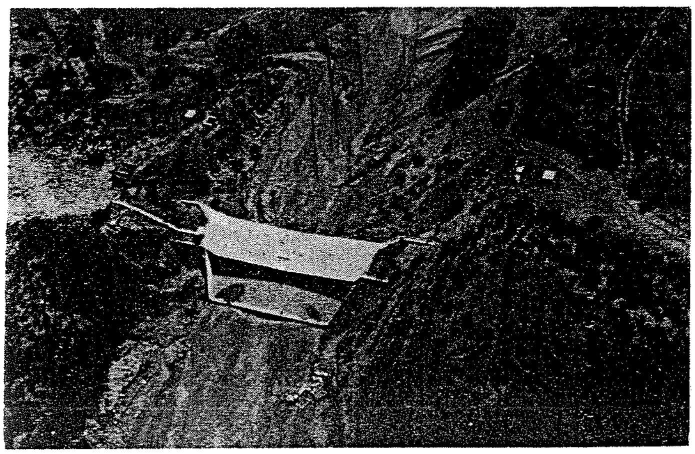

Figure 20b An aerial view of the flume showing the porous training fences used to direct the thalweg into the center of the measuring flume

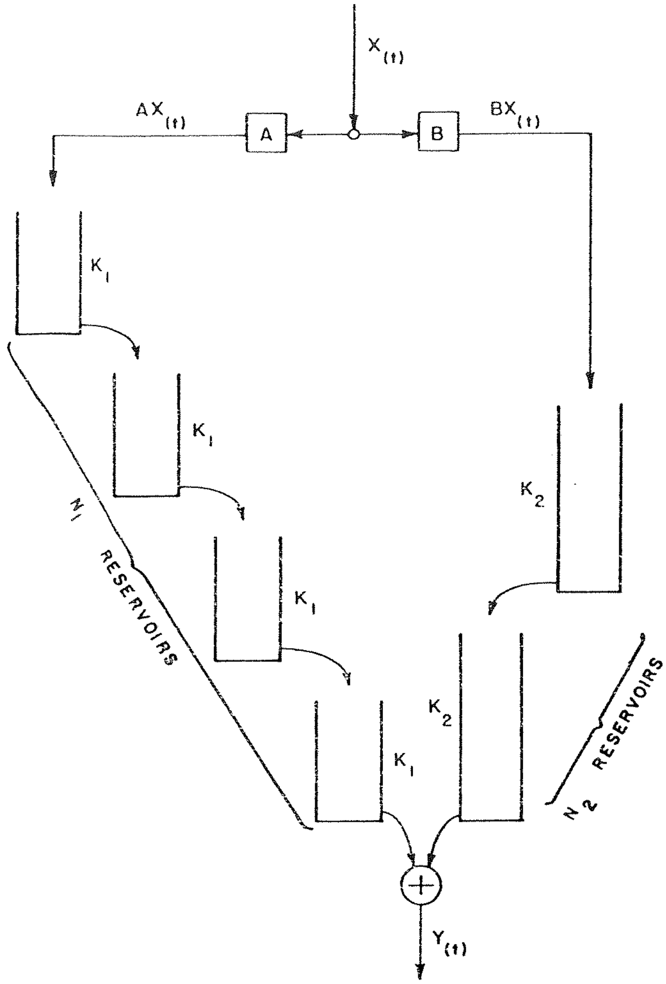

Figure 21 Parallel combination of two cascades of linear reservoirs (Diskin and McCarthy, 1972)

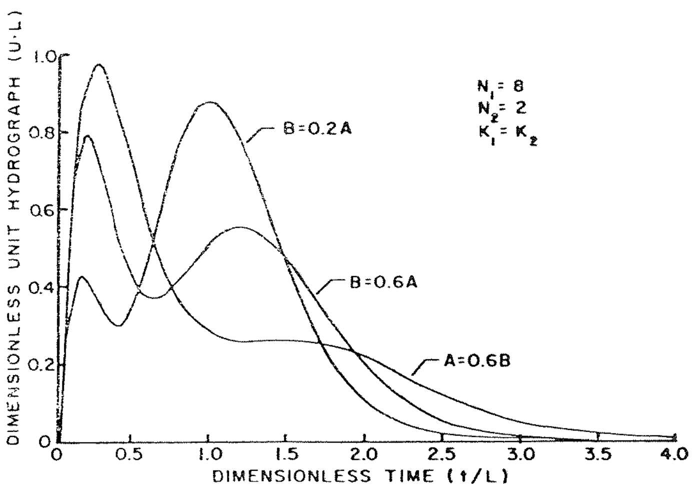

Figure 22 Comparable dimensionless instantaneous unit hydrographs for various parameter values (Diskin and McCarthy, 1972)

watershed area contributes to runoff (partial area analysis work now in progress (Lane and Wallace, 1976) indicated this is not the case).

The shape of the double triangle unit hydrograph is specified by four parameters. A fifth parameter needed for a complete description is obtained from the other four by the condition that the hydrograph enclose a unit area. The four independent parameters, shown in Figure 23, are the time to peak (T_p), the recession time (T_R), the ratio, α, between the ordinate at break point on the recession and the peak ordinate, and the ratio, β, between the time from the peak to the break point and the total recession time. Using the condition of unit area, the peak ordinate, U_p, is obtained from

$$U_p = \frac{2}{T_p + T_R(\alpha+\beta)} \tag{9}$$

The runoff hydrograph ordinates, Q_t, are obtained from the unit hydrograph ordinate, U_t, and rainfall excess, R_t, by a numerical convolution procedure.

The double triangle unit hydrograph was demonstrated to offer an improvement over the single triangle unit hydrograph. The ratio of the mean relative deviations obtained in the two cases was between 1.5 and 1.6 for the 10 storms studied. The larger number of parameters for the double triangle, four instead of two for the single triangle, does not cause any computation difficulties. The search technique adopted for evaluating the optimal parameters was just as simple for four parameters as it is for two, and the numerical convolution is the same, except for the initial computation of the unit hydrograph ordinates.

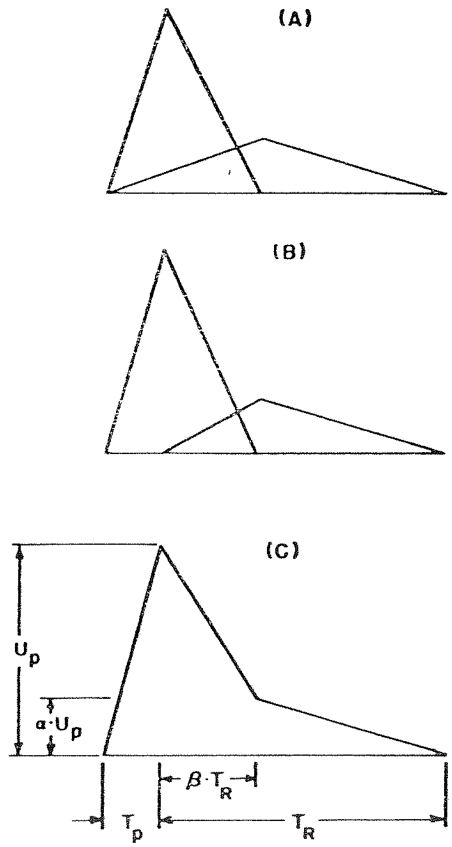

Figure 23 The double triangle unit hydrograph definitions (Diskin and Lane, 1976)

(ii) Stochastic runoff model

Stochastic models are a valuable tool in runoff studies, because they make it possible to extend existing data and generate the large amounts of data needed for the study and comparison of water use schemes for the basins concerned. The stochastic model developed by Diskin and Lane (1970 and 1972) works especially well for conditions encountered in thunderstorm-dominated runoff, because each runoff event begins and ends with zero flow and thus is an easily definable, succinct event.

The stochastic model of runoff developed by Diskin and Lane (1972), summarized in Figure 24 and Table II, generates intermittent and independent runoff events. Two variables were used to describe the runoff season: (1) S, the starting date of the runoff season and (2) N, the number of runoff events recorded per season at the watershed outlet. The temporal distribution of the runoff events was described by two variables: (1) T, the event time of day and (2) D, the interval between events. Each runoff event was described by two random variables: (1) L, runoff volume and (2) P, peak discharge. Because the peak discharge and volume were highly correlated, peak discharge was generated from the runoff volume. The assumed distribution (chosen with a Kolmogorov-Smirnov test) for describing these parameters is shown in Table II.

Extension of the stochastic model from a single watershed to a region requires knowledge of the relationships between model parameter values and watershed physical characteristics. For the Diskin-Lane model, the parameters involved are the mean and standard deviation of the independent variables (Table II) andthe regression equation constants and the standard deviations of residuals for the dependent variables. They found that:

(1) The mean starting date of the summer runoff season is earlier with increasing watershed area up to 155km^2 (60 mi^2);

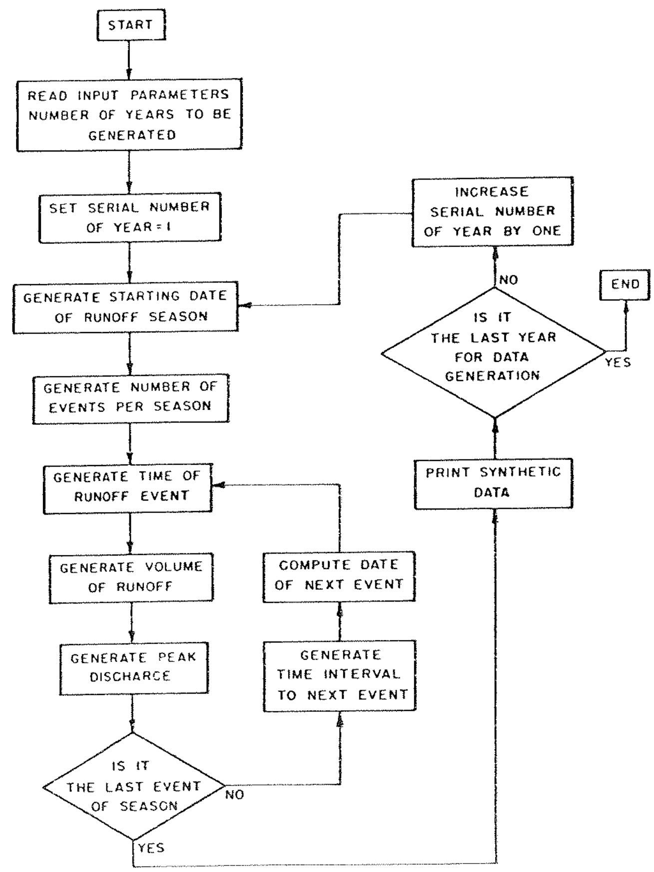

Figure 24 Flow chart of stochastic model for runoff events (Diskin and Lane, 1972)

TABLE II
PROBABILITY DISTRIBUTIONS ADOPTED FOR RUNOFF VARIABLES
(Diskin and Lane, 1972)

Runoff variable	Symbol used	Theoretical distribution	Parameters
Start of runoff season	S	Normal	Mean, standard deviation
No. of events at outlet per runoff season	N	Normal	Mean, standard deviation
Begin time of each event	T	Normal	Mean, standard deviation
Logarithm of volume of runoff for each event	L	Normal	Mean, standard deviation (of logarithms)
Interval between events	D	Exponential	Mean

(2) The mean number of events per runoff season increases with watershed size;
(3) The mean time interval between runoff events during the season decreases as watershed area increases;
(4) The mean beginning time of runoff events during the day is essentially independent of watershed size but rather is controlled by meteorological conditions associated with convective thunderstorm development;
(5) The mean ratio of event runoff volume to watershed area decreases as watershed area increases.

The standard deviations for these variables were found to be fairly constant and independent of watershed area up to areas of 200 km^2 (77mi^2).

This model structure was subsequently used by Land and Penard (1972) to demonstrate how a relatively short record could be extended for a frequency analysis. A sediment transport scheme was coupled with the model to demonstrate the probabilities of various annual sediment yield values when only a limited amount of sampling data for sediment concentration is available (Renard and Lane, 1975).

