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# HYDROLOGIC MODELS FOR ARID SOUTHWEST UNITED STATES

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## ABSTRACT

Hydrology manuals were prepared for the arid southwest regions of Clark County (Las Vegas vicinity, Nevada), and Maricopa County (Phoenix vicinity, Arizona). Both of these hydrology manuals were prepared in 1990. Other hydrology manuals pertaining to runoff in the arid southwest have been prepared by San Bernardino County, San Diego County, and Riverside County, California. Kern County recently published their manual (1992) for use in developing the flood flow quantities that are used in the planning and design of flood control systems, master plans of drainage, dams, flood plains, among other topics. The hydrology manuals contain hydrologic methods, runoff modeling approaches, and data requirements, for use in the arid southwest region of the United States. In this paper, these hydrology manuals are compared as to modeling approaches, and the individual modeling components are examined for similarities.

## INTRODUCTION

Recently, hydrologic runoff study criteria manuals (or hydrology manuals) were prepared for the arid southwest regions of Clark County (Las Vegas vicinity, Nevada), and Maricopa County (Phoenix vicinity, Arizona). Both of these hydrology manuals were prepared in 1990. Other hydrology manuals pertaining to the arid southwest have been prepared by San Bernardino County, (1986), San Diego County (1985), and Riverside County (1978), California. A hydrology manual is near completion for Kern County, (1991), and closely follows the procedures used in the San Bernardino County hydrology manual (due to the similarity in procedures, reference to the San Bernardino County procedures will be assumed to also reference the Kern County procedures). These hydrology manuals are required by the respective County agencies, for use in developing the flood flow quantities that are used in the planning and design of flood control systems, master plans of drainage, dams, flood plains, among other topics. The five hydrology manuals contain hydrologic methods, modeling approaches, and data requirements, for use in the arid southwest region of the United States. In this study, these hydrology manuals are compared as to modeling approaches, and the individual modeling components are examined for similarities.

## RUNOFF MODELING TECHNIQUES

All five hydrology manuals provide different flood flow computation methods dependent upon catchment size. All five manuals advocate use of a Rational Method technique, and limit this technique's application to catchment areas according to the limits shown in Table 1.

### Unit Hydrograph Techniques

For catchment area greater than the Rational Method application limits of Table 1, other modeling techniques are used, such as the Clark unit hydrograph or an S-graph unit hydrograph approach (in Maricopa County); an S-graph unit hydrograph approach (San Bernardino and Riverside Counties); an U.S. Department of Agriculture Soil Conservation Service or "SCS" unit hydrograph or kinematic wave approach (Clark and San Diego Counties).

Table 1. Rational Method Maximum Area Limitations

| County | Catchment Area Limits (Acres) |
|---|---|
| San Bernardino | 640 |
| Maricopa | 160 |
| Clark | 20 |
| Riverside | 500 |
| San Diego | 320[1] |
| (mean) | (328) |

Notes:

[1] Modified rational methods may be used up to 15 square miles.

All five hydrology manuals advocate use of a unit hydrograph approach for areas greater than one square mile. The use of unit hydrograph methods are recommended according to the area limits of Table 2.

From Table 2, all the hydrology manuals include S-graph or SCS unit hydrograph methods for computing flood flow quantities for areas greater than about 5 square miles.

For catchment areas greater than about 5 square miles, and less than 150 square miles (San Bernardino County area limit), unit hydrograph convolution methods are provided for use in all five hydrology manuals. This section will focus upon the catchment area range of between 5 and 150 square miles. All the manuals use the well-known unit hydrograph convolution technique, which can be found in numerous texts (see Hromadka et al, 1987). Because all the manuals use unit hydrographs developed from catchment area, lag, and unit hydrograph shape, a comparison can be readily made. Table 3 compares lag estimation formulae.

Table 2. Recommended Unit-Hydrograph Method Area Limits

| County | Area (Square Miles) | Method |
|---|---|---|
| San Bernardino | Greater than 1 | S-graph |
| Maricopa | Less than about 5 | Clark[1] Unit-Hydrograph |
| Maricopa | Greater than about 5 | S-graph |
| Clark | Greater than 20 acres | SCS |
| Riverside | Greater than 500 acres | S-graph |
| San Diego | Greater than 320 acres | SCS |
| (mean) | (Greater than 936 acres) | |

Notes:

[1] The "Clark" UH technique is not associated to "Clark" County, Nevada.

