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HYDROLOGY OF SEMIARID RANGELAND WATERSHEDS

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INTRODUCTION

Arid and semiarid lands make up one-third of the world's land mass, occur on most continents of the earth, and support about one billion people, or one-fifty of the human population. UNESCO (1977) used Penman's (1948) formula for evaporation to modify a climatic map developed by Meigs (1953) to delineate the distribution of the world's drylands (Fig. 1). The map shown in Fig. 1, which excludes the cold, polar regions, has become the accepted standard for the distribution of the drylands of the world. The Mojave, Sonoran, and Chihuahuan deserts dominate the arid and semiarid environment of the southwestern United States and northern Mexico.

About 96% of arid and semiarid zones are classified as rangeland. Rangelands are those lands where the primary use of the forage produced is for grazing animals. Generally, these lands are fragile ecological systems, very sensitive to changes in climate, soils, and vegetation (Wight and Skiles, 1987). They are characterized by a mixture of slopes including many that are steep, shallow soil mantles, and extremes in the various components of the hydrologic cycle; examples being the extreme spatial and temporal variability of precipitation, high evaporation rates, and low water yield. If the vegetation cover is reduced by occurrences of droughts, mismanagement, or combinations of both, soil erosion by wind and water can accelerate to the extent that the entire soil mantles are lost (Wight and Skiles, 1987).

The purpose of this paper is to describe work with special focus on the characteristics of hydrologic processes associated with semiarid rangeland watersheds. The paper presents experience gained in the semiarid areas of the southwestern United States, primarily in terms of the research conducted at the Walnut Gulch Experimental

Watershed operated by the U.S. Department of Agriculture (USDA) - Agriculture Research Service (ARS) in Tucson, Arizona.

HYDROLOGIC RESEARCH AT THE WALNUT GULCH WATERSHED

Research on Walnut Gulch Experimental Watershed in the southwestern United States was initiated by the ARS in 1954. In 1961 the Southwest Watershed Research Center, with headquarters in Tucson, Arizona, was established to continue the work. Most of the research has been devoted to the 150-square-kilometer Walnut Gulch Experimental Watershed (31°43'N, 110°41'W) near Tombstone, Arizona, just north of the transition between the Chihuahuan and Sonoran deserts. Mean annual temperature at Tombstone, Arizona and the surrounding Walnut Gulch Experimental Watershed is 17.6 °C and mean annual precipitation is between 300 and 600 mm depending upon the record period. Following the modified Koppen's climate classification method (Trewartha, 1954), the climate at Tombstone can be classified as hot semiarid or steppe with a dry winter (BSh) but is quite close to being a cold arid or desert climate (mean annual temperature less than 18°C and mean annual rainfall less than 318 mm). The climate-soil-vegetation complex at the Walnut Gulch Watershed is taken here to be representative of approximately 60 million hectares of brush and grass covered rangelands found throughout the semiarid southwestern United States and northern Mexico. Cattle grazing is the primary land use within the watershed with mining, limited urbanization, and recreation making up the remaining uses.

The Walnut Gulch water balance, although variable from year to year as well as across the area, is obviously controlled by precipitation. Fig. 2 illustrate the water balance for average conditions. Given the average 305 mm input precipitation, approximately 254 mm (83%) is detained on the surface for subsequent infiltration. Essentially all of the infiltrated moisture is either evaporated or transpired by vegetation back to the atmosphere. Based on data collected from small runoff plots, approximately 51 mm (17%) of the incoming precipitation is in excess of that which is intercepted and/or infiltrates. We refer to this as "on-site runoff." As the runoff moves over the land surface and into the dry land alluvial channels, transmission losses begin. Approximately 45 mm (88% of the "on-site runoff") of transmission losses occur and approximately 6 mm (12%) of surface runoff are measured at the watershed outlet. The 45 mm of transmission losses result in some ground water recharge and some evaporation and transpiration from vegetation along the stream channels. Fig. 2 does not show quantities for ground water recharge and evaporation and transpiration of channel losses, because their quantification is difficult and site specific. The geology along and beneath the stream channel creates some reaches that are underlained by impervious material, whereas in other locations, the channel fill material extends to regional ground water and permits recharge to occur. Where the channel is underlained by impermeable material, riparian aquifers connected to the channel support phreatophytes and saturated alluvium following major runoff events. Potential evaporation from Class A USWB pan is approximately 267 cm per year which is approximately 8.7 times the annual precipitation.

Research at the Walnut Gulch Experimental Watershed has been oriented towards at: 1) obtaining information needed for planning and designing measures for controlling flash floods and sediment damage; 2) determining the optimum utilization of available water for local and downstream uses; and 3) determining the future water yield potential of semiarid rangeland watersheds as related to measures for their conservation and sustained forage production. These research objectives have been realized in two stages pursued simultaneously. The first stage involved identifying and quantifying the relevant factors controlling hydrologic processes and the mobilization and transport of sediment and associated pollutants. The second stage involves evaluating the effect of range improvement practices and other experiments on watershed water quantity and quality, and sediment balances.

Precipitation

Precipitation in the semiarid rangeland watersheds of the southwestern United States varies considerably from season to season and from year to year. Fig. 3 shows the seasonal nature of the precipitation and runoff on Walnut Gulch Watershed. Approximately two-thirds of the annual precipitation on the Walnut Gulch occurs as summer rainfall resulting from moist air masses advancing into Arizona from the Gulf of Mexico. These summer storms are characterized by high-intensity, short-duration, limited areal extent, air-mass thunderstorms. Winter storms result primarily from cyclonic storms originating in the North Pacific Ocean and 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. Runoff from winter storms is limited to extremely small areas where the water storage potential of the soil and of the stream channel alluvium is minimal. Thus, the runoff shown in Fig. 3 results from the intense thunderstorms of July through September.

Osborn (1983) reported, based on records from 1956-80, that annual precipitation varied from 170 mm in 1956 to 378 mm in 1977 (Fig. 4). Summer rainfall (July-September) varied from 104 mm in 1960 to 290 mm in 1966; and winter precipitation (December-February) varied from 25 mm in 1966-67 to 233 mm in 1978-79.

Precipitation Modeling

Stochastic precipitation models are characterized by at least two and sometimes three classes of random variables and their probability distribution functions. First, there is the random number of events or alternatively, the interarrival time between events. Herein, an event is defined as one in which a storm center (point of maximum rainfall) occurs within a watershed. Second, there is a description of the event characteristic such as storm depth, duration or maximum intensity for a specified period of time, or a combination of these variables. A third class is the location of the storm center on a particular sub-area of a watershed.

Summer Precipitation Model - Thunderstorms in the southwestern United Sates seem to occur in an independent manner in time and space. Data collected from the Atterbury Experimental Watershed in Tucson, Arizona, indicated a definite trend towards a Poisson variate for the number of storm events per season. Further evidence justifying the Poisson distribution has been obtained by Kisiel et al. (1971), Baran et al. (1971), Woolhiser and Todorovic (1974), Bogardi and Duckstein (1978) and others. Interarrival times, T, between events follow an exponential distribution function. Inasmuch as the occurrence of summer storms is seldom a pure Poisson process, the distribution for interarrival times can sometimes be described by a gamma (or negative binomial) distribution rather than an exponential (or geometric) distribution.