(iii) Kinematic cascade modeling approach

Under conditions where the momentum equation can be approximated by maintaining only terms expressing bottom slope and friction slope, flow is called "kinematic". With these conditions, local depth and discharge on a plane have the simple functional relation

$$Q = \alpha h^n \qquad (10)$$

where: Q = local discharge

h = local depth

α = a coefficient incorporating slope and roughness

n = exponent reflecting flow type (laminar or turbulent).

Although these definitions are for flow over a hydraulically smooth plane, the same form can be used for irregular surfaces where the mean flux per unit width is proportional to the storage in an incremental area. The early work of Lighthill and Whitham (1955) presented the theory of kinematic waves.

Lane, Woolhiser and Yevjevich (1975) presented the development of the kinematic cascade model from the early work of Henderson and Wooding (1964), Wooding (1965a, 1965b, and 1966), and Brakensiek (1967) to Kibler and Woolhiser (1970), who defined a kinematic cascade as a sequence of N discrete overland flow planes or channel segments in which the kinematic wave equations are used to describe the unsteady flow. Each plan or channel is characterized by a length, ℓ_k, width, w_k, and a roughness-slope factor, α_k (Fig. 25).

Thus, the kinematic cascade is a distributed (each element may have different characteristics including precipitation and precipitation excess) model with lumped parameters in the sub-elements. The model is nonlinear because the exponent of depth in Eq. 10 is generally not equal to unity.

Lane, Woolhiser and Yevjevich (1975) illustrated the effects of watershed geometry simplifications (Table III) on the simulation of surface runoff. Their modeling procedure is shown in a block diagram in Figure 26, which shows details of the topographic analysis as well as the hydrologic analysis. They defined the goodness-of-fit statistics as indicating how well a watershed component is represented in a mathematical model. The three geometry goodness-of-fit statistics are defined in Table IV. The hydrograph goodness-of-fit statistic is a measure of how well the simulated runoff corresponds with the observed runoff.

Lane, Woolhiser and Yevjevich (1975) observed that for the watersheds they examined, there was a diminishing return in hydrograph goodness-of-fit ($\bar{R}_Q^2$) for increasing geometric complexity, i.e. the rate of increase in R_Q^2 decreases with increasing R_p^2, geometric goodness-of-fit.

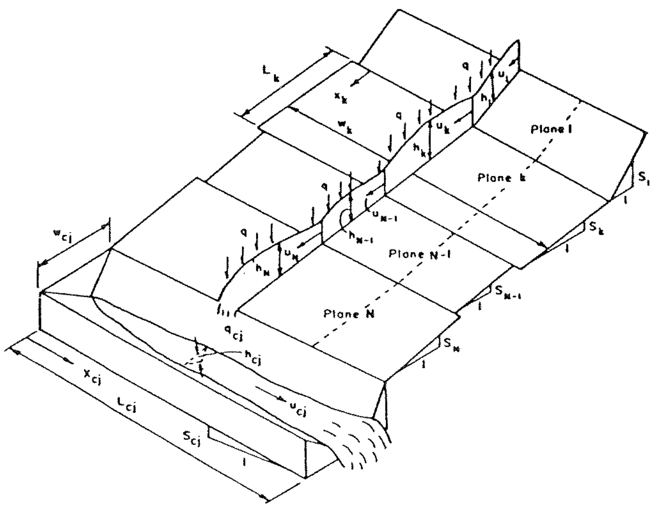

Figure 25 Cascade of N planes discharging into the j^{th} channel section (Kibler and Woolhiser, 1970)

TABLE III
SOME WATERSHED CHARACTERISTICS AFFECTED BY GEOMETRIC SIMPLIFICATIONS ADOPTED IN MODEL FORMULATION (LANE, WOOLHISER AND YEVJEVICH, 1975)

Characteristics Essentially Preserved		Characteristics Slightly Changed		Characteristics Distorted	
A,	Area	F(x),	Hypsometric curve	u,	Stream order
L_c,	Main Channel Length	H,	Total relief	D_d,	Drainage density
S_c,	Main Channel Slope	$\bar{H}$,	Mean watershed elevation	B_f,	Topographic roughness
S_w,	Mean Watershed Slope	I_h,	Hypsometric integral	C, K,	Hydraulic roughness coefficients
		U,	Potential energy	-	Channel characteristics such as cross sections, concavity, etc.
				-	Watershed shape

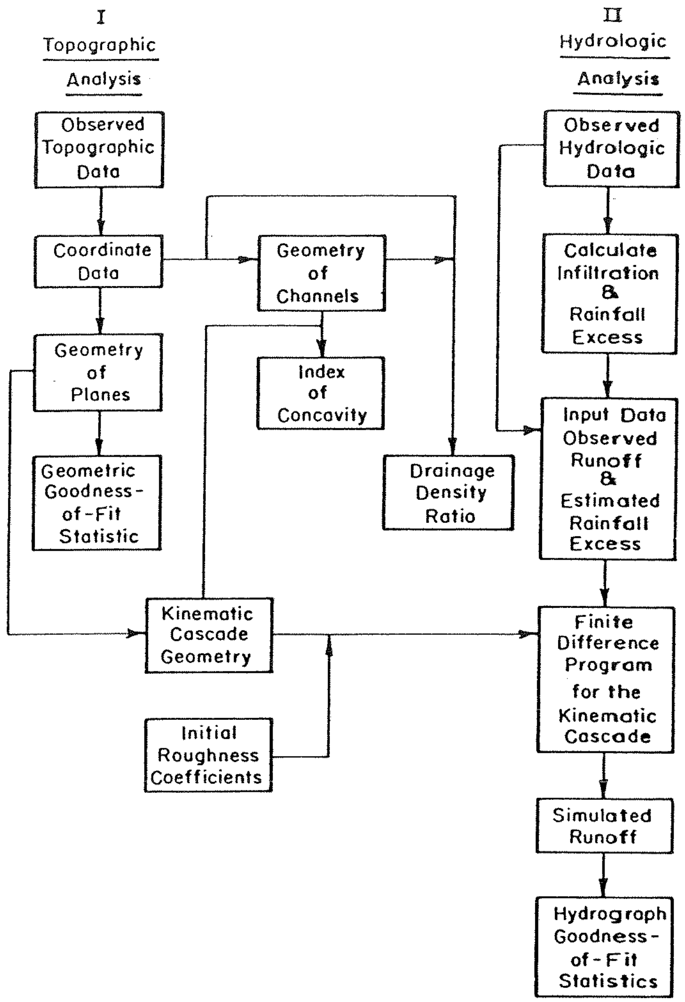

Figure 26 Summary of modeling procedure (Lane, Woolhiser and Yevjevich, 1975)

TABLE IV
SUMMARY OF PROPOSED GOODNESS-OF-FIT STATISTICS FOR THE SIMPLIFIED GEOMETRICAL REPRESENTATION (LANE, WOOLHISER AND YEVJEVICH, 1975)

Element or Component of System: Watershed	Model	Goodness-of-fit Statistic for the Simplified Geometry	Comments
Hillslope or Watershed	Cascade of Planes	R_p^2	Ratio of residual variance about fitted planes to original variance of elevation coordinate data. Also used for entire watershed.
Main Channel	Cascade of Channels	I_c	Index of concavity, ratio of height of equal area, equivalent slope triangle to total relief of main channel.
Watershed	Cascade of Planes and Channels	I_d	Ratio of drainage density in model to observed drainage density in the watershed.

(iv) Systems approximation method

Deterministic surface water models (e.g. kinematic wave models) have progressed from modeling subunits of a watershed to combining the subunits into more comprehensive models of entire watersheds. Considerable confidence has been developed in the representation of such comprehensive models of the hydrologic system. In the process, however, such models have become complex and relatively difficult and expensive to use.

Chery, Clyde, and Smith (1977) have proposed a complex, physical model as an intermediate step to develop parameters for a simplified model. The simpler and more economical system model may then be used operationally with a spectrum of inputs for predictive purposes. Their scheme is conceptually represented in Figure 27. The variable distributed precipitation is sampled at several points, and serves as input to the deterministic model where precipitation excess is determined. The excess is routed over infiltrating planes and through an infiltrating channel network by the deterministic model to predict the output (q_k), which is compared with the measured output (q_m). Parameters for this model are obtained from field measurements. This complex model was developed with a subjective choice of planes and channels in cascade, which seemed to duplicate the topographic map. There is no indication that a much simpler combination of planes and channels would not do as well in duplicating the watershed response to precipitation.

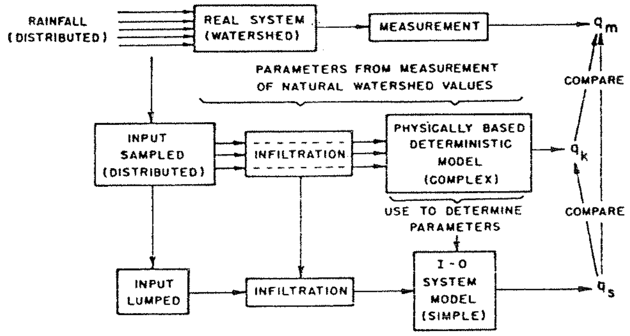

Figure 27 Scheme of study (Chery, Clyde and Smith, 1977)

The input for the simple system model is obtained by lumping the input to the complex model and using the same infiltration routine to obtain precipitation excess. This excess is convoluted with a transfer function (the parameters of which were derived from the complex model), to produce a predicted system output (q_S). The system model output is compared with both the deterministic complex model output and that of the measured real system to evaluate its performance. In this scheme, the deterministic model followed that developed by Kibler and Woolhiser (1970) using the Smith and Chery (1973) rainfall excess routine.

Representation of flow from a triangular plane and employment of a nonlinear convolution were developed in the study by Chery, Clyde, and Smith (1977). Representation of flow on a triangular plane, illustrated in Figure 28, was described as follows:

> Computations are made for the longest length of overland flow (L_0 in Fig. 28). The numerical solution is made by dividing the maximum length (L_0) into several equal segments. Thus, the solution for plane flow from the top to the end of any segment is also the flow at the bottom edge of a triangular plane where the flow path is the same length as the segment .... The outflow from one triangular plane-channel set can be doubled to give the response from the geometrical configuration as shown in the alternate configuration (Fig. 28b).

The watershed model has the facility to represent independent channels (having the geometry shown in Fig. 28c) which may have lateral input and may have input from as many as three upstream channels.

A discrete nonlinear convolution model (1-min unit hydrograph) was employed for the simple model.

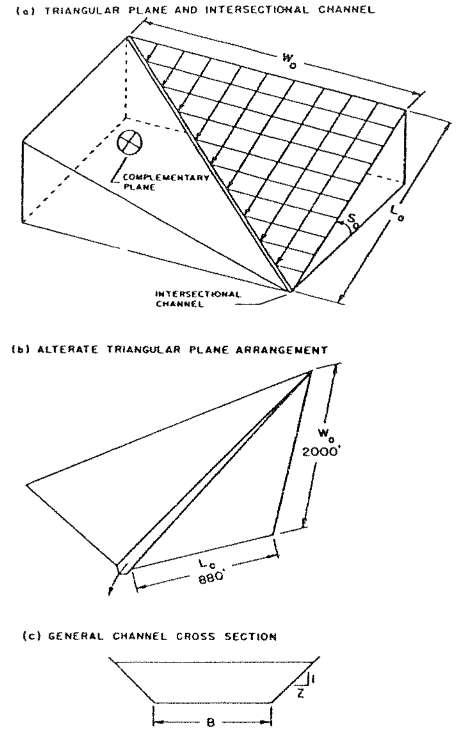

Figure 28 Geometrical elements used in the physically-based model (Chery,Clyde and Smith, 1977)

In this model, a different pulse response was used for each input excess range, with the resulting total model described as being a discrete nonlinear model. The "S" hydrograph differencing method was used to identify the unit pulse response for a series of constant input (excess) rates. The kinematic model was used with constant input rates to obtain equilibrium outflow (Fig. 29a) and the unit pulse response, $U_p(t)$ is obtained by off-setting the equilibrium response and normalizing the results to obtain the corresponding pulse responses. These pulse responses were then adjusted to obtain the desired shape and then reduced by 20% to account for errors in rainfall-excess estimation. The curves are shown in Figure 29b.