The U.S. Army Corps of Engineers Los Angeles District office, (hereinafter termed "COE") prepared a comprehensive hydrologic documentation study for Clark County, Nevada (1988) which is based upon hydrologic methods similar to the subject hydrology manuals. For further comparison purposes, the COE (1988) results are included in Table 3.

In Table 3, L is the length of longest watercourse (miles); $L_c$ is the length along longest watercourse upstream to a point opposite the basin centroid (miles); S is the longest watercourse slope (feet per mile). The parameter pairs ($K_i$, $m_i$) shown in Table 3 are compared in Table 4.

In Table 4, the exponent variation of 0.33 versus 0.38 produces negligible variation in lag, in that with respect to use of 0.38, a one hour lag value has no variation, a 2-hour lag is reduced to 1.83 hours, and a 3-hour lag is reduced to 2.6 hours. Therefore, the lag estimation procedures between all three hydrology manuals are essentially identical for the subject catchment area limits.

## Unit Hydrograph Shape

The remaining consideration, regarding the unit hydrograph methods, is the unit hydrograph shape. Figures 1a and 1b compare the S-graphs used in the three manuals, normalized with respect to lag as defined in the respective manuals.

In Fig. 1a are shown the San Bernardino County "Valley Developed" and "Valley Undeveloped" S-graphs, Maricopa County's "Phoenix Valley" and "Phoenix Mountain"; and Clark County's standard SCS unit hydrograph as converted into S-graph form using the same definition of lag used by San Bernardino County. Riverside

County uses a "Desert" S-graph which is the Whitewater River S-graph (Fig. 1a); San Diego County uses the SCS unit hydrograph. From Fig. 1b, four manuals have S-graph shapes that closely agree; namely, Clark and San Diego County's SCS (converted), San Bernardino County's "Valley Developed", and Maricopa County's "Phoenix Valley" [the COE (1988) study, for the Las Vegas area, also recommends use of the Phoenix Valley S-graph. The similarity in S-graphs is also noted in COE (1988; p.41)]. This close similarity in County S-graphs is somewhat surprising due to the sources of the S-graphs; namely, the "SCS" S-graph was developed from the standard SCS unit hydrograph which is regionalized nationwide; the "Valley Developed" S-graph was synthesized from coastal urbanized catchments in Los Angeles, California; and the "Phoenix Valley" S-graph was developed from Phoenix, Arizona severe storms.

Table 3. Catchment Lag Formulae

| Agency | lag formulae |
|---|---|
| San Bernardino [1] | $Lag = K_1 (LL_c/S^{0.5})^{m_1}$ |
| Maricopa [2] | $Lag = K_2 (LL_c/S^{0.5})^{m_2}$ |
| Clark [3] | $Lag = K_3 (LL_c/S^{0.5})^{m_3}$ |
| Riverside | $Lag = K_4 (LL_c/S^{0.5})^{m_4}$ |
| San Diego | $Lag = K_5 (LL_c/S^{0.5})^{m_5}$ |
| COE (1988) | $Lag = K_6 (LL_c/S^{0.5})^{m_6}$ |

Notes:

[1] A calibrated lag estimator used is Lag = 0.8 $T_c$

[2] For smaller catchments, $T_c$ is utilized

[3] $T_c$ is noted to be related to lag for smaller catchments

Table 4. Lag Formula Parameters

| i | Agency | $K_i$[2] | $m_i$ |
|---|---|---|---|
| 1 | San Bernardino | $24\bar{n}$ | 0.38 |
| 2 | Maricopa[1] | $20\bar{n}$; or $26\bar{n}$ | 0.38; or 0.33 |
| 3 | Clark | $20\bar{n}$ | 0.33 |
| 4 | Riverside | $24\bar{n}$ | 0.38 |
| 5 | San Diego | $24\bar{n}$ | 0.38 |
| 6 | COE (1988) | $24\bar{n}$ | 0.38 |
|  | (mean) | ($23.14\bar{n}$) | (0.366) |

Notes:

[1] For Maricopa County, ($K_2$, $m_2$) pairs are ($20\bar{n}$, 0.38) or ($26\bar{n}$, 0.33)