Fogel and Duckstein (1969) derived a geometric distribution for point rainfall depths under the assumption that the occurrence of thunderstorms and the maximum depth of rainfall within that storm are independent variables. Under the same conditions, Duckstein et al. (1972) showed that the distribution for mean areal rainfall could be described by a negative binomial distribution. Analysis of rainfall data in Tucson, Arizona, suggests that the two-parameter J-shaped gamma distribution, a continuous version of the negative binomial distribution, can provide a better fit to rainfall depths per event than the derived geometric distribution; this is especially important for a proper fitting of the tail of the distribution.

Winter Precipitation Model - Duckstein et al. (1975) developed a probabilistic winter precipitation model for the Sonora Desert based on the assumption that the occurrence of a particular event or sequence of events is somewhat dependent on past events. In the case under consideration, an event was defined as a sequence of consecutive wet days in which an amount of precipitation equal or greater than 0.25 mm was recorded for each day. The model employs a mixed distribution to describe the number of events in an interval of time. Random variables used in this model are schematically shown in Fig. 5. The number of storm sequences as described by a Poisson distribution and the interarrival time between sequences is exponentially distributed. The number of dry days between groups is described by a uniform distribution. The amount of precipitation per storm group was described by a gamma distribution.

Interception and Throughfall

Precipitation interception by vegetation results in the incoming precipitation being partitioned into three components; part is retained on the foliage, part is channeled down the branches and stems, and part drips off the branches. Runoff is also modified because of the altered intensity and distribution characteristics and the improved soil permeability caused by the presence of the vegetation. This particularly applies to the portion of the precipitation which is channeled down the trunks of the trees since root density and soil permeability are highest in this zone. In semiarid rangeland watersheds, this is of special importance since it concentrates water and raises the chances of deep infiltration.

Measurements of precipitation interception have usually been made with trees or other woody plants because of the difficulties in arranging adequate interception devices on more ephemeral or smaller plants. The amount of precipitation intercepted depends on the diversity of the vegetation, its morphological structure, and the duration and intensity of the precipitation. As an example of the degree of interception which can take place with semiarid plant communities, the study of Haworth and McPherson (1991) should be cited. This study was conducted in oak woodlands of the southeastern Arizona to determine the loss of rainfall as the result of its interception by oak trees. The study reported that up to 70 percent of the late summer and early fall rainfall was intercepted directly under the canopies of Emory oak trees (*Quercus amoryi* Torr.). Little differences in precipitation were observed between the edge of the canopies and tree-free locations. Throughfall varied from 100% (all trees, large storms) to about 30% (large trees, small storms). Small Emory oak trees affected rainfall distribution only during small storms of relatively limited duration. Larger trees affected rainfall during larger storms up to about 25 mm depth. Rainfall was distributed evenly under and around trees in storms generally larger than 25 mm. Simanton et al. (1991) found no difference in runoff and erosion response from canopy clipping in a rainfall simulator experiment on brush dominated plots.

Interception Modeling

Simple empirical models have been proposed to describe interception losses. Classic examples are the models proposed by Horton (1919) and Linsley et al. (1949). Horton (1919) related the total interception loss for a storm to the storage capacity of the vegetation and the rate of evaporation. Horton developed a series of empirical equations for various types of vegetal cover. Linsley et al. (1949) presented an equation based on the assumption that the total interception loss for a storm would be approached exponentially with rainfall increasing from zero to some high value. Following the concept of Linsley and others, Meriam (1960) modified the Horton equations to produce a model that describes interception reasonably well since it considers an exponential increase in storage with increasing precipitation. Amisial et al. (1969) developed a model of the surface runoff process for use in sparsely vegetated watersheds subjected primarily to thunderstorm runoff. The model contained a retention rate which defined losses due to the combined effects of depression storage and vegetation interception.

In some recent efforts to develop catchment-scale hydrologic models, interception losses have been lumped with infiltration to provide an estimate of the precipitation excess when subtracted from the gross precipitation. Interception is larger on small storms and in heavy cover conditions. On the other hand, it is smaller (even in forests) or in light cover situations (such as sparse cover rangelands) and on a volume basis, may not have much of an effect of flood flows.

Evaporation and Transpiration

For most rangelands, evaporation and transpiration represents by far the largest water loss from land surfaces. Evaporation from free-water surfaces, ranging from small farm ponds to irrigation channels and large reservoirs, is a major factor in reducing water storage in arid and semiarid watersheds. Semiarid rangeland watersheds annually lose about, 1,690 mm of free-water surface evaporation on the average (Cooley, 1970). Extremes in annual evaporation from free-water surfaces in the southwestern United States ranges from 1,563 to nearly 1,750 mm. In addition, because of the low plant density, direct evaporation of water from the soil surface is of enhanced importance, and frequently as much as one-half of the annual rainfall can be lost in this manner. Determination of evaporation losses is required in quantification of catchment water balance under existing management practices and proposed alternatives.

Transpiration, while basically a physical process in that the energy for the evaporation of water from plants is derived form solar radiation, is also affected by the physiological and anatomical characteristics of the plants themselves.

Because of the low plant density and relative physiological inactivity characteristic of arid and semiarid plant communities, evapotranspiration rates, even when the soil water is freely available, are usually well below those characteristic of physiologically active, dense communities, which can reach levels close to those for potential evapotranspiration.

Evapotranspiration Modeling

One problem that has limited the development of catchment water balance models at present is the large but poorly defined evapotranspiration component; this component is invariably derived as a residual on the closure of the water balance after other components are measured directly. Evapotranspiration estimated in this fashion thus contains errors associated with measurement of the other components, and the time resolution of this evapotranspiration is coarser than desired for catchment-scale water balance modeling.

Several methods have been proposed for relating evapotranspiration to fundamental meteorological variables (Jensen et al., 1989). Most of these methods estimate potential evapotranspiration, which is the evapotranspiration of a reference crop when soil moisture is freely available to the plants. The most practical and widely used of these methods have been summarized by Doorenbos and Pruitt (1977). Penman's method (1948) is based only on available energy, wind and humidity deficit of the air. The Priestley-Taylor method (1972) is a simplification of Penman's method that is based on available energy only. The Blaney-Criddle method (1962) is the simplest method, being based on mean monthly temperature and empirical coefficients. Potential evapotranspiration can also be estimated from pan evaporation. A variety of methods have been proposed to relate actual to potential evapotranspiration, but all of them necessarily rely on assumptions concerning the way in which water is retained in the soil and the ultimate disposition of soil moisture. This is clearly unsuitable for estimates whose goal is actually determining the fate of water once it has fallen on the earth.