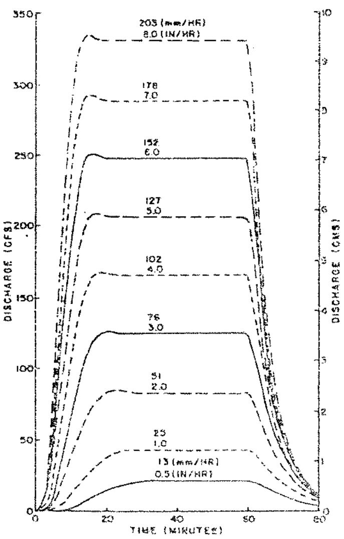

Fig. 29a - Responses of kinematic model, triangular planes (Figure 28b), to constant input rates and no infiltration (Chery, Clyde, and Smith, 1977).

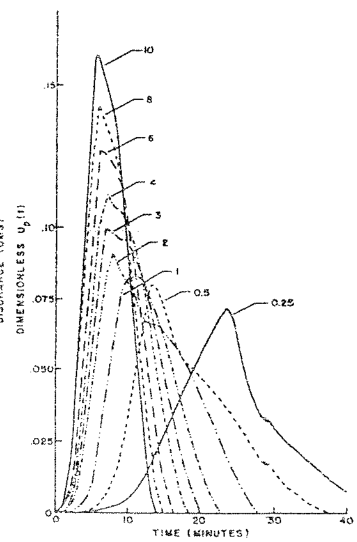

Fig. 29b - One minute pulse responses for triangular planes (Figure 28b) (Chery, Clyde, and Smith, 1977).

To test the two modeling approaches, 18 storm events with similar antecedent conditions were used for a 16.2-ha (40.1-ac) watershed west of Albuquerque, New Mexico. Precipitation input was measured by two recording raingages and watershed discharge was measured by a broadcrested V-notch weir. Peak runoff responses varied from 0.076 to 3.34 m^3/sec (2.7 to 118.0 cfs). In the kinematic model, 16 planes and 26 channel segments were used to simulate the watershed.

Chery, Clyde, and Smith (1977) pointed out that both the kinematic and convolution model responses fit better for the larger events. The kinematic model also predicted the overall response better than the convolution model, as would be expected, although by the integral square error test, the convolution model was a better predictor for four events of the 18 storms modeled. Errors in measurement (runoff and precipitation), modeling, and infiltration variation on the watershed undoubtedly explain the observed differences between the predicted and measured runoff. Other errors may result because the kinematic model can represent infiltrating surface flow where the convolution model passes excess at a point to the output without any loss during flow over surfaces or in channels.

The computer time required to make convolution model discharge predictions is considerably less than that needed for the kinematic model. In the sample run of 18 events, the cost was $8.25 for the discrete convolution versus $9.72 for the kinematic model. The advantage would increase for a larger number of events because the fixed initial cost for generating the unit pulse response ($8.00 of the $8.25 cost) would be distributed over more events. The precipitation excess predictions cost about $0.20/event with an additional $0.05 for the convolution.

They estimated that predicting a 50-year flow sequence with 10 events/year would cost about 17 times more using the complex kinematic model than with the proposed applications model procedure.

(v) Future runoff modeling work

Although future work will undoubtedly be directed toward empirical and stochastic runoff models, apparently the questions being asked of hydrologists by environmentalists will require using more physically based principles as in the kinematic cascade model. Questions, like those associated with planning for elimination of non-point pollution (Public Law 92-500, the United States 1972 Water Quality Improvement Act), will require coupling erosion/sediment transport and chemical transport routines with hydrologic models. To establish guidelines for controlling such pollution will undoubtedly require developing physically based models with the provisions to handle:

a. Nutrient cycling subroutines;
b. Background levles of all pollutants;
c. Atmospheric loadings of all pollutants;
d. Cattle concentration influences, like feed lots;
e. Information related to pesticide loading;
f. Effects of varying management systems on pollutants;
g. Effects of nutrients on sediment; and
h. Problem forecasting resulting from varying land use (e.g. rural to urban).

Improved estimates of pollution require accurate information of the portion of a watershed contributing runoff (partial-area response) at the outlet or point of interest. Lane and Wallace (1976) stated that this concept is included in a broader one-- that of spatial variability of rainfall, infiltration, and thus rainfall excess. The concept evolved in considerations for more humid areas (Hewlett, 1961; Dunne and Black, 1970; and Patten, 1975) but has also been successfully applied to semiarid watersheds (Arteaga and Rantz, 1971; Lane and Wallace, 1976).

Lane and Wallace (1976) used a partial area-kinematic cascade model based on watershed geomorphic features to divide a 2-ha (4-acre) catchment into homogeneous zones. Their work agreed with the results of Arteaga and Rantz (1971) which related average percent contributing area with average runoff loss rate.

To further extend these results, the same watershed and the four geomorphically homogeneous subzones were treated with broadcast herbicides in the summer of 1976. Concentration of each water soluble herbicide in runoff was measured to evaluate the percentage of runoff from each subzone. The zones were also sampled periodically after application to determine the herbicide concentration remaining in the soil. Results of this work are very encouraging.

While the importance of such partial area runoff analysis may not be apparent, we anticipate two major uses. It should be possible on the basis of geomorphic features and a simulation model to predict the probability of an herbicide applied to a rangeland area for brush control to enter a stream and move through the channel. It is also possible with such results to more accurately predict the flow depths at interior watershed points to provide better estimates of the shear responsibility for the erosion measured at a downstream point. Additional work is now being undertaken at our Center to use chemical tracers in nested watersheds to provide interior checks as well as measurements at the outlet.

(c) Transmission Losses

Much of the runoff in rangelands of the southwastern U. S. infiltrates the course-textured alluvial streambeds. Thus, runoff, especially when the channels are very dry, may be completely absorbed by the channel before reaching the outlet of even a moderate-sized drainage area. On semiarid areas, like Walnut Gulch, these losses have a marked effect on the response of a watershed to a precipitation event and significantly decrease water yield with increasing drainage area.

Whereas in more humid areas, water yield per unit area may increase with increasing drainage (Fig. 30), in arid lands the reverse is true. For this reason, the hydrologic balance of an area includes a rather large component for these losses (Fig. 31). The hydrologic balance on Walnut Gulch contains almost 15% of the total water input to the cycle as transmission losses, or a total of 6.7×10^6 m^3 for this 150-km^2 watershed.

(i) Storage routing model

Lane (1972) proposed a general form of a storage routing model based on the continuity equation

$$S + L + Q = P \qquad (11)$$

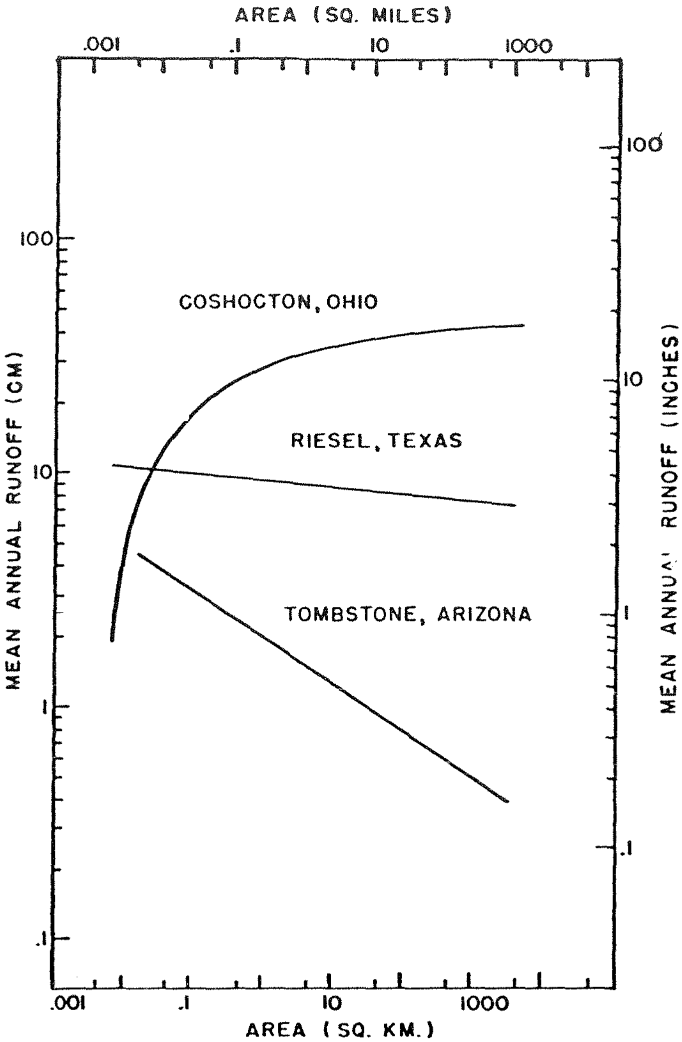

Figure 30 Mean annual runoff versus size of drainage area for several vicinities (Glymph and Holtan, 1969)

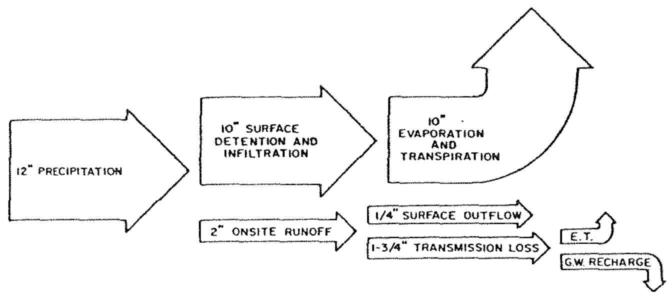

Figure 31 Water balance of Walnut Gulch Watershed (Renard, 1970)(1 in = 25.4mm)

Where S = time derivative of the storage
L = transmission loss rate
Q = outflow from the reach
P = inflow to the reach

Further, with L = F(S) and Q = G(S), he assumed that

$$L(t) = F(S) = C_1 S^{b_1}$$

and $$Q(t) = G(S) = C_2 S^{b_2}$$

which on substitution gives a general form for the storage equation for flood routing in ephemeral channels as

$$S = C_1 S^{b_1} + C_2 S^{b_2} = P \qquad (12)$$

where C_1 and C_2 are coefficients, and b_1 and b_2 are exponents. He then proposed as a basic component of the model, a reservoir with abstractions or losses and a siphon outflow. Thus, the general model would be a cascade of such components similar to the Nash (1957) cascade of linear reservoirs conceptual model.

For the situation where both the inflow and outflow are known and with the transmission losses expressed as a linear function of the storage in the channel reach, the discrete form of Eq. 11 becomes

$$S_N = \frac{2}{C_1\Delta t + 2}\left[\sum_{i=1}^{N} P_i\Delta t - \sum_{i=1}^{N} Q_i\Delta t - C_1\sum_{i=1}^{N} S_i\Delta t - \frac{C_1\Delta t}{2} S_{N-1}\right] \qquad (13)$$

where S_N is the storage at time $t = N\Delta t$. An example of the solution of this equation, solved by an iterative technique until successive values of C_1 are arbitrarily close, is shown in Figure 32. Lane then showed that C_1 was related to the peak discharge of the inflow hydrograph for a particular channel reach.

(ii) Border irrigation advance and ephemeral flood waves.

Smith (1972) described a method to predict advance rate, surface profiles, and modifications with time to the kinematic wave flow over an initially dry infiltrating plane. Interaction of surface flow with infiltration loss was treated explicitly with point infiltration rate considered as a function of time since setting. The continuity equation for unsteady open channel flow in a wide channel with a Chezy or Manning surbulent flow friction slope relation is

$$\frac{\partial h}{\partial t} + (m + 1)\,\alpha h^m \frac{\partial h}{\partial t} = q(x,t) \qquad (14)$$

where U = local velocity = αh^m
h = depth
q(x,t) = local inflow (+) or outflow (-)
m = exponent = 2 for laminar flow, 1/2 for Chezy, or 2/3 for a Manning relation in turbulent flow
α = coefficient = a function of turbulent resistence coefficient and slope.