[2] $\bar{n}$ parameters are similar for all manuals (see Hromadka et al, 1987), and COE (1988)

Thus, for the same lag value, four of the hydrology manuals will develop nearly identical unit hydrographs. However, San Bernardino County does not use the "Valley Developed" S-graph for undeveloped arid regions, but uses the "Valley Undeveloped" S-graph shown in Fig. 1a. The Riverside County "Desert" S-graph is the Whitewater River S-graph of Fig. 1a. From Fig. 1a, the "Valley Undeveloped" S-graph closely matches the Whitewater River arid S-graph. Use of the "Valley Undeveloped" S-graph would result in a unit hydrograph that, when convoluted with a design rainfall pattern, would generally result in lower peak flow values (about 10-percent) than when using the "Valley Developed" S-graph, but would not affect total storm runoff volume.

## Synthetic Regional Arid S-Graph Development

The conventional approach to unit hydrograph development is to analyze measured rainfall hyetographs and runoff hydrographs using the following procedure:

1. Separate baseflow from total runoff to get the distribution of direct runoff.
2. Compute the volume of direct runoff.
3. Eliminate initial abstraction losses.
4. Assume a loss function to separate the remaining distribution of rainfall into losses and rainfall excess such that the volume of rainfall excess equals the volume of direct runoff.
5. Convert the distribution of direct runoff to a 1-inch unit hydrograph (UH).
6. Set the unit-duration of the UH equal to the duration of rainfall excess.

A number of important assumptions are made with this procedure: (1) a baseflow model must be selected; (2) an initial abstraction model must be selected; and (3) a loss function must be selected. Each of these components will have a significant effect on the shape and magnitude of the UH.

Using this procedure to develop unit hydrographs requires data for many storms for each watershed and data from many watersheds to regionalize the UH. Typically, the UH's for storms will be quite different in shape and magnitude. Averaging of the storm-event unit hydrographs usually yields a reasonable UH but it may not produce a UH that will accurately reproduce the measured runoff for each storm.

Where data are available, the above procedure is the most frequently used approach. However, sufficient data are rarely available except at hydrologic research stations. Very little hyetograph/hydrograph data are available in most localities. This is especially true in desert environments. Thus, the procedure described above cannot be used to develop unit hydrographs for desert regions because of the absence of sufficient hyetograph/hydrograph data.

Peak discharge data are more readily available, including for desert regions. An alternative approach that can be used to fit a unit hydrograph and that makes use of peak discharge data is as follows:

1. Assume a known dimensionless functional form to represent the distribution of the unit hydrograph.

2. To scale the dimensionless UH, use the peak discharge records to compute a peak rate factor (K), which is typically defined by

$$q_p = \frac{KAQ}{t_p} \tag{1}$$

where $q_p$ is the peak discharge (cfs); A is the drainage area (square miles); Q is the runoff depth (inches); and $t_p$ is the time-to-peak (hours).

Since unit hydrographs usually have a shape that closely follows a gamma probability function, the gamma pdf can be selected as the dimensionless UH. The time axis can be set by the time-to-peak and the ordinates can be dimensionalized with Eq. 1. For a given drainage area, the time-to-peak can be computed using the time of concentration. For a unit hydrograph, Q equals one-inch. If a mean value of the peak rate factor K can be computed for a region, then the regionalized unit hydrograph should provide accurate designs in the region.

The gamma distribution for the random variable t is:

$$f(t) = \frac{t^{c-1}\, e^{-t/b}}{b^c g(c)} \tag{2}$$

in which c and b are the shape and scale parameters, respectively, and g(c) is the gamma function with argument c, which is given by

$$g(c) = c^c e^{-c} \left(\frac{2\pi}{c}\right)^{0.5} \left[1.0 + \frac{1}{12c} + \frac{1}{288c^2} - \frac{139}{51840c^3} - \frac{571}{2488320c^4}\right] \tag{3}$$