The best practical model for estimating evapotranspiration would take advantage of existing data bases and be relatively insensitive to parameters that are difficult to measure precisely or vary considerably in the locale of the weather station. Some of the most significant variables related to evapotranspiration are vapor pressure deficit, wind, radiation balance, soil moisture and the deference between air temperature and canopy (or surface) temperature. As evapotranspiration is strongly influenced by vegetation when the surface is not saturated, the type, condition and maturity of vegetative cover is important. It is thus necessary to evaluate "classical" evapotranspiration models, as well as to test new models of actual evapotranspiration.

Soil Water and Infiltration

Because of the short but high rainfall amounts associated with thunderstorms, surface soil infiltration rates play a critical role in determining the partitioning between runoff and soil storage. Many dryland soils are specially sensitive to disturbances in infiltration capacity because they contain little organic matter and have a low aggregate strength. The impact of rain on exposed soil is a major factor in dispersing particles, a fact that leads to low-permeability crusts and increased runoff (Summer and Stewart, 1992).

Infiltration Modeling

Much progress has been made in soil physics and porous media flow for theoretically describing unsaturated soil water movement. Some of this recent progress has been associated with rapid developments in digital computers which has facilitated numerical solutions of partial differential equations. For example, 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.

Infiltration work at the Walnut Gulch Watershed has been in two general areas of infiltration: (1) the use of infiltration equations to compute rainfall excess in runoff simulation modeling, and (2) infiltration measurement and control through soil surface management to improve forage production and to reduce soil erosion.

In the semiarid rangeland watersheds of the southwestern United States, the problem of computing precipitation excess (gross precipitation minus infiltration) is compounded not only by the precipitation variability but also by infiltration variability. A typical soil profile varies appreciable from ridge top to the channel bottom, with corresponding changes in its infiltration capacity. Partial area runoff dominates in many rangelands with high infiltration beneath a plant canopy and low infiltration in the interspaces between plants where surface seals persist (Summer and Stewart, 1992). An objective procedure to account for this variability is presently deficient.

Runoff and Streamflow

Most of the rain falling on semiarid rangeland watersheds is intercepted by vegetation, absorbed by the porous mantle of soil and rock waste, or evaporated. Since dryland rainfall is naturally infrequent and short-lived, these initial losses are proportionately greater than in humid regions, so that, in general, percentage runoff tends to decrease with annual rainfall and is lees than 10% in most arid zones (Slatyer and Mabbutt, 1964). We do not agree with this statement. In general, annual runoff increases with annual rainfall in a mildly exponential model of the form $Q = aP^2$, where Q is annual runoff and P is annual rainfall. The intensity of rainfall, in general is often as important as the total amount of rainfall in producing runoff. In many semiarid areas, thunderstorms with high intensity can be very important in runoff generation. The contributions of subsurface and groundwater flows to stream flow are characteristically minimal.

Runoff is difficult to measure in ephemeral streams. An early effort at the Valnut Gulch Watershed involved designing and building suitable measuring structures o provide a satisfactory hydraulic control while allowing the high sediment and debris oads to pass through the structure. Conventional current metering stations were mpractical because of the extremely high point velocities (up to 7.0 m/s) and the rapidly hanging stages. Following hydraulic models studies, supercritical measuring flumes vere installed in the Walnut Gulch. Field observations of these flumes have indicated atisfactory field performance and close comparison with hydraulic model studies in aboratories (Gwinn, 1970; Smith et al., 1982).

Runoff Modeling

By far the most popular empirical model for storm runoff prediction is the Curve Number (CN) method (Soil Conservation Service, 1972), originally developed by the SDA for use in conservation planning and engineering design, mostly in croplands. urve number values required to apply the method are available for a variety of soils and egetative types. A step towards testing of this approach involves determing Curve umbers values for rangeland watersheds from local rainfall and runoff data obtained om instrumented watersheds (Hawkins, 1981).

The kinematic wave approach, a major component of process-based hydrologic iodels, is a widely used method to simulate the movement of rainfall excess water over ie land surface and through small channels. Although the kinematic wave method quires simplifying assumptions regarding solution of the complete equations for ontinuity of mass and momentum, its hydraulic requirements are well established Wooding, 1965; Woolhiser and Liggett, 1967) and has been extensively verified by xperiments (Rovey and Woolhiser, 1977; Lopes and Lane, 1990; Woolhiser et al., 990). Its testing and application to semiarid rangeland watersheds depend largely upon ata gathering and analysis from carefully designed field experiments with both natural nd simulated rainfall conditions. This approach further requires a geometrical atershed representation which usually consists of sequences (cascade) of overland flow lanes discharging into channel elements. Each plane or channel element must be haracterized by a length, width, slope, hydraulic conductivity parameter, and a oughness parameter. For channel elements, a cross-section geometry also is needed.

Transmission Losses

An important component of a semiarid catchment water budget is streamflow bstraction or transmission losses from infiltration in the channel beds and banks. Transmission losses are important because water infiltrates when flood waves move rough the normally dry stream channels, reducing runoff volumes and flood peaks

(Babcock and Cusing, 1942; Renard, 1970), and affecting components of the hydrologic cycle, such as soil moisture and ground water recharge. An example of transmission losses is presented in Figs. 6 and 7. The August 27, 1982 storm, illustrated in Fig. 6, was isolated in subwatershed 6 on the upper 95 km^2 of the Walnut Gulch Watershed (and not all of that produced runoff). The streamflow measured at Flume 6 (Fig. 7) amounted to $2.46x10^5$ m^3 with a peak discharge of 107 m^3/s. Streamflow traveling 4.2 km of dry streambed between Flume 6 and Flume 2 resulted in significant infiltration losses (Keppel and Renard, 1962; Renard, 1970; Lane, 1983). For example, in the 4.2 km reach the peak discharge was reduced to 72 m^3/s and 48,870 m^3 of water infiltrated into the channel alluvium. During the course of the 6.66 Km from Flume 2 to Flume 1, the peak discharge was further reduced, and 41,930 m^3 of water infiltrated into the channel alluvium.

Transmission Losses Modeling

Procedures have been developed to estimate transmission losses for flow events in ephemeral stream channels. For example, Lane (1983, 1990) developed a differential equation describing transmission losses in a channel reach based on the assumption that the volume of losses in a channel reach is proportional to the upstream inflow volume, a constant or steady-state loss rate, and the lateral inflow rate per unit channel length. Woolhiser et al (1990) used an infiltration equation with kinematic flow routing.

Erosion and Sediment Yield

Erosion and sediment yield in the southwestern United States have been the object of numerous investigations. Renard and Foster (1983) presented the general principles of water erosion on semiarid rangelands. A more comprehensive overview of the mechanics of erosion, sediment transport, and deposition processes was presented by Foster (1982). Several studies of sediment transport in ephemeral streams have been reported. Langbein and Schumm (1958) showed that most of the sediment movement originates from sparsely vegetated stream banks. Much of this sediment is generated from channel cutting and bank sloughing (Osborn and Simanton, 1986; Renard and Laursen, 1975; Lane, 1982a,b). Erosion pavements have also been demonstrated to have a dramatic effect on reducing hillslope erosion (Simanton and Renard, 1992).