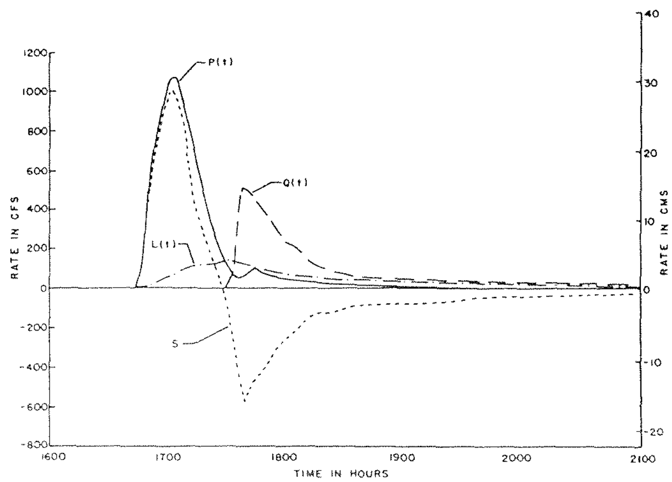

Figure 32 Solution to the differential equation assuming inflow and outflow are known for channel reach 11-8 on Walnut Gulch for the event of July 30, 1966 (Lane, 1972)

This relation was extensively developed using a kinematic chock or flow discontinuity to describe the wave front movement in a channel. Solutions for border irrigation problems were presented using the method of characteristics and a rectangular grid finite difference approximation showing solution instabilities both across the shock and at the peak of a hydrograph. The results were then compared with experimental results illustrating the agreements between the two for point infiltration from a ponded surface using the infiltration concepts described earlier. Smith stated:

> The principal feature of shock-type flood wave movement over an infiltrating bed can be shown by the example shown in Figure 33. The hypothetical input hydrograph is shown in the inset. Shock height grows as the wave moves until the peak is reached because velocity behind the chock exceeds shock velocity; e.g., ∂Q/∂x for this region is negative. At the same time, the peak flow is decreasing due to infiltration, and the slope of the hydrograph behind the peak is decreasing because ∂Q/∂x is positive in this region. Infiltration accentuates the increase in slope of the flow profile behild the chock, and also the decrease in slope behind the peak because the loss rate increases at an increasing rate from the rear to the front of the profile.

The finite difference solution for the kinematic wave compares very favorable with the characteristic method solution. Although the finite difference solution slightly underestimated the peak discharge and some diffusion was observed in the shock front, the difference between the solutions is in the direction of the momentum effects, which are ignored by the kinematic model. The solution also ignores the soil air pressure wave associated with the flood passage and subsequent displacement of air by the

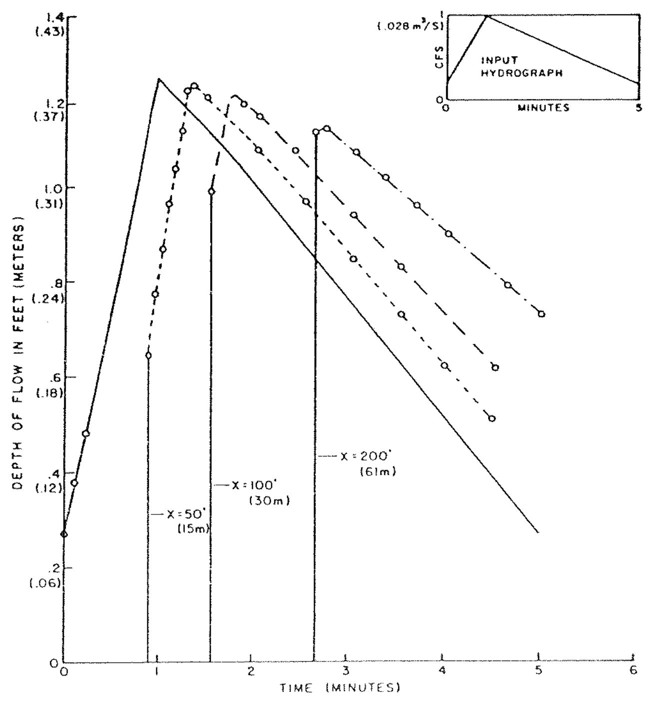

Figure 33 Sample results for flood routing on initiallu dry infiltrating bed by characteristic kinematic method (Smith, 1972)

infiltrated water. The modeling of transmission losses also needs to treat the problem of bed sealing by fine sediment and the disturbance of fine material by the turbulence of subsequent flows.

The kinematic model was applied to a flood wave for a channel reach on Walnut Gulch to illustrate the type of solution possible. The severe infiltration losses change the hydrograph characteristics dramatically, which is very similar to the model prediction (Fig. 34). Work is continuing in this promising endeavor with emphasis on the infiltration relationships, channel shape changes, and rating relations for the runoff measurements.

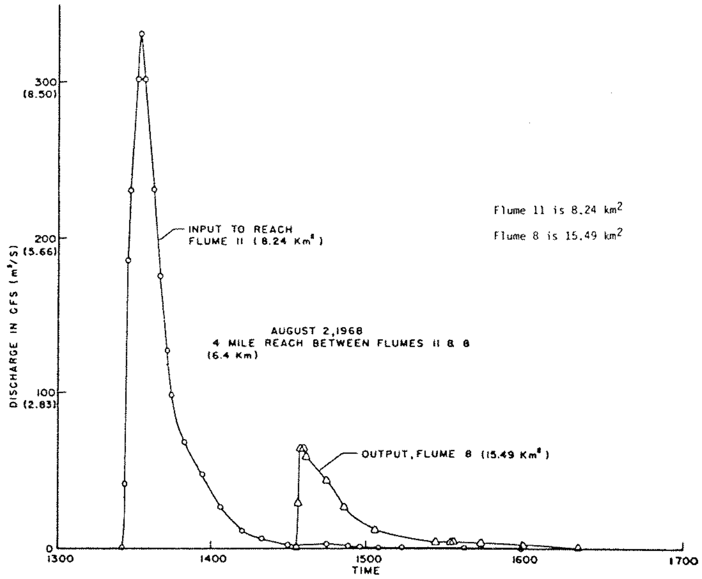

Figure 34 Sample of flash flood movement and attenuation in Walnut Gulch Experimental Watershed, Southeastern Arizona (Smith, 1972)

5 WATER QUALITY

Environmental quality, although long the concern of conservationists, has received extra significance in the past decade. Increasing demands on our limited land and water resources have resulted in part from dramatic population increases. Even in the free economic system of the U. S., social concern for environmental preservation and enhancement has added new dimensions to water development problems. This concern has understandably carried into our research program where water quality considerations now occupy a position of importance parallel to our hydrologic problems.

Of major importance is the concept of sediment as a pollutant and a carrier of pollutants including agricultural chemicals. Thus, the physical and chemical properties of sediments are responsible for the sorption, desorption, transportation, and deposition of chemicals occuring both naturally and introduced by agriculture. In addition, many chemicals are transported in solution phase with runoff.

(a) Sedimentation

Sedimentation includes the detachment, entrainment, transportation, and deposition of soil material. Sediment has been labeled the greatest pollutant because of the enormous quantities of sediment eroded from the land each year.
Sediment is a scavenger or carrier of other pollutants, releasing or absorbing chemicals in the environment, and can sometimes lead to the desirable situation of absorbing problem chemicals.

Sediment yield in the sparsely vegated areas of mixed brush-grass cover where thunderstorms dominate the runoff production, areas like Walnut Gulch, is near the peak of the relationship produced by Langbein and Schumm (1958) (Fig. 35). The figure illustrates in a striking way the importance of sedimentation in arid and semiarid areas. Such high erosion explains the shallow soil profiles in many areas (Fig. 36a) and often the absence of an A-horizon. The most desirable soil with its organic matter is often non-existent because the erosion carries the soil away before its development from the parent geologic material is complete. Such erosion also explains the erosion pavements dominating the soil surface in many sparsely vegetated areas (Fig. 36b).

(i) Universal soil loss equation

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965) is widely used for estimating annual erosion from field-sized watersheds. The equation has also been modified to estimate the erosion for individual storms (Williams 1974), although the original development did not include such a use (Wischmeier, 1976).

Some work has been completed to adapt this erosion-estimating technique, which has developed with data from the more humid cultivated areas east of the Rocky Mountains, to the conditions encountered in the rangeland areas of the southwestern U. S.

Predictive equations are based on indices of measureable factors, consequently the prediction is no better than the measured indices. The USLE is:

$$A = RKLSCP \qquad (15)$$

where A = estimated soil loss (tons/acre/year)
R = rainfall factor (EI)
K = soil-erodibility factor
L = slope length factor
S = slope gradient factor
C = cropping-management factor
P = erosion control practice factor.

Of the six variables of the USLE, the rainfall factor is perhaps the most difficult to describe in terms of distribution and probability in basin and range topography that

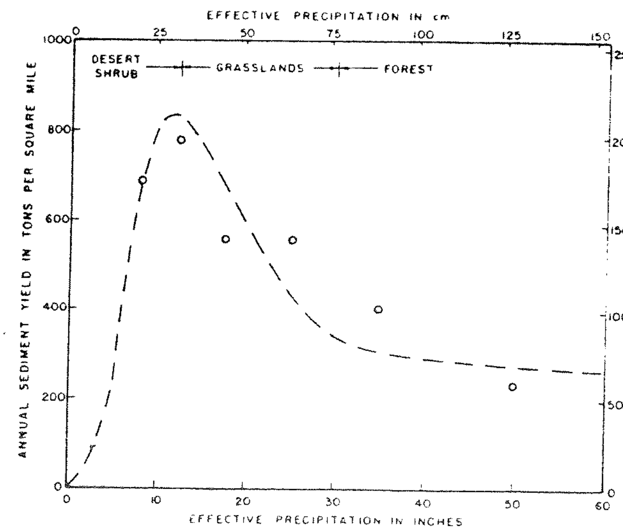

Figure 35 Effect of rainfall variation on sediment yield, determined from records at sediment sampling stations (Modified from Langbein and Schumm,1958)

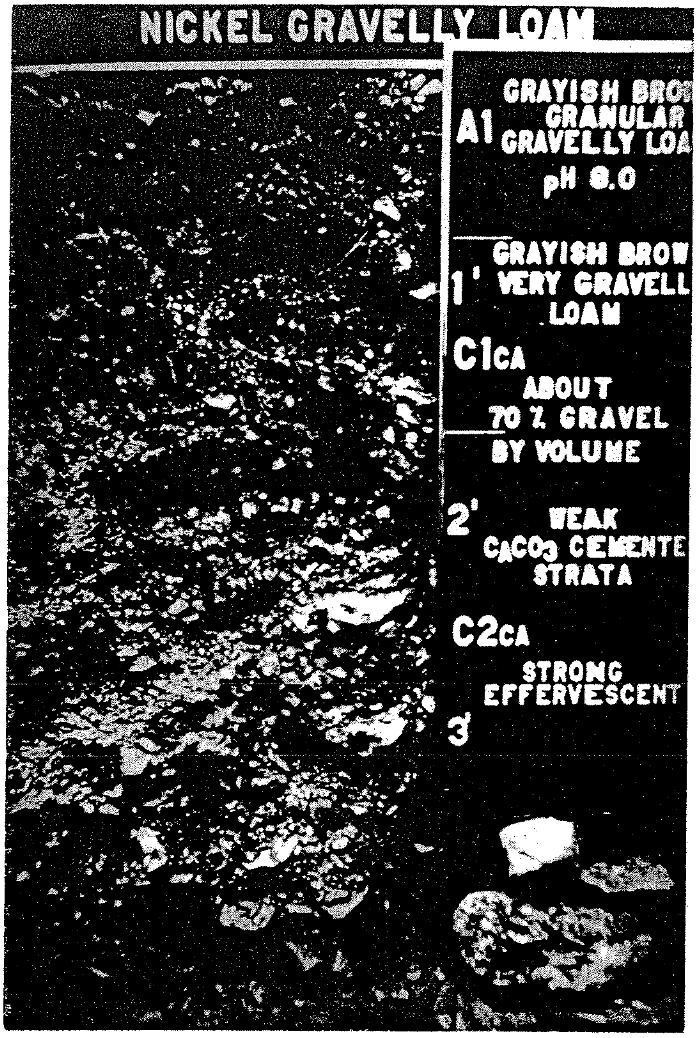

Figure 36a A typical soil profile in the semiarid areas of southeastern Arizona. The profile which is often 70% gravel by volume generally has a caliche layer at depths up to 1m which restricts moisture movement and root development.