At the peak of the function, with the magnitude denoted as $q_p$ and the time denoted as $t_p$, the following relationship holds:

$$q_p = \frac{t_p^{c-1}\, e^{-t_p/b}}{b^c\, g(c)} \tag{4}$$

It is known that the mode of the gamma distribution occurs for the value of t where

$$t_p = b(c - 1) \tag{5}$$

Substituting Eq. 5 into Eq. 4 yields a relationship between the magnitude of the mode, $q_p$, and the shape and scale parameters:

$$q_p = \frac{(c-1)^{c-1}\, e^{1-c}}{bg(c)} \tag{6}$$

Substituting Eq. 5 into Eq. 1, and equating the result of Eq. 6 yields:

$$KAQ = \frac{(c-1)^c e^{1-c}}{g(c)} \qquad (7)$$

For $q_p$ in cfs, $t_p$ in hours, A in square miles, and Q in inches, Eq. 7 becomes

$$K = 645.3 \frac{(c-1)^c e^{1-c}}{g(c)} \qquad (8)$$

Equation 8 indicates that the peak rate factor of a unit hydrograph is directly and independently related to the shape parameter of the gamma distribution. Once K is set, and a function is assumed for the unit hydrograph, then the UH can be computed with A, Q, and $t_p$ for any watershed. It appears from data analysis, that the peak rate factor is a regional characteristic, with small values for high-storage watersheds such as in coastal areas and large values for low-storage watersheds such as those in mountainous areas.

The following third-order polynomial can be used to compute c for a given value of K

$$c = 1.006 + 1.104(10)^{-3} *K + 1.267(10)^{-5} *K^2 + 1.646(10)^{-9} *K^3 \qquad (9)$$

Figure 2 shows the relationship between c and K.

Since there are little hyetograph/hydrograph data available for the desert areas of southern California, the peak-rate-factor approach is used. Twenty-one watersheds have sufficient information available for the South Lahontan-Colorado desert region (see Fig. 3). The location of the 21 gauging stations is shown in Fig. 4. Using the 100-year LP3 peak discharges, peak rate factors were computed. The average peak rate factor is 444. This is slightly lower than the value of 484 used for the SCS standard unit hydrograph, with 284 used in coastal areas of Maryland.

To test the peak rate factor of 444, 83 watersheds (see Fig. 5) in the desert area of Pima County, Arizona, were used to compute an average peak rate factor. Based on data from 83 watersheds, the average was 436, which yields a UH that is identical to the UH developed from the 21 watersheds from the Southern California region.

Based on the desert-area computations of peak rate factors, a value of 440 is recommended. The dimensionless unit hydrograph is shown in Fig. 1b in S-graph form; along with the other S-graphs previously discussed. To dimensionalize the UH, the drainage area (sq. mi.), runoff depth (inches), and time to peak (hours) are required. These values are used with Eq. 1 to compute the peak discharge, which scales the ordinates. The time axis is scaled using the time to peak. From Fig. 1b, the synthetic regional arid S-graph closely matches several other S-graphs derived from rainfall-runoff data.

In summary, the five hydrology manuals and the COE (1988) study provide unit hydrograph techniques, for catchment areas between about 5 and 150 square miles, which are nearly identical, except that use of the San Bernardino "Valley Undeveloped" S-graph or the similar Riverside County "Desert" S-graph, would generally result in lower runoff peak flow rate estimates. The San Bernardino County "Valley Developed" S-graph closely matches three other County arid S-graphs shown in Fig. 1b. Additionally, a synthetic S-graph developed from use of a gamma function, closely agrees with the several other S-graphs shown in Fig. 1b.

## DESIGN STORM INPUT

In comparing the hydrology manuals, the focus need not be upon the runoff generator technique (as all five manuals use essentially identical methods, except than San Bernardino's "Valley Undeveloped", and the similar Riverside "Desert" S-graph, are milder peak flow rate estimators), but upon the input into model; that is, the design storm rainfall input, including pattern shape, depth-area adjustments, and rainfalls.

### Design Storm Patterns and Storm Duration

Maricopa and Clark Counties both utilize sets of 6-hour storm patterns as representative of local thunderstorm tendencies. Clark County uses a set of two 6-hour patterns, one for areas less than 10 square miles, the other for greater areas, as taken from a set of five storm patterns used in COE (1988). Maricopa County utilizes a set of five 6-hour patterns, based on catchment areas of about 0.5, 2, 15, 90, and 500 square miles, with interpolation according to catchment area size. Each of the above storm patterns are rigid relationships with respect to a single rainfall input; namely, the 6-hour rainfall. Thus, regardless of location, a specific rainfall pattern defines a fixed rainfall depth versus duration relationship, with respect to the 6-hour rainfall depth.