On semiarid rangeland watersheds in southwestern United States, the rate of sediment transport in the alluvial channels composed of noncohesive sediment is controlled by a number of noteworthy phenomenon characteristic of these lands. These phenomena are: 1) high intensity thunderstorms which result in large peak discharges per unit area; 2) limited areal extent rainfall which results in partial area runoff; 3) erosion pavements which protect the land surface from raindrop energy; 4) transmission losses on normally dry stream beds which result in a decrease in sediment transport capacity in the downstream direction; 5) generally steep channels which result in high flow velocities with increased potential for transporting more sediment; and 6) unconsolidated stream bed material and unprotected stream banks, enhancing sediment supplies or sources.

Erosion and Sediment Prediction Modeling

Existing modeling technology for sediment yield assessment and prediction on semiarid rangelands include the Universal Soil Loss Equation (USLE), (Wischmeier and Smith, 1978), the Revised Universal Soil Loss Equation (RUSLE), (Renard et al., 1991), SPUR (Simulation of Production and Utilization of Rangelands), (Wight, 1983; Wight and Skiles, 1987), the Water Erosion Prediction Project (WEPP) (Lane and Nearing, 1989), and the Watershed Erosion Simulation Program (WESP) (Lopes, 1989). A more comprehensive overview of erosion and sediment prediction modeling approaches was presented by Lopes and Ffolliott (1992; 1993).

The USLE is the technology most widely used today for upland erosion prediction. The equation was developed as a method to predict long-term average annual soil loss from interrill (sheet erosion) and rill areas. Despite its widespread use and the breadth of experience which it incorporates, the equation is empirically based on data gathered from uniform slope test plots. Several modifications of the USLE have been proposed to overcome its conceptual limitations (Renard et al., 1974; Williams, 1975; Onstad and Foster, 1975). All these modifications, however, do not eliminate the primary limitations of the USLE for application to rangelands affected by severe rilling or gully erosion. A revision of the USLE (RUSLE), is currently under development by researchers of the ARS (Renard et al., 1991; Renard, 1992). Although this effort is nearing completion, there will be a need for continuing effort by ARS scientist to address question arising from use of the equation on semiarid rangelands.

The SPUR model (Wight and Skiles, 1987) is another ARS effort to develop a model for use with rangeland resource planning. The model provides a basis for management decisions by predicting runoff, erosion (using the modified USLE), herbage yields and livestock production. The sediment load in stream channels is divided into suspended particles (sizes less than 0.062 mm in diameter), and bed load (sizes greater than 0.062 mm). Only the bed material has a particle size distribution associated with it. Bed load (assumed at transport capacity condition) is computed with a modified Duboy's equation. Suspended load is determined from a modified Bagnold equation (Lane, 1982b).

The WEPP (Water Erosion Prediction Project) is a modeling effort initiated by the ARS in 1985 (Foster and Lane, 1987; Lane et al., 1988). This effort involves three separate model versions: hillslope, watershed, and grid models. The modeling approach used in WEPP is limited to areas where the hydrology is dominated by overland flow and should not be applied where partial area response hydrology and subsurface flow dominate. The WEPP computer program is a continuous simulation model with a daily time step. The hillslope profile version computes the soil, surface, residue, and crop conditions on a daily basis, and if there is rain, it computes surface runoff and soil erosion. Soil erosion is modeled using fundamental erosion concepts. The WEPP model has a number of components including soils, infiltration, winter (snow) hydrology, erosion, crop growth and residue decomposition. A climate generator constructs a representative period of daily weather for a particular location. This daily weather includes precipitation amount and characteristics, temperatures and wind. Input data include management, topography, soil and climate information. The watershed and grid versions require additional information about channel networks and structures.

WESP (Lopes, 1989) is a process-based, distributed parameter, numerical model for simulating surface runoff, erosion and sediment yield on small semiarid watersheds. The model includes components for computing rainfall excess rates, broad sheet flow (interrill flow), concentrated flow (rill and stream channel flow), erosion, sediment transport, and deposition. Rainfall excess is estimated using the Green & Ampt infiltration equation with the ponding time calculation for an unsteady rainfall. The broad sheet and concentrated flow components are based on the kinematic wave equations. The erosion and sediment yield component is based on nonequilibrium dynamic sediment transport equations for simultaneous rates of entrainment and deposition. The watershed geometry is represented on WESP by a simplified scheme consisting of discrete broad sheet flow planes discharging into concentrated flow elements. The model was tested using runoff and sediment data from the Walnut Gulch Watershed. The results indicated that the governing equations, the initial and upper boundary conditions, and the structural framework of the WESP model can describe the spatial-temporal variability of runoff and sediment processes on small semiarid rangeland watersheds.

Erosion and sediment prediction on semiarid rangelands requires a modeling approach that begins with the soil detachment process by raindrop impact and runoff, and accounts for the spatial and temporal variability of the flow and sediment transport-deposition processes as the sediment moves downstream from its point of origin. It is equally important that this modeling approach has the capability to predict erosion and sediment yield under current and alternative range management conditions. It is necessary that such a model identify the underlying causes of the erosion and sediment damages, determine the sources of erosion and sediment causing such damages, and formulate cost-effective erosion and sediment pollution control measures. Although erosion prediction technologies such as RUSLE, SPUR, WEPP, and WESP have been, or will soon be, used for sediment yield assessment and prediction on rangeland watersheds, many assumptions associated with the mathematical formulations in these models are in need of refinement. There are additional problems which the models need to address using better hydrologic and sediment research knowledge in order to enhance overall model utility.

CONCLUSIONS

The scientific challenge is to understand how the hydrology of semiarid rangeland watersheds functions and to recognize and distinguish changes resulting from natural climate variation, changes associated with management practices, and changes reflecting new climatic regimes that result indirectly from human activity. The following conclusions are based on the experience gained in the semiarid areas of the southwestern United States, primarily from research conducted at the Walnut Gulch Experimental Watershed operated by the U.S. Department of Agriculture (USDA) - Agriculture Research Service (ARS).

a) Hydrologic processes in rangeland areas are characterized by extreme variability in precipitation, soil moisture, and runoff.

b) Precipitation from various moisture sources in the southwestern United States and areas of northern Mexico result in extreme runoff variability.

c) Transmission losses (infiltration in normally dry alluvial channel beds) dominate the runoff response of watersheds in individual storm events.

d) Transmission losses from ephemeral stream channels can be a primary source of groundwater recharge.

e) A comprehensive database like that available from the Walnut Gulch experimental watershed is essential for model building and testing in order to manage a watershed's natural resources.

f) Sediment yield in many semiarid areas is dominated by erosion from the stream bed and banks.