Figure 36b 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 36a

has orographic influences. An additional complication is the unpredictability of the air-mass thunderstorm, which is characterized by high intensity, short duration, and limited areal extent. Such storms produce most of the runoff (except for snowmelt on the highest mountain areas) in the semiarid Southwest. It is difficult to develop a method to estimate the average annual erosion, which is dependent on thunderstorm precipitation that varies widely in space and time.

The spatial variability of air-mass thunderstorms has been extensively documented (E.G. Osborn and Renard, 1969). The isohyetal map for the storm of July 22, 1964 (Fig. 37) illustrates the spatial variability of the precipitation depth and the erosion index for one such storm where almost 46 mm (1.8 in) of rain fell in 20 min at the storm center. Similar variability has been observed in Alamogordo Creek (Renard and Simanton, 1975a).

Such spatial variability from individual storms leads to the obvious expectation of appreciable annual variability in both precipitation and EI. Figure 38 illustrates the annual variability for Walnut Gulch for the same year that was used to illustrate the individual storm variability. In general, highs and lows of both precipitation and EI agreed for both areas, although EI units per unit of rainfall differed. At the lowest rainfall depth on Walnut Gulch there were 2.7 units of EI per 1 in of annual rainfall. In other years at Walnut Gulch, the annual maximum precipitation depth has been almost twice the minimum depth, with no apparent pattern to the position of highs and lows on the watershed. For the lowest rainfall depth on Alamogordo Creek, there were 6.4 units of EI per 1 in of annual rainfall, whereas at the maximum rainfall depth, there were 21.1 units of EI per 1 in of annual rainfall. Thus, we must conclude that the record from a single gage yields an EI value for that point only and the results should not be extended to more than about a mile to estimate the erosion from a storm or from an individual year.

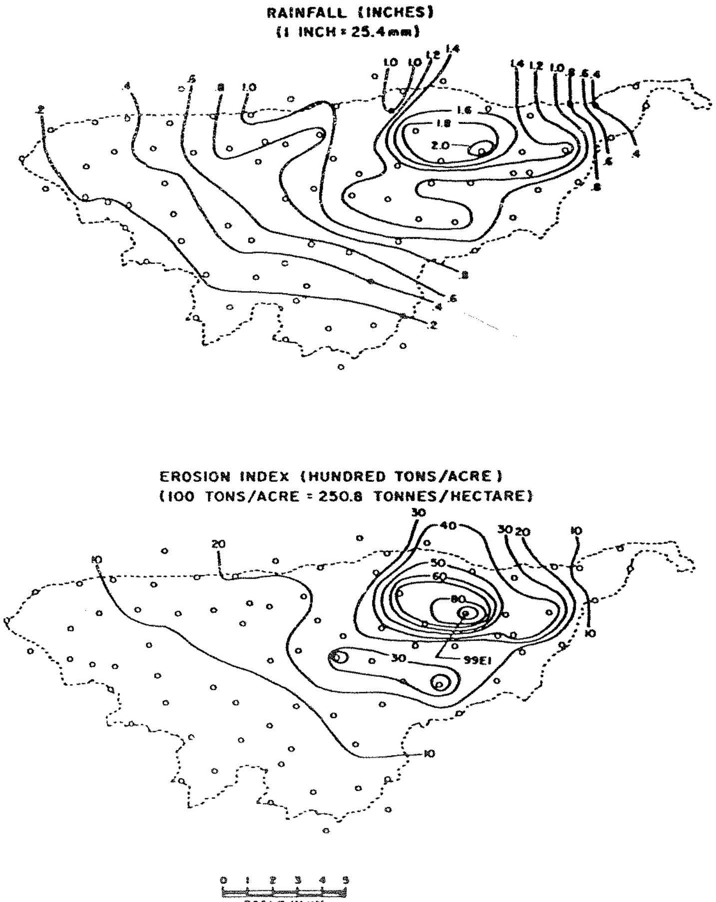

Figure 37 Isohyetal and iso-rainfall-erosion index maps for the July 22, 1964 storm on the Walnut Gulch Experimental Watershed. Each small circle represents the location of a recording raingage used to develop the maps (Renard and Simanton, 1975a)

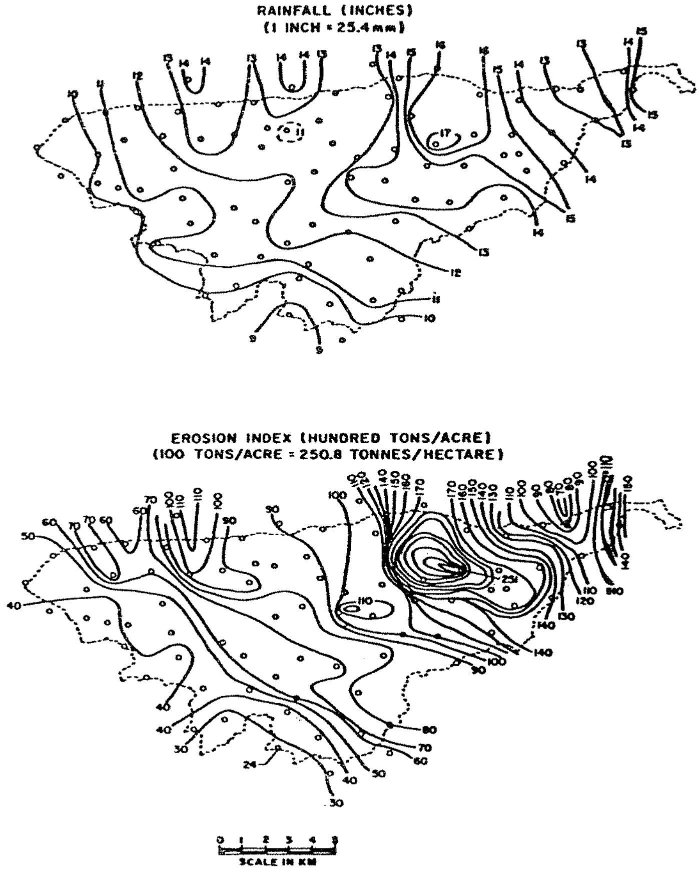

Figure 38 Isohyetal and iso-rainfall-erosion index maps for 1964 annual totals on Walnut Gulch (Renard and Simanton, 1975a)

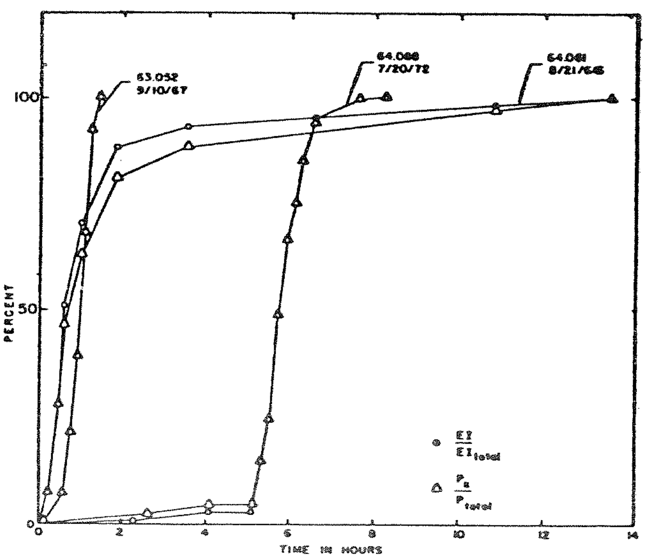

Figure 39 Comparison of dimensionless precipitation and rainfall-erosion index for three select storms on Walnut Gulch (63.052) and Alamogordo Creek (64.088 and 64.061)(Renard and Simanton, 1975a)

Because EI computation is based on maximum 30-min rainfall intensity, most of the EI units are derived from a relatively short, high-intensity portion of the storm (Fig. 39). The September 10, 1967, storm produced 87.6 mm (3.45 in) of rainfall in only 86 min and most of this fell in 1 hour. The dimensionless EI and rainfall points essentially coincide for this storm and for the July 20, 1971, storm. The first 5 hours and the last 1 hour of the latter storm probably produced very little rainfall exceeding the infiltration rate and, therefore, most of the EI units did not result from these low intensities. The August 21, 1966, storm produced 139 mm (5.46in) of rainfall, lasted for 13.5 hours, and resulted from a thunderstorm superimposed on a slow-moving cold front. Of the 266 EI units resulting from this storm, almost 80% were produced during the first 2 hours, the period of highest intensity.

Thus, in thunderstorm-dominated precipitation areas, such as Arizona and New Mexico, one must use recording raingages capable of measuring the depth for short time intervals to compute the EI for the USLE. Standard rain gages or hourly precipitation values may greatly underestimate the EI value.

Analysis of precipitation records from the Walnut Gulch and Alamogordo Creek watersheds led to the following conclusions (Renard and Simanton 1975a):

1. Records from a single precipitation gage in climatic areas dominated by thunderstorms can be used to estimate the EI only for the point in question on individual storms or for a specific annual value. Extrapolating the results for more than about a mile (1.61 km) leads to serious error when using the USLE to estimate erosion;
2. Short time intervals precipitation depths must be used to obtain an adequate estimate of the EI when using the USLE;
3. The variability of the annual EI can be approximated with a log-normal distribution. Gages 2 to 5 miles (3.2 to 8.1 km) apart may differ appreciably in both the mean and standard deviation of the EI;
4. Although EI is correlated with annual precipitation, it is better correlated with individual storms for the Alamogordo Creek area but not on Walnut Gulch;
5. Investigations are needed to facilitate estimating the average annual EI from precipitation data as reported in state climatological summaries for states west of the 104th meridian;
6. Additional work is needed to facilitate the EI value from the precipitation data available in most areas of the Southwest where thunderstorms dominate the rainfall pattern.

Ateshian (1974) suggested that the average annual EI could be related to the 2-year frequency, 6-hour rainfall depth as originally suggested by Wischmeier and Smith (1965). He then presented two dimensionless precipitation distribution curves to represent differing storm patterns encountered in the western U. S., and developed two equations from them to compute the storm EI. In discussing this work, Renard and Simanton (1975b) showed that the two equations postulated by Ateshian for precipitation (one independent of storm duration and one considering storm duration) generally underpredicted the EI units encountered on some of the larger point rainfall depths measured on Walnut Gulch and Alamogordo Creek (Table V). However, these point values are not the 2-year frequency, 6-hour depths, nor do the storms represent the annual total EI. Since this work was completed, Clyde et al. (1976) presented a map of average annual EI units for the intermountain area of the West, but their work is largely untested.

The cropping management factor (c) was developed primarily to handle conditions encountered with crops and rotations in cultivated agriculture. On rangelands, guidelines for determining a C value are not generally available, although the SCS (1972) in Technical Resease 51, with Wischmeier's assistance, presented a table of C values for different canopy types and percent ground covers (Table VI). The work at the Southwest Watershed Research Center indicated that a reasonable C value could be obtained from this table if the cover term includes the erosion pavement. The Center work also proposed that even in very small watersheds, less than 4 ha (10 ac), an additional term may be needed when a watershed contains a stream channel. The term is larger than unity reflecting the contribution to the watershed yield from a channel (Fig. 40).