Riverside County uses a set of 1-, 3-, 6-, and 24-hour storm patterns. A catchment is tested by each storm pattern application in order to develop the maximum design storm condition. Each storm pattern is a fixed relationship with respect to total storm rainfall. San Diego County uses a single fixed 6-hour storm pattern for arid conditions.

The San Bernardino hydrology manual uses is a single 24-hour storm pattern that is constructed by nesting T-year return frequency rainfalls to achieve rainfall intensity-duration relationships, fitted to local rainfall data. Rainfall data used are the 5-, 15-, 30-minutes, 1-, 3-, 6-, and 24-hour rainfalls of a prescribed return frequency. The construction of the storm pattern closely follows the procedures given in the U.S. Army Corps of Engineers Hydrologic Engineering Center (or HEC) Training Document #15 (1982).

Thus, all five hydrology manual design rainfall patterns would agree, for a 6-hour storm pattern, as to the 6-hour rainfall depth to be used (to construct a T-year return frequency design storm), but would disagree at smaller peak durations of the T-year return frequency pattern, unless the fixed storm pattern happened to match local rain gauge intensity-duration tendencies.

It is noted that the storm pattern construction includes another influence from so-called "depth-area" relationships, that transform the storm pattern shape (and rainfall intensity-duration) according to catchment area. This influence will be discussed in a following section. However, for small catchment areas such as one square mile, all the hydrology manuals provide for negligible depth-area effects, and hence the above storm pattern construction is essentially used directly. In this case, unless the fixed storm pattern follows the local rainfall intensity-duration tendencies, the storm pattern is not providing a T-year return frequency rainfall depth for a prescribed duration. This topic will also be further addressed in a subsequent section.

It is noted that three Counties use a 6-hour duration storm pattern, whereas San Bernardino County uses a 24-hour storm pattern (the San Bernardino procedures include extension of the storm pattern to longer multi-day durations) and Riverside County uses a set of multi-length storm patterns, up to 24-hours. For the arid southwest region, most of the 24-hour design storm rainfall falls within the peak 6-hours, with the remaining rainfall distributed in the other 18-hours. For example, McCarran Airport (Las Vegas, Nevada) information shown in the Clark County Hydrology Manual indicates that, at the 100-year return frequency, 94-percent of the rainfall occurs in the peak 6-hours, with the residual 6-percent occurring in the remaining 18 hours. For a 25-year return frequency event, the peak 6-hour percentage falls to 85-percent.

Consequently, use of a 24-hour storm pattern would not be an issue in computation of flood flow quantities (especially for flood control systems that are most sensitive to storm durations less than the peak 6-hours), except that storms of durations greater than 6-hours are not addressed by a storm pattern restricted to 6-hours, and hence large-scale detention effects possibly may escape being tested by a storm pattern of the most critical duration. Reference to long duration summer "general storms", in which thunderstorms are embedded, is made in COE (1988, p.11).

## Design Storm Areal Extent

Several counties address catchment sizes according to the storm size area limits shown in Table 6. Beyond the area limits of the table, several county manuals recommend special consideration of other approved hydrologic estimation techniques.

## Design Storm Rainfall

All five manuals use some form of T-year rainfall data to produce a T-year design storm pattern (e.g., 10-, 25-, 100-year). Each manual utilizes NOAA rainfall statistics or NOAA Atlas II (1973), as discussed in Table 7.

From Table 7, Clark County uses a set of adjustment factors that result in a significant increase in high return frequency storm rainfall values. For a 100-year return frequency event, the adjustment is to multiply 100-year return frequency NOAA Atlas II rainfalls by 1.43. For a 2-year return frequency rainfall, the adjustment factor is 1.0.

Table 6. Design Storm Areal Limits

| County | Design Storm Maximum Area (Square Miles) |
|---|---|
| San Bernardino | 150 |
| Maricopa | 100 |
| Clark | 200 |
| Riverside | 300[1] |
| San Diego | 100[1] |
| (mean) | (170) |

Note:

[1] Limits from county depth-area reduction curves.