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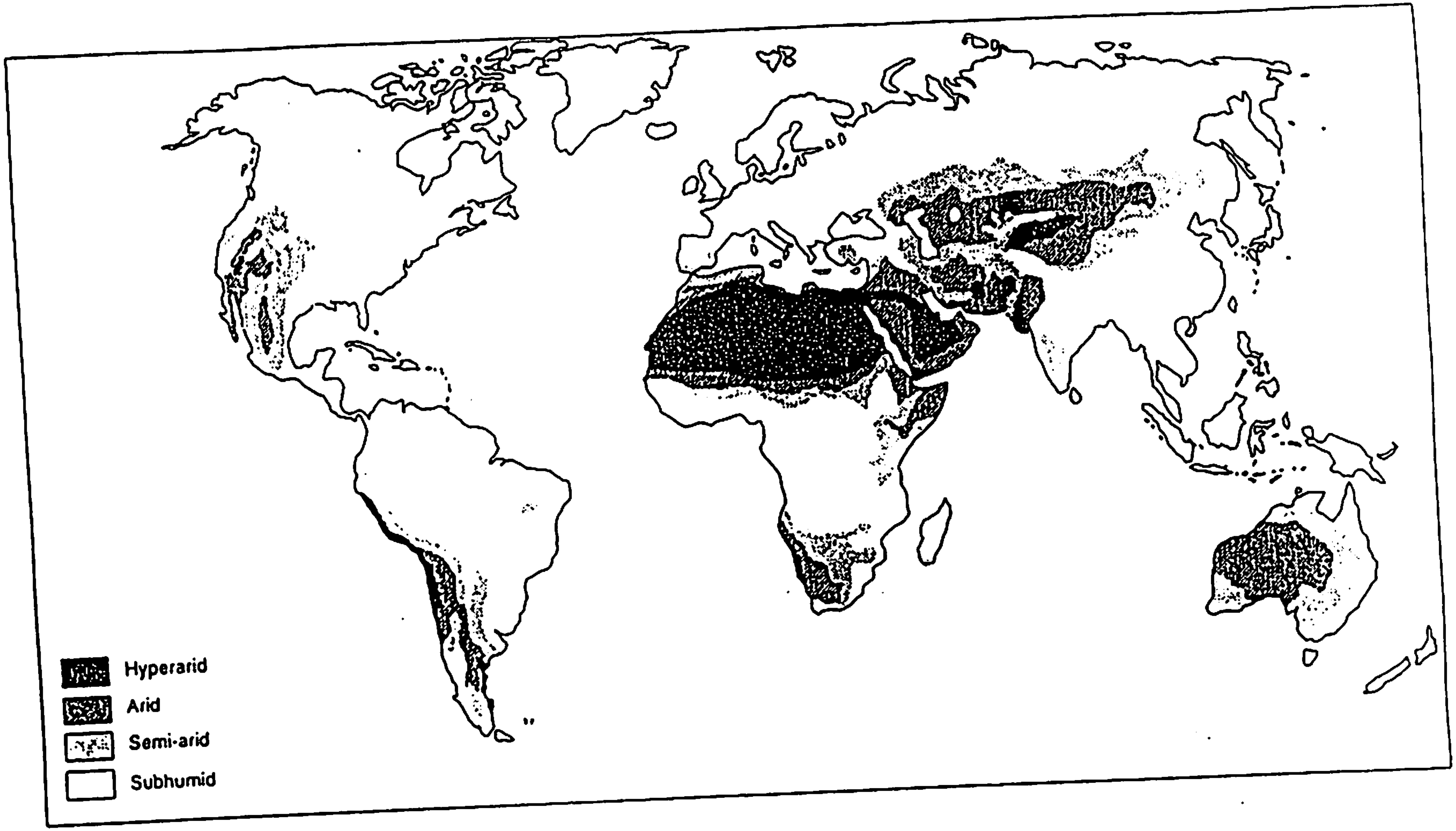


Figure 1. Arid regions of the world (UNESCO, 1977).

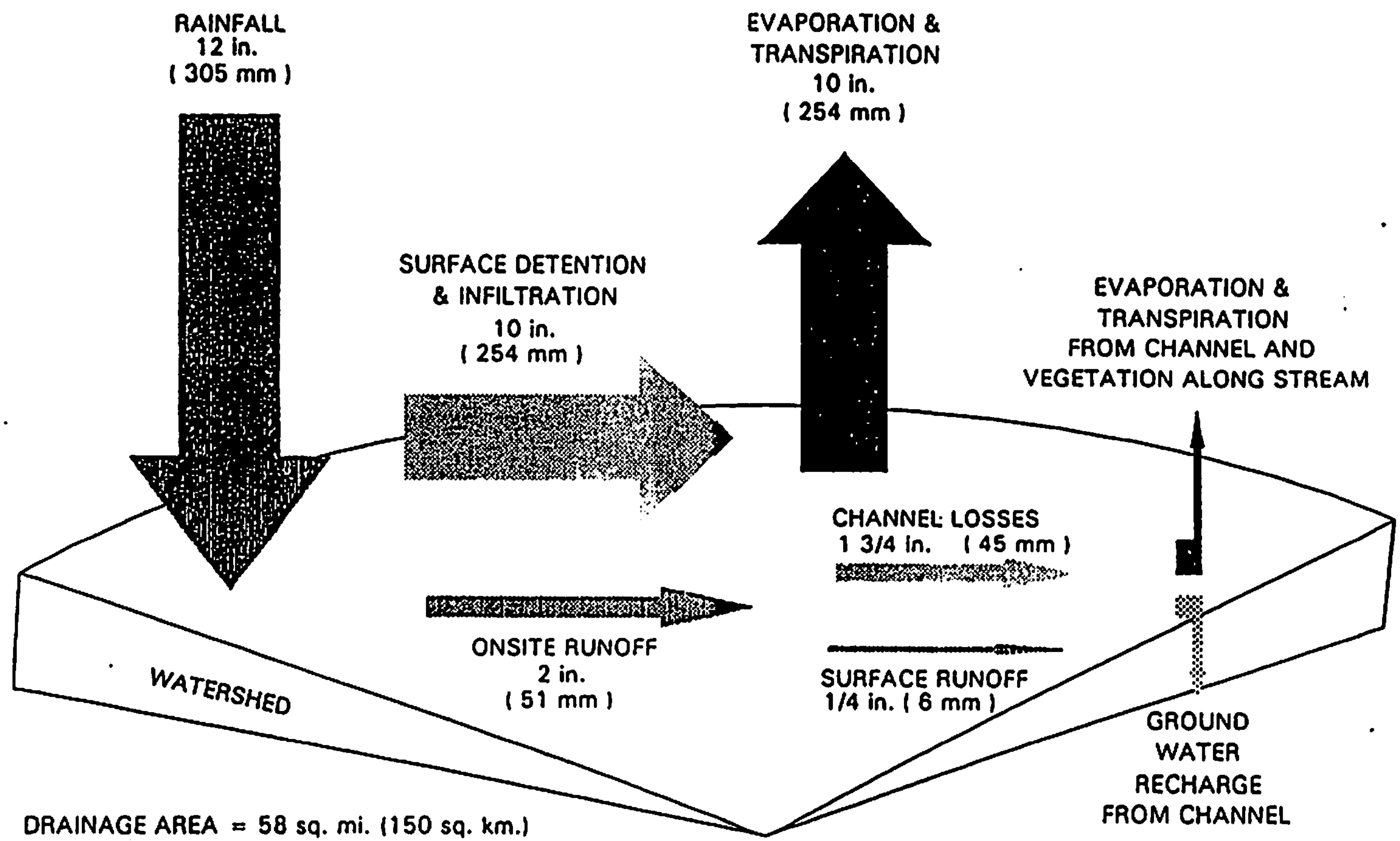
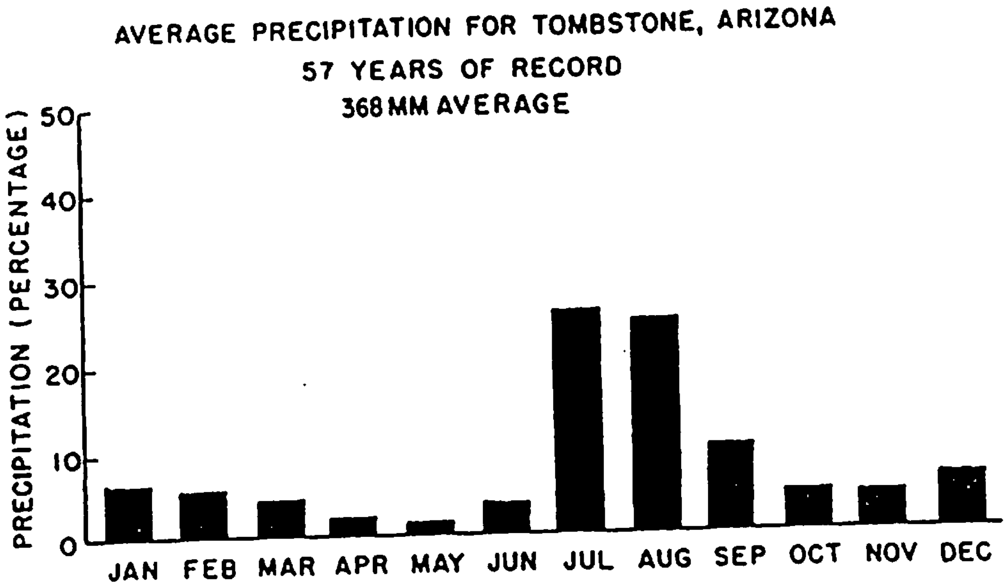