TABLE V
RAINFALL EROSION INDEX FOR INDIVIDUAL STORMS (RENARD AND SIMANTON, 1975b)

Location (1)	Gage number (2)	Date (3)	Depth, in inches (4)	Duration: Minutes (5)	Duration: Hours (6)	Actual[a] (7)	Rainfall Erosion Index From[b] Eq. 5 (8)	Rainfall Erosion Index From[b] Eq. 7 (9)
Walnut	45	August 17, 1957	2.65	212	3.53	135	37	91
Gulch	56	July 22, 1964	2.54	302	5.03	111	34	70
	52	September 10, 1967	3.45	86	1.43	193	67	248
	02	August 25, 1968	3.07	239	3.98	80	51	119
	59	July 24, 1972	3.20	137	2.28	121	56	169
Alamogordo	34	June 5, 1960	4.07	210	3.50	350	96	235
Creek	21	July 13, 1961	3.53	108	1.80	298	70	235
	34	June 16, 1966	3.98	202	3.37	259	91	228
	61	August 21, 1966	5.46	808	13.47	266	183	239
	38	July 5-6, 1968	3.32	1,549	25.82	17	61	59
	88	July 20, 1972	3.73	1,025	17.08	138	79	93

[a]Computed from raingage chart breakpoints using Wischmeier and Smith (1958) method.

[b]Eq. 5 from Ateshian predicts EI for an individual storm from precipitation only, whereas Eq. 7 includes an additional term for storm duration.

TABLE VI
"C" VALUES FOR PERMANENT PASTURE, RANGELAND AND IDLE LAND[1/] FROM SCS T. R. 51

VEGETAL CANOPY: TYPE AND HEIGHT OF RAISED CANOPY 2/	CANOPY COVER % 3/	TYPE 4/	COVER CONTACTS SURFACE, PERCENT GROUND COVER: 0	20	40	60	80	95-100
COLUMN NO.	2	3	4	5	6	7	8	9
NO APPRECIABLE CANOPY		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.090	.043	.011
CANOPY OF TALL WEEDS OR SHORT BRUSH (0.5 m. FALL HEIGHT)	25	G	.36	.17	.09	.038	.012	.003
		W	.36	.20	.13	.082	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.075	.039	.011
APPRECIABLE BRUSH OR BUSHES (2 m. FALL HEIGHT)	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.085	.042	.011
	50	G	.34	.16	.085	.038	.012	.003
		W	.34	.19	.13	.081	.041	.011

1/ All values assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists.

2/ Average fall height of waterdrops from canopy to soil surface.

3/ Portion of total-area surface that would be hidden from view by canopy in a vertical projection

4/ G Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 inches deep

W Cover at surface is mostly broadleaf herbaceous plants (LIKE WEEDS).

in slugs/ft^3 or pounds/sec^2/ft^4; f = function of the term; and w = fall velocity of sediment, in ft/sec.

To quantify the dynamic behavior of a stream, a relationship was needed to estimate the tributary contributions of runoff and sediment. Analysis of the tributary intersections with the Walnut Gulch main channel involved counting the streams by order (Horton, 1945; Strahler, 1957) on aerial photographs. A minimum least-squares criteria for the normalized data indicated good agreement using a geometric distribution function given as:

$$F(U) = (1-p)^{(U-1)}p \qquad (19)$$

in which U = the stream order; and p = occurrence probability. The agreement obtained in this manner is shown in Figure 42a for four separate channel reaches on Walnut Gulch.

To complete the model for tributary intersections, the frequency, p, and the number of intersections, N, were related to physically measureable watershed characteristics. The relationship (Fig. 42b), which related these terms to the drainage area increases per unit channel length, $\Delta A/L$, seems physically realistic. Thus, as the drainage area increases or as the channel reach length decreases, higher order streams join the channel reach and a corresponding decrease occurs in the number of intersections for the reach.

The simulation also required determining the drainage area, slope and channel width associated with each tributary order, U. The results of this work are shown in Figures 43 and 44.

Although the scatter of data is fairly large in these figures, the results of other investigators (e.g. Leopold and Miller, 1956) lend confidence to the scheme. Variations like those shown in the figures are probably associated with complexities of land form evolution. The displacements of the Leopold and Miller data are probably associated with varying map scale and differences in the structural geology of the watershed involved.

The Diskin-Lane (1972) stochastic ephemeral stream runoff model was used to generate the tributary runoff. The random variables of the model, discussed earlier, were described by distributions related to drainage area.

The entire model was used to simulate the behavior of the lowest 10.9 km (6.8 mi) of channel on Walnut Gulch. The model was verified using the depth-integrated sample data available at the upper and lower ends of the reach. Figure 45 illustrates the variability of the samples collected in 1970 at the outlet of Walnut Gulch. The concentration scatter encountered for a given water discharge is similar to that measured in other years. The lines in Figure 45 represent the predicted concentration-discharge relationship for a rectangular channel using the Manning-Laursen computation relationship. The mean grain size, μ, and the standard deviation, σ, listed on each line are the parameters of a log-normal probability distribution used to describe the size composition of the bed material. The sensitivity of the concentration to differences in the bed material composition and to differences associated with changing the Manning roughness coefficient, n. The shaded portion in the upper left-hand corner of the figure demonstrates the magnitude of the concentration of bedload transport for the listed size distribution and Manning roughness. Observed bed material

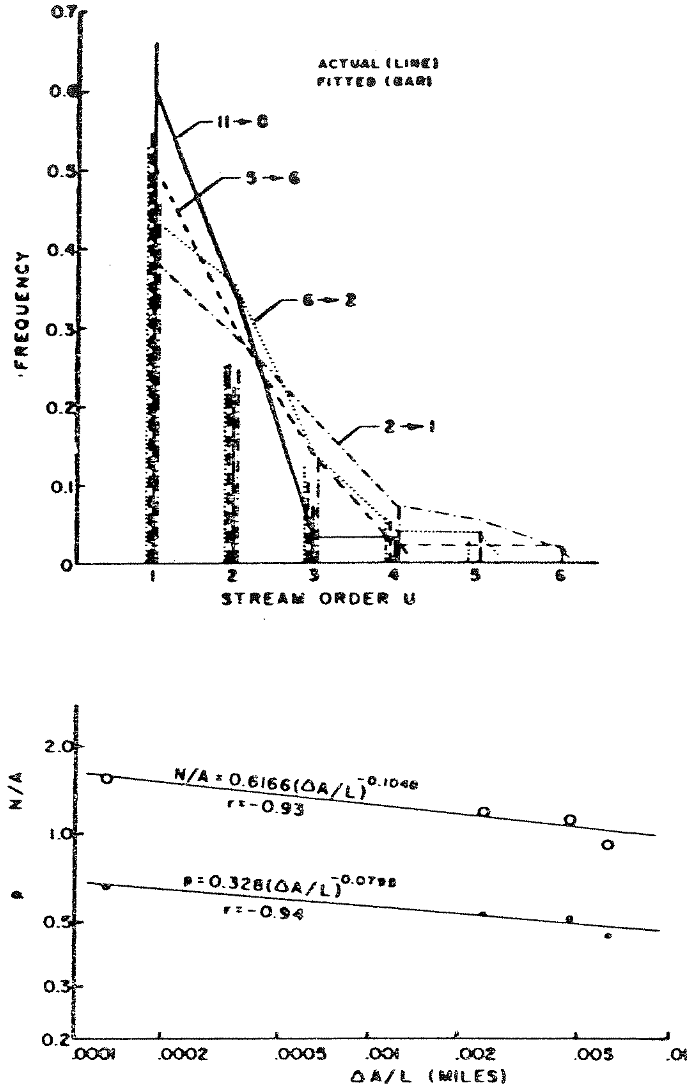

Figure 42 Parameters of geometric probability distribution versus drainage area changes per unit channel length. A = drainage area, in square miles at end of channel reach L, in miles; N = number of stream channel intersections; p = probability of intersection. 1.61km = 1mi. Equations are for English units (Renard and Laursen, 1975)

composition changes are somewhere within the ranges shown in this figure. The bed material size ranges change between flows in response to flow sequences and sources of the runoff itself, because some tributaries are composed of finer materials.

Synthetic runoff and sediment data from both the tributaries and the main channel for the 11,000 m (36,200 ft) channel reach between Flumes 6 and 1 were added for all storms for a 10-year period, using a computer program developed to perform the computations. When just the upstream and downstream stations were considered, a single large storm in each year produced a large portion of the runoff and a still larger portion of the annual sediment discharge. The cumulative water inflow from the tributaries and the upstream end of the channel reach exceeded the outflow, with the difference being transmission losses. As expected, the average loss rate was highly variable with an average of $5.9 \times 10^5 m^3/yr$ (480 ac-ft/yr). Converting this simulated data to infiltration predicts that

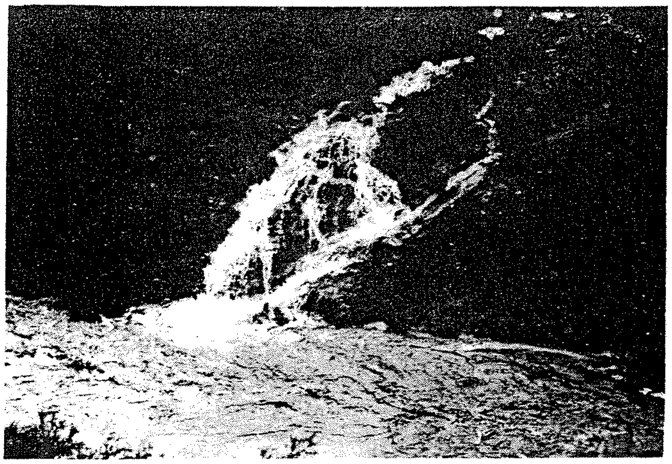

Figure 40 The water moving off the land in this photograph is relatively free of sediment compared to the stream channel in the foreground which has a concentration greater the 2% by weight

(ii) Effects of cover changes on sediment yield

A 44 ha (109 ac) brush-covered watershed in Walnut Gulch was root plowed in 1971 and subsequently reseeded in 1972. The cover changed dramatically as a result of this treatment (Fig. 41).

Figure 41 The fenceline contrast shows the root plowed and reseeded area on the left whereas the untreated area on the right is brush dominated, has little forage production and produces greater erosion than the treated area.

Cattle were excluded from the area from 1971 until the early spring of 1975 when 22 Hereford cattle were allowed to graze for 2 months on 32 ha (80 acres) of the area. The grazing represents 29 animal units/mi^2/yr, or over twice the 12 animal units/mi^2/yr (4.6 animal units/km^2/yr) "rule of thumb" grazing capacity for such an area (the unimproved area will only support about 5 animal units/mi^2/yr). This grazing work continues so it is not yet possible to evaluate the economic gain of such a treatment (cost was $40/ac ($100/ha) for root plowing and seeding). More important is the fact that there was some reduction in runoff and an appreciable reduction in sediment yield (Table VII)

TABLE VII
RUNOFF AND SEDIMENT YIELDS DURING 3 PERIODS OF WATERSHED CHANGE

PERIOD	AVE SUMMER PRECIP		AVERAGE SUMMER RUNOFF				SEDIMENT YIELD			
			Observed		Predicted		Observed		Predicted	
					Per 1" Rainfall	Per 25mm Rainfall	Tons	Tonnes	Per 1" Runoff Tons	Per 25mm Runoff Tonnes
	(in)	(mm)	(in)	(mm)	(in)	(mm)	ac/yr	ha/yr	ac/yr	ha/yr
Before Treatment (Brush Vegetation) 1966 - 1970	9.43	240	0.904	23.0	0.096	2.44	1.67	3.746	1.85	4.150
Transition 1971 - 1973	9.32	237	1.329	33.8	0.143	3.63	1.14	2.557	0.86	1.929
Present Condition After Treatment (Grass Cover) 1974 - 1976	6.84	174	0.131	3.3	0.019	0.48	0.13	0.292	0.99	2.221

Although some brush is again invading the area, only additional data will show whether such treatments have an economic return. However, the reduction in sediment yield would indicate that the important soil resource is being maintained.

(iii) Sediment movement in larger alluvial streams

Two tendencies are apparent in an ephemeral stream channel: (1) To be conves due to losses of discharge by infiltration in the normally dry channel alluvium; and (2) to be concave due to more flow downstream because of tributary inflow. Thus, in addition to variations in sediment transport in perennial streams, with ephemeral streams, the uncertain temporal and spatial precipitation variability plus transmission losses further complicate predicting their behaviour. On most of the larger channels in Walnut Gulch, the channel profile is nearly constant varying above and below a mean value of 1%.

A conceptual model was developed (Renard and Laursen, 1975) to describe this phenomenon. Included was a stochastic model for runoff (Diskin and Lane, 1972) and the Laursen (1958) sediment transport relation. Pertinent equations in the model are:

Manning's equation

$$q = Vy = \frac{1.49}{n} y^{5/3} S_0^{1/2} \qquad (16)$$

where q = discharge per unit width; V = average velocity; y = flow depth; S_0 = bed slope; and n = Manning roughness coefficient:

$$Q_s = B \int_T q_s \, dt = B \int_T \frac{\bar{C} q_w}{265} \, dt \qquad (17)$$

where Q_s = sediment yield (volume); B = stream width; q_s = sediment discharge rate per unit width; q_w = water discharge rate per unit width at time t; T = total timeof an individual hydrograph; and $\bar{C}$ = sediment concentration obtained from the Laursen relationship:

$$\bar{C} = \sum P_i \left(\frac{d_i}{y}\right)^{7/6} \left(\frac{\tau'_0}{\tau_c} - 1\right) f\left[\frac{\sqrt{\frac{\tau_0}{\rho}}}{w}\right] \qquad (18)$$

in which $\bar{C}$ = mean instantaneous total sediment concentration, as a percentage by weight; P_i = bed material fraction of diameter d ($\Sigma P_i = 1.0$); d = diameter of sediment particle, in feet; y = depth of flow, in feet; τ'_0 = boundary shear stress associated with sediment diameter; τ_0 = boundary shear or tractive force at the streambed = $\gamma y S_0$; τ_c = critical tractive force for the beginning of sediment movement; ρ = density of water,

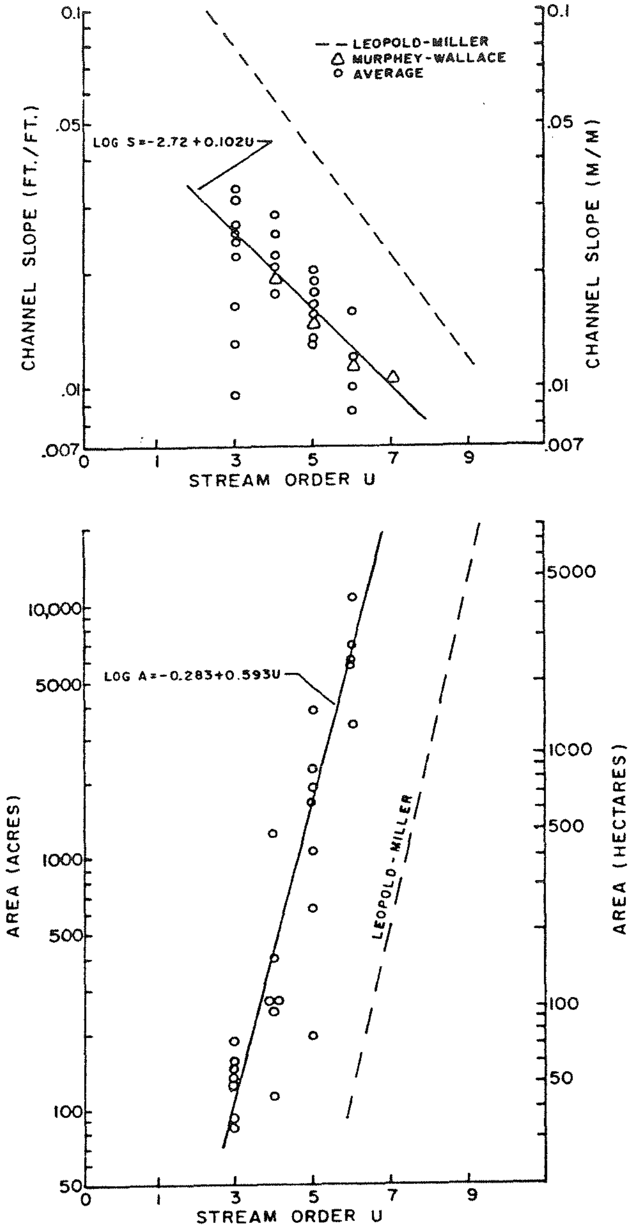

Figure 43 (a) Channel slope versus stream order for Walnut Gulch main channel tributaries; (b) drainage area versus stream order for Walnut Gulch main channel tributaries (4,047m^2 = 1ac). Equations are for English units (Renard and Laursen, 1975)

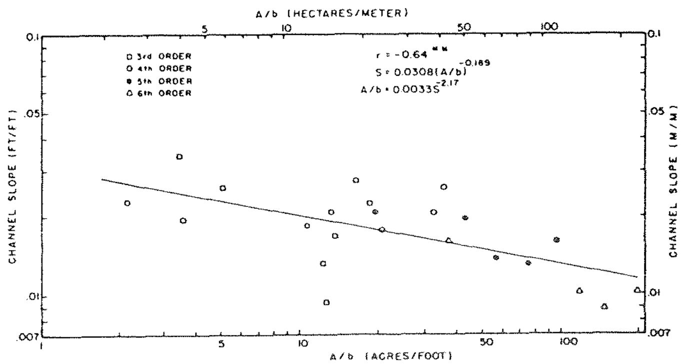

Figure 44 Channel slope versus area per unit channel width from tributaries to main channel of Walnut Gulch. Equations are for English units (Renard and Laursen, 1975)

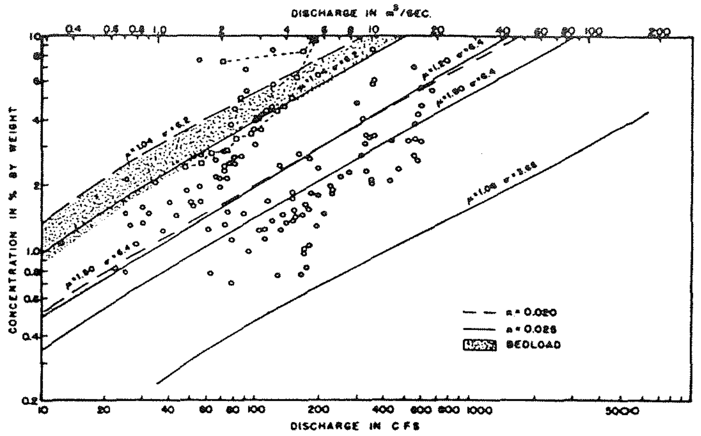

Figure 45 Instantaneous concentration-discharge variations at Flume 1 on Walnut Gulch, and Laursen relation for various μ, σ, and n (roughness coefficient) values. Connected concentration line between individual squares shows typical "7" pattern for samples collected during July 30, 1970 storm; shaded areas shows effect of bedload discharge on concentration (Renard and Laursen, 1975)

1.2 m (3.8 ft) of water per unit wetted area were lost in this reach eachyear, an important item considering that this loss represents the primary groundwater recharge mechanism in many semiarid watersheds.

Cumulative erosion or deposition were also simulated for the channel reach. Although inflow and outflow values vary highly each year, the average erosion and deposition (based on the size distributions assumed for the bed material) was about 15,000 m^3/yr (12 ac-ft/yr) or about 0.3 m in 10 years. Such uniform values would not be expected, however, because bank scour would alter the results.

This same model was used to simulate the relationship between average sediment yield and drainage area (Fig. 46). 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 2,300-ha (450-ac) watershed in this figure. The sediment yield variability corresponding to the runoff variability produced was appreciable. To further illustrate the model sensitivity, the mean grain size was altered to reflect observed size distribution changes, which would produce the range shown. Under most conditions, the sediment transport probably adjusts in some selective process with particle shear changes associated with runoff variability. The bed composition at any time, therefore, is responding to the rate at which material is being supplied to the channel from sediment sources during various hydrologic events.

(b) Chemical Water Quality

The extensive hydrologic studies of the Center's rangeland watersheds are complemented by studies of the chemical quality of waters sampled from stock ponds, groundwater reservoirs, and stream runoff. Chemical analyses yield valuable information about several hydrologic processes, as well as indicate the effects of geology, land management practices, and runoff event characteristics on

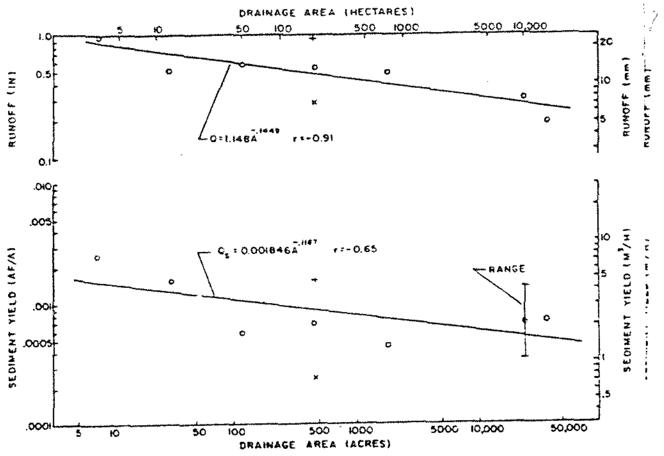

Figure 46 Average annual runoff and sediment yield as functions of drainage area for watersheds in southeastern Arizona, based on Walnut Gulch simulation data. Equations are for English units (Renard, 1972)

water quality. Chemical analysis of water samples includes sediment separation and measurement, pH determination, electrical conductivity measurement, and quantitative analysis of numerous ions.

Wallace and Cooper (1970) conducted a geochemical survey of the Walnut Gulch Watershed, in which they divided the area into generalized sedimentary, igneous, volcanic, and alluvial areas, and analyzed water samples from 82 groundwater wells to determine concentration of calcium, magnesium, sodium, and chloride ions. The chemical and geologic data were coupled to determine subsurface flow patterns throughout the watershed.

On several smaller Walnut Gulch watersheds, a considerable amount of runoff is trapped in man-made stock-watering tanks. Changes in tank water quality with time and their causes and their effects were studied by Wallace and Schreiber (1974). Algae were found to be an important factor in the quality of stock tank water, having a pronounced affect on ion concentrations as the pond receded and the algae died, releasing nutrients it had withdrawn, particularly nitrogen.

The most extensive study of runoff water quality began in 1974 with the collection of samples at four runoff-measuring sites. The areas selected for the water quality study included three small watersheds with varied soils, vegetation, and land use. Samples were also taken at Flume 1, the outlet of the 15,000-ha experimental area. Table VIII compares several characteristics of the four watersheds. Schreiber and Renard (1977) related ion concentrations, pH, and electrical conductivity to sediment concentration, land use, and flow discharge. They stated that high early-season nitrate concentrations in the runoff water could reflect microbial activity in the soil, resulting in nitrification of organic materials made available during the preceding winter and spring. Another explanation may be that all the ingredients required for nitrification are available, but plant uptake is less, early in the runoff season. Phosphate relationships are not similar to those of nitrate. Each area contributes a relatively constant amount per event with the disturbed area contributing consistently higher amounts. There is a better correlation between sediment and P than between sediment and N or EC. Actually, a multifactor relationship could exist: P concentrations are highest when flow rates are lowest and sediment concentrations high. One conclusion is that the amount of P per event might tend to be a fixed amount, or at least a discontinuous function of flow volume: above a threshhold amount of runoff, a relatively fixed increment of P is dislodged from the soil surface.

The geology of each watershed was found to affect the quality of runoff, as would be expected. Calcareous soils produce waters higher in calcium, lower in other cations. Phosphate was found in larger quantities in water from watersheds with less-calcareous soil. Phosphate was hypothesized to be strongly related to soil source, regardless of land use: watersheds Nos. 104 and 121 varied greatly in land use (ungrazed, uninhabited land vs suburban usage), yet their runoff contained similar phosphate concentrations, reflecting their similar non-calcareous soils.