Figure 2 Annual water balance for the Walnut Gulch Experimental Watershed (Renard, 1970)



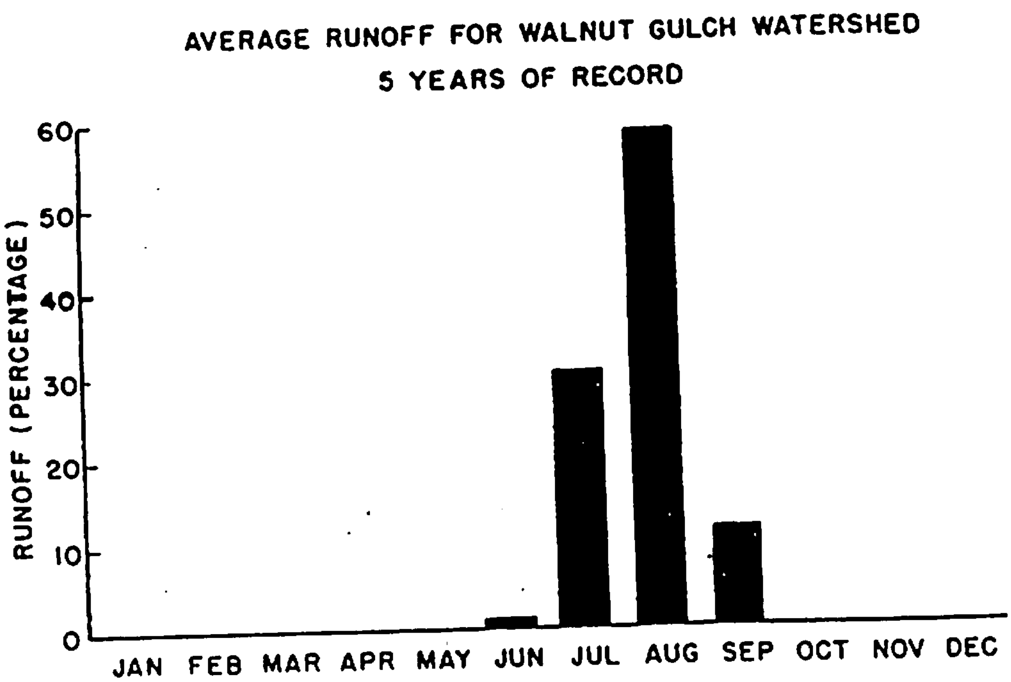
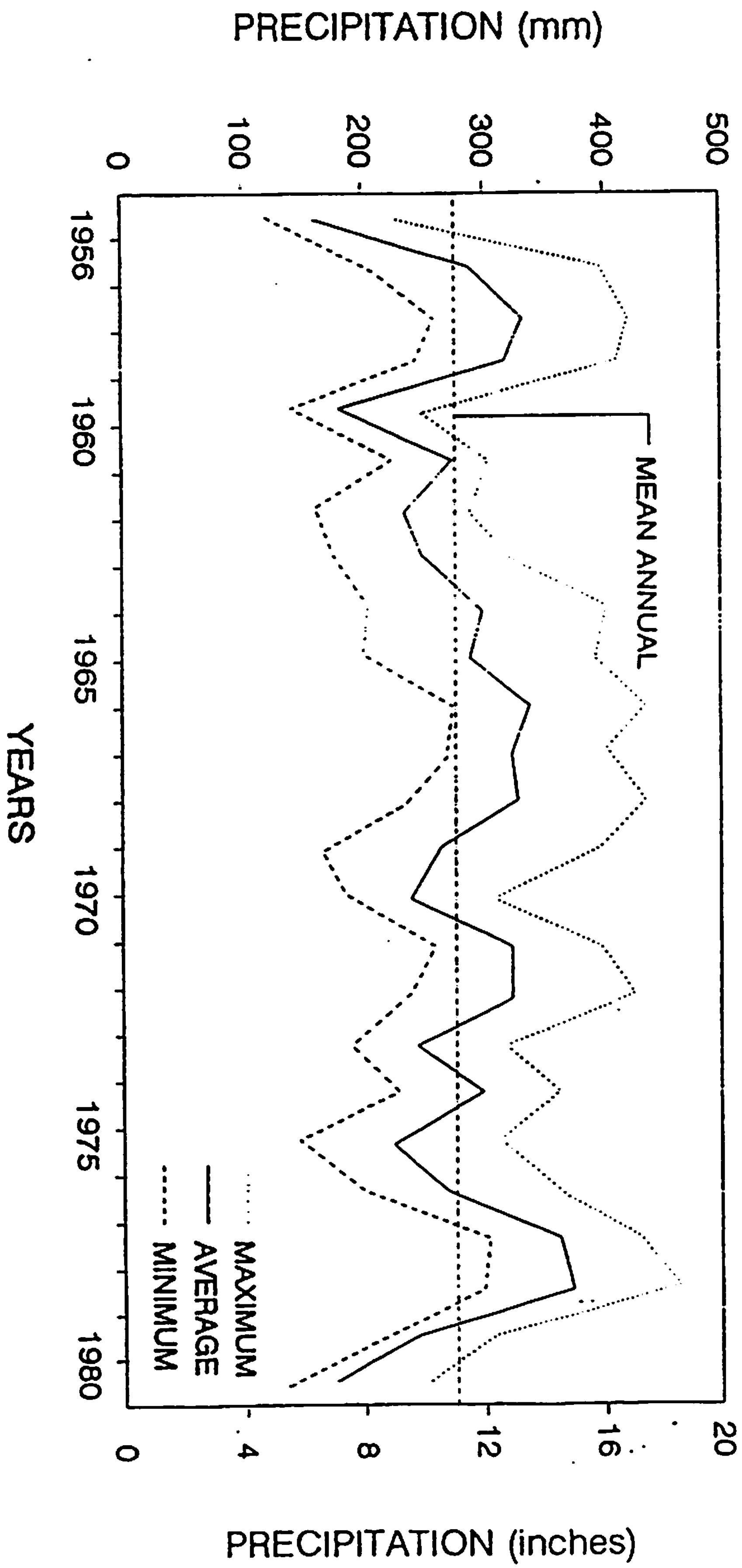