Land use was shown to have a marked effect on nitrate concentration, which is greater on grazed than on ungrazed areas, and increased rapidly with urbanization.

TABLE VIII
WATERSHED CHARACTERISTICS

Watershed	Drainage Area (ha)	Vegetation	Soils	Land Use
001	15,000.	mixed grass-brush	70% Calcareous	Mixed
121	5.26	brush	Rillito-Laveen Gravelly loam	Suburban
112	1.86	grass	Bernardino-Hathaway Gravelly loam	Grazed
104	4.54	brush	Rillito-Laveen Gravelly loam	Ungrazed

TABLE IX
MINIMUM, MAXIMUM AND MEAN OF VARIOUS WATER QUALITY VARIABLES MEASURED ON WALNUT GULCH IN 1974 (Schreiber and Renard, 1977)

Variable	Units	63.121 1/			63.112 2/			63.104 3/			63.001 4/		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
pH		7.80	8.70	8.34	7.00	7.59	7.48	7.40	8.90	8.17	7.4	8.5	8.21
EC	µmhos/cm	85.0	167.	123.	60.0	159.	92.5	80.0	196.	103.	77.0	216.	156.
NO_3-N	ppm	0.03	1.09	0.62	0.20	0.67	0.30	0.08	0.57	0.24	0.01	0.72	0.23
PO_4-P	ppm	0.007	0.50	0.06	0.05	0.70	0.22	0.001	0.25	0.03	0.001	0.16	0.05
HCO_3	ppm	53.	119.	70.7	24.0	45.0	38.6	31.0	120.	58.8	53.0	109.	78.6
Na	ppm	0.65	3.05	1.87	0.92	2.00	1.87	.56	3.65	1.50	1.20	2.40	2.08
K	ppm	1.60	7.15	4.39	4.00	11.5	5.03	1.60	5.40	2.52	2.8	5.60	3.75
Ca	ppm	10.9	29.2	20.9	7.10	13.8	12.3	12.0	28.0	16.5	17.0	34.0	25.1
Mg	ppm	0.52	1.27	0.88	0.48	1.04	0.77	0.49	2.38	1.00	0.93	2.05	1.32
SUM CATIONS	me/L	0.72	1.80	1.31	0.60	1.02	0.89	0.74	1.94	1.03	1.17	2.10	1.55

1/Based on 107 samples - Recently urbanized (1 family dwelling/ha)
2/Based on 33 samples - Heavily-grazed, grass-covered watershed
3/Based on 121 samples - Grazing and other man-related activities excluded for 15 years
4/Based on 65 samples - Outlet of the entire watershed

Table IX contains the minimum, maximum, and mean values of chemical quality variables at the four sites. Sediment concentration at each watershed outlet was observed to vary during individual events, but ion concentrations remained consistent within events, varying more among the watersheds. Seasonal variation of ion concentration was also found, independent of flow discharge rate, sediment concentration, and electrical conductivity.

The chemical constituents examined and reported by Schreiber and Renard are within acceptable ranges for most uses, assuming prior removal of suspended sediment, which is excessive in all the water samples.

(c) Future Water Quality Work

Accelerated activity will be required to meet mandates and deadlines of recent legislation for non-point pollution control. Sediment, the primary pollutant in the arid and semiarid rangeland areas, will thus be a focal point for such work.

Of primary concern will be the development of a more physically-based, complex model to replace USLE. Such an effort was recently demonstrated by Smith (1976) where a kinematic cascade runoff model was used to estimate the shear and subsequent erosion from the land slope within a watershed. Unfortunately, the lack of adequate field data has restricted progress along this line. Thus, a major thrust of our recent work at the Research Center has involved developing a measuring device to automatically collect water quality samples. Development of such a unit (Renard, Simanton, and Donica, 1976), continues with 10 prototype units presently in field operation. The unit illustrated in Figures 47 and 48, is powered by a solar-charged 12-v battery, collects about 1.9 liter (0.5 gal) samples at preset intervals throughout the hydrograph. Despite problems with electronic failures, the unit operated reliably in 1976. The data should be an invaluable aid to both sedimentation and chemical water quality model development.

Besides the erosion from the land surface, channel erosion and stability are important items presently receiving very little research effort. A major deterrent to progress is that the economics of widespread application of channel stability work is not favorable with the current prices of red meat. Social concerns for environmental quality may allow society to bear a portion of the costs for any corrective measure developed.

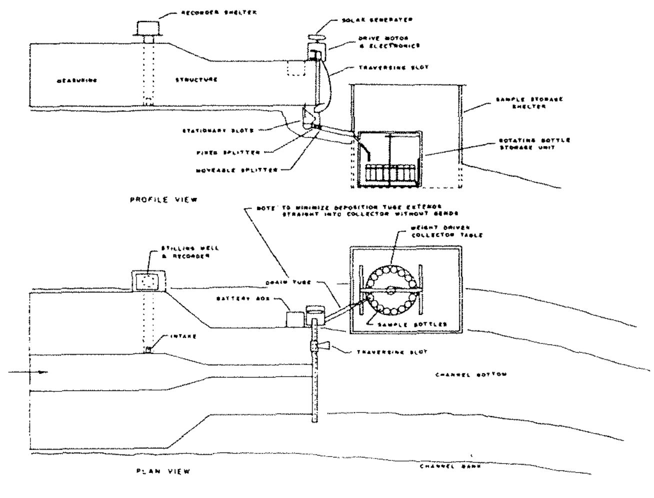

Figure 47 Plan and profile views of the sampler system adapted to a 2.2m^3/sec trapezoidal flume (Renard, Simanton and Donica, 1976)

6 CONCLUDING REMARKS

In 1961, the University of Arizona became the first American university to offer the degrees of Bachelor and Master of Science and Doctor of Philosophy in Hydrology. Thus, hydrology as a recognized discipline is recent. We have all taken part in the transformation of hydrology from an obscure pseudoscience to a precise analytical science, which is still rapidly expanding and becoming increasingly refined. With the modern advances in computers, we can simulate responses which cannot even be measured on a broad scale in

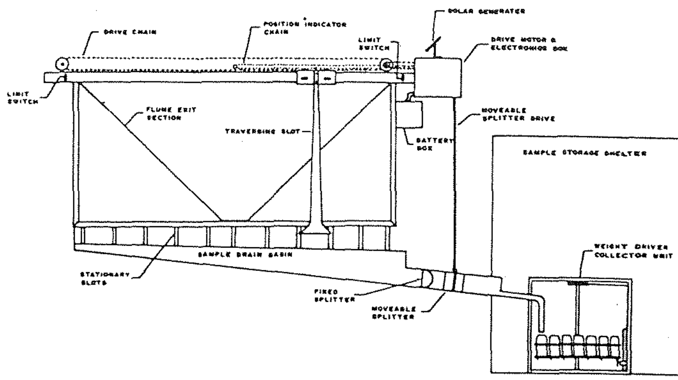

Figure 48 Schematic of sampler details looking upstream into flume (not to scale)(Renard, Simanton, and Donica, 1976)

prototype watersheds. Thus, our field equipment needs refining to collect the quantity and quality of data needed for model development. Much of our hydrologic information is being collected with equipment developed before World War II. Modern technology (like remote sensing, electronic transducers replacing mechanical recording systems, central data recording, and real time data analysis) must be incorporated into our hydrologic (watershed management) research programs. This can best be accomplished by including electronic engineers in our hydrologic research teams.

I see a need and a future trend for hydrologic researchers to justify their work to a greater extent than we have done (in the U.S. particularly). Such work will mean that some researchers will, of necessity, become more involved in technology transfer rather than continuing to proliferate manuscripts in scientific journals where other researchers may read them but where the practicing hydrologist faced with day-to-day decision making does not have the time or the resources to adapt research findings to his particular problem.

Finally, as models become more complicated because of increased understanding of the physics of the system involved, I see a need to use these detailed models as a means of calibrating simpler models, which can be used more efficiently in wide-scale problem solving for specific geographic and climatic areas. Certainly we cannot expect a practicing hydrologist to collect all the data required for some of our models. Rather, a simpler model which can provide the required answers along with estimates of the anticipated confidence limits will be an important end product of our research watersheds.

Increasing competition for research resources will also lead to greater emphasis on "worth of data". This activity which has received considerable attention by some scientists at the University of Arizona (Davis and Dvoranchik, 1971; Davis, D.R., Kisiel, C.C., and Duckstein, L. 1972) will become part of the repertoire of most researchers and will apply widely to planning water resource data networks.

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NOTATION

A,B,b,C,D,	Model parameters.
A	Total area; Estimated soil loss in USLE.
AEI	Air-earth interface.
a	Area within isohyet of air-mass thunderstorm.
b	Channel width.
C	Cropping-management factor of USLE.
$\overline{C}$	Instantaneous sediment concentration.
d	Depth of rainfall within isohyet of air-mass thunderstorm; Diameter of sediment particles.
EI	Erosion index, rainfall factor (also called R) of USLE.
f	Infiltration rate; Function of term.
F & G	Functions of terms.
h	Elevation; Depth of flow.
h_a	Air pressure head.
h_s	Effective surface head.
h_w	Surface water head.
I_v	Infiltration volume.
IUH	Instantaneous unit hydrograph.
K	Soil-erodibility factor in USLE: Time Constant of a linear reservoir.
l	length
L	Transmission loss rate; Time to centroid of IUH: Slope length factor in USLE: Length of plane or channel.
L_o	Maximum length of overland flow.
l_a, l_o	Latitude and longitude.
ln	Natural (base e) logarithm.
log	Base 10 logarithm.
m	Exponent in flow velocity relation.
n	Exponent in flow discharge relation; Julian day of year; Day of season; Manning roughness coefficient.
N	Number of planes in cascade model; Number of reservoirs in cascade model; Average number of storms in season.
p	Probability.
P	Inflow in storage routing model; Erosion control practice factor in USLE; Precipitation; Bed material fraction.
q	Discharge per unit width.
Q	Outflow: Local discharge; Runoff hydrograph ordinate.
Q_s	Sediment yield.
q_k	Outflow predicted by deterministic kinematic model.
q_m	Outflow measured in real system.
q_s	Outflow predicted by systems model.
r	Rainfall rate.
R	Rainfall rate; Rainfall factor (also called EI) in USLE: Rainfall excess.
R^2	Goodness-of-fit statistic.
RC	Rough, closed air-earch interface model.
RO	Rough, open air-earth interface model.
RP	Rough, partly open air-earth interface model.
S	Slope; Slope gradient factor in USLE: Storage.
$\dot{S}$	Derivative of storage with respect to time.
SC	Smooth, closed air-earth interface model.
SO	Smooth, open air-earth interface model.
SP	Smooth, partly open air-earth interface model.
SEE	Standard error of estimate.
T	Time.
T_o	Normalizing time.
T_p	Time to hydrograph peak; Time of ponding
T_R	Time (duration) of hydrograph recession.
t	Time.
U	Stream order; Local flow velocity.
U_p	Peak ordinate in double triangle unit hydrograph.
$U_p(t)$	Unit pulse response.
U_t	Instantaneous unit hydrograph ordinate at time t.

USLE	Universal Soil Loss Equation.
u	Local flow velocity.
w	Fall velocity of sediment in Laursen relationship.
W	Width of plane or channel.
x	Daily rainfall depth; Channel length.
X	Seasonal rainfall depth; Inflow to IUH model.
X_c	Inflection point in rainfall depth curve.
y	Depth of flow.
Y	Outflow in IUH model.
Z	Inverse of slope
α	Coefficient in flow continuity equation; Roughness slope factor; Ordinate ratio in double triangle unit hydrograph model; Parameter in models.
β	Time ratio in double triangle unit hydrograph model; Parameter in models.
Δ	Increment
θ	Percent water content of soil.
λ	Parameter in rainfall depth distribution formula.
μ	Mean
ρ	Density of water
τ_c	Critical shear for incipient motion.
τ'_0	Boundary shear associated with sediment diameter.
τ_0	Tractive force at the streambed.
ψ	Soil capillary potential.

SUBSCRIPTS

*	Dimensionless.
∞	Variable at t = infinity.
0	Initial.

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