Figure 3. Precipitation and Runoff distributions on Walnut Gulch Experimental Watershed.


PRECIPITATION (mm)
0
100
200
300
400
500
1956
1960
1965
1970
1975
1980
YEARS
MEAN ANNUAL
MAXIMUM
AVERAGE
MINIMUM
0
4
8
12
16
20
PRECIPITATION (inches)

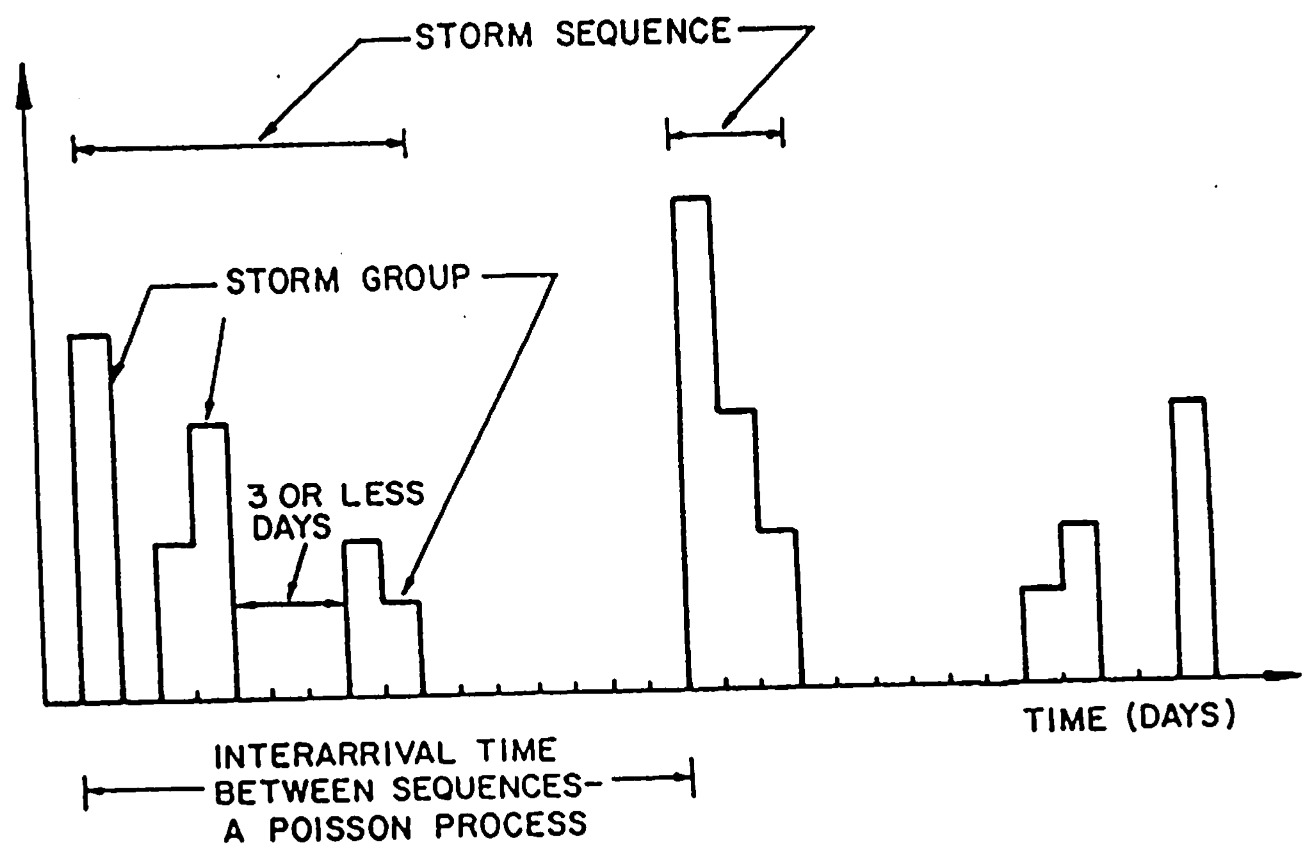
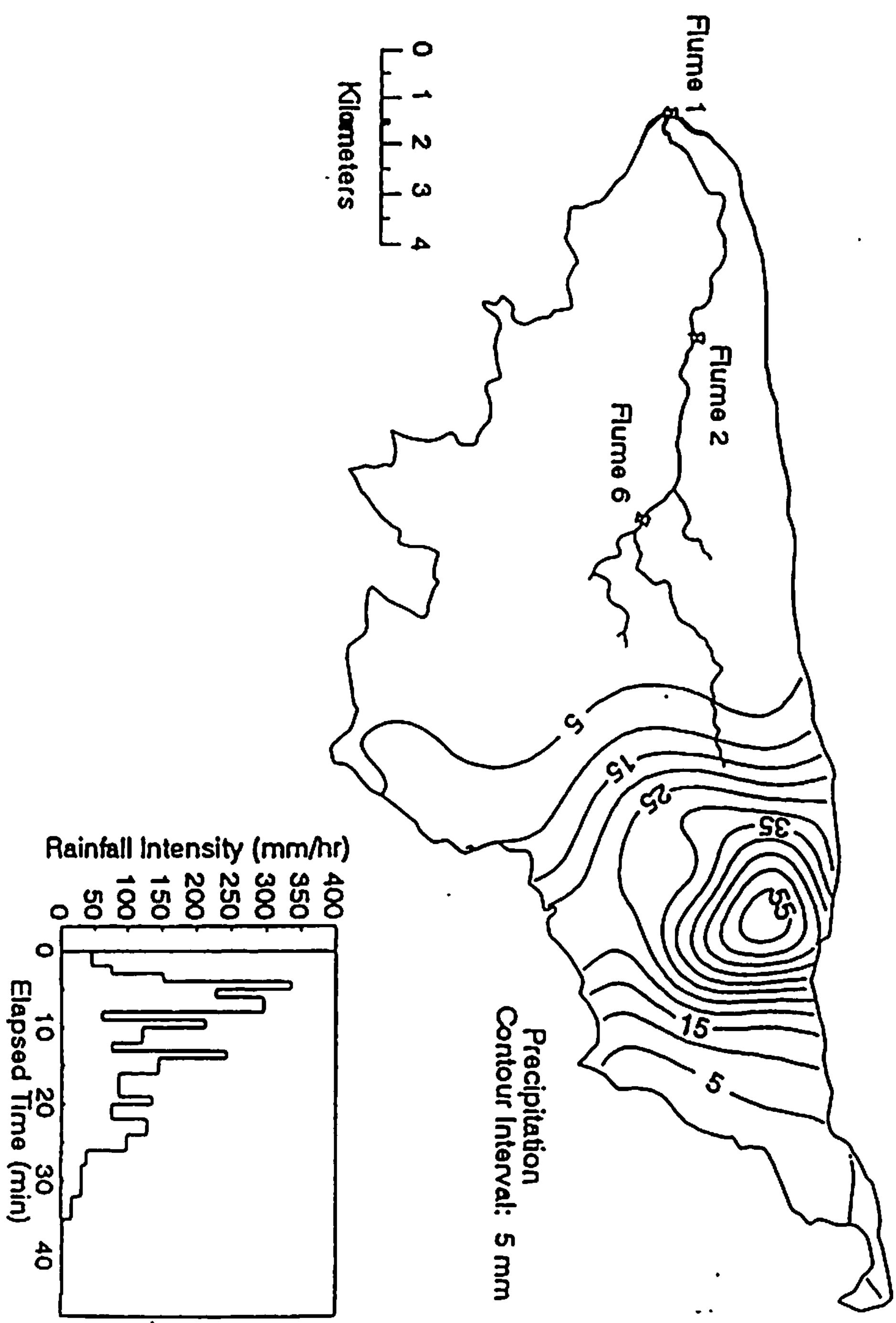


Figure 5. Schematic representation of event-based winter rainfall model (Duckstein et al., 1975).



Flume 1
Flume 2
Flume 6
0 1 2 3 4
Kilometers
5
15
25
35
55
15
5
Precipitation
Contour Interval: 5 mm
Rainfall Intensity (mm/hr)
0 50 100 150 200 250 300 350 400
0 10 20 30 40
Elapsed Time (min)

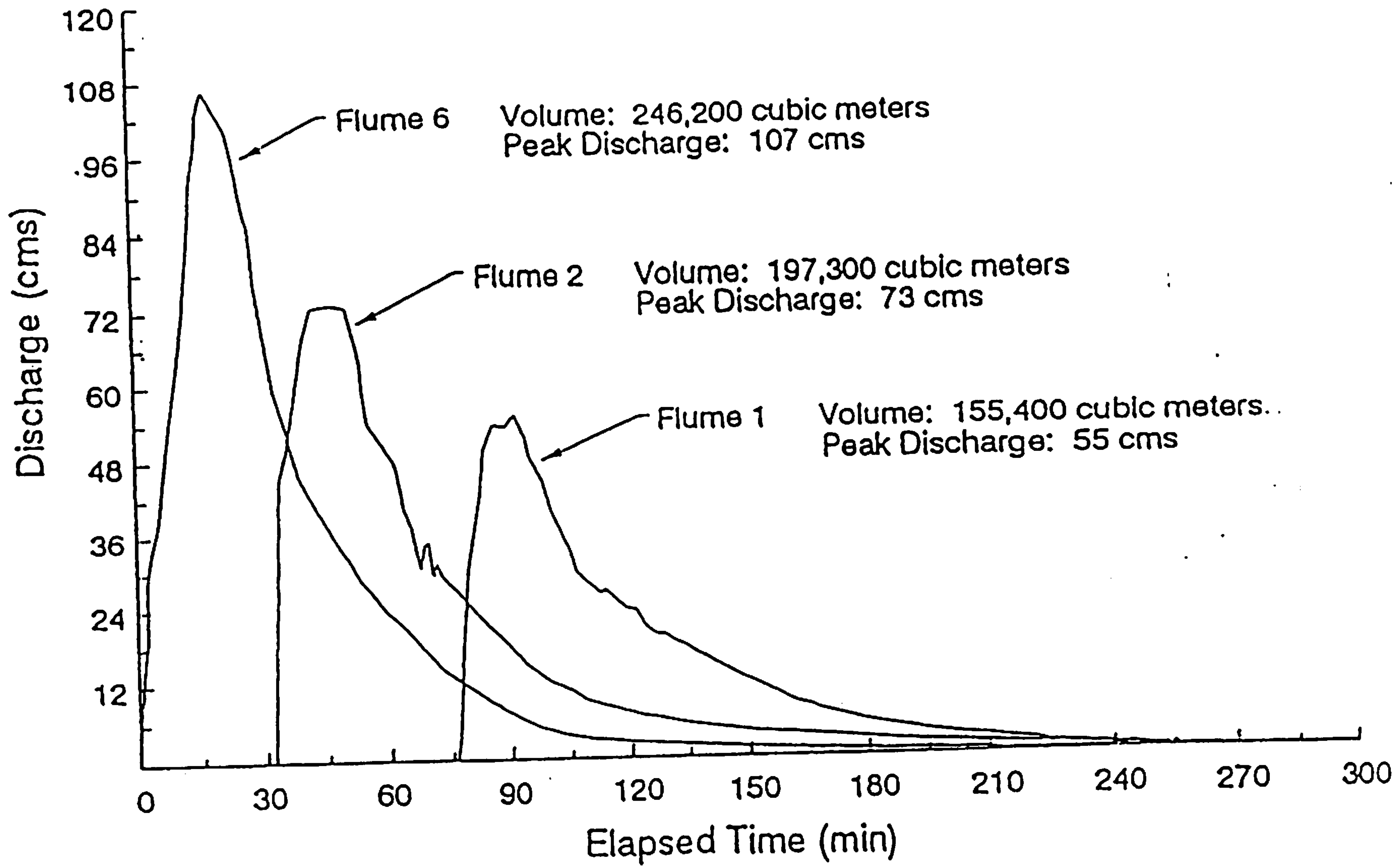


Figure 7. Hydrograph resulting from the storm event on August 27, 1982.