Table 7. NOAA Rainfall Data Usage

| County | Usage |
|---|---|
| San Bernardino | NOAA Atlas II, modified (as approved by Agency) by local rain gauge analysis[1]. |
| Maricopa | NOAA Atlas II. |
| Clark | NOAA Atlas II, modified by adjustment factors[2]. |
| Riverside | NOAA Atlas II. |
| San Diego | NOAA Rainfall Statistics. |

Notes:

[1] The State of California Department of Water Resources (or "DWR") provides regional rain gauge analysis, with frequent updates. One such region focuses on the arid southern California.

[2] Adjustment factors provide for an increase in rainfall values of up to a factor of 1.43 for a 100-year return frequency event. A 2-year return frequency rainfall has an adjustment factor of 1.0.

In order to better examine the Clark County adjustment factor of 1.43 with 100-year return frequency NOAA Atlas II rainfall estimates, a comparison of rainfall return frequency estimates, developed in other studies, was prepared based upon the

McCarran Airport rain gauge (which is a principal rain gauge used in the original development of the 1.43 factor). In Fig. 6a are shown the McCarran Airport rain gauge peak 1-hour rainfall data (shown in median plotting position), along with rainfall estimates developed by the State of California Department of Water Resources ("DWR") in 1988; DWR in 1983; NOAA Atlas II (1973); rainfall estimates developed by French (1983); estimates prepared by Randerson (1984); and estimates from the Clark County hydrology manual for McCarran Airport. Fig. 6b show similar comparisons as in Fig. 6a, but for a peak rainfall duration of 3-hours. From Figs. 6a, 6b, there is a significance difference in estimates of rainfall, and it is not clear whether the adjustment factors used in the Clark County hydrology manual are transferable to other arid regions of the southwest United States, for use in estimating T-year return frequency rainfall depths from NOAA Atlas II.

## Design Storm Pattern Shape

In general, all five hydrology manuals use single peaked storm patterns. For comparison purposes, the peak 6 hours of the San Bernardino County design storm pattern may be examined with respect to the Maricopa, Clark, Riverside, and San Diego, 6-hour design storm patterns. It is recalled that by construction, each County storm pattern (or set) would necessarily agree as to the total 6-hour rainfall depth data to be used (neglecting depth-area effects). The ratio of the design storm time-to-peak versus the total storm duration (i.e., 6 hours) is given in Table 8. Table 9 shows the total mass of design storm rainfall that is specified to occur prior to the design storm time-to-peak.

From Tables 8 and 9, the five hydrology manuals are in general agreement as to storm pattern shape and time-to-peak (with respect to the peak 6 hours of the design storm pattern).

## Desert Rainfall Intensity-Duration Characteristics

Tables 10a,b provides a comparison of typical rain gauge intensity-duration characteristics for the arid regions of Clark, Maricopa, Riverside, San Diego, and San Bernardino Counties. From the Tables, up to 80-percent of the total 24-hour rainfall occurs in the peak 3-hours; similarly, up to 90-percent of the peak 6-hour rainfall occurs in the peak 3-hours. For Clark and Maricopa Counties, 67-percent of the 24-hour rainfall occurs in the peak 1-hour duration, which corresponds to near 75-percent of the 6-hour rainfall. Thus, the arid rainfall intensity-duration characteristics indicate that the dominant runoff producing rainfalls generally occur between the 1- and 3-hour peak durations, with larger storm durations being of importance for modeling substantial detention effects. San Bernardino arid rainfall intensity-duration characteristics generally differ from Clark and Maricopa Counties for shorter storm durations such as the peak 1-hour duration; consequently, Clark and Maricopa County storm pattern techniques may not be directly transferable between each other, nor to San Bernardino County arid conditions. Similar differences in rainfall depth-duration statistics can be found with Riverside and San Diego County arid region rain data, and hence transferability of localized design storm events to other arid regions may be inappropriate due to the differences in rainfall intensity-duration characteristics. Because the San Bernardino storm pattern is constructed according to local rainfall intensity-duration data, it is transferable to other regions (see HEC TD#15, 1982). This property of design storm transferability exhibited by the San Bernardino County storm pattern, will be useful in rainfall mass comparisons to be developed in a later section.

### Depth-Area Effects

The technique of modifying catchment area-averaged rainfall data, due to catchment size, is well-known and is generally classified as "depth-area" adjustments (e.g., Hromadka et al, 1987). The five counties use depth-area effects, but procedures differ. Table 11 compares depth-area specifications. Each of the hydrology manuals use area-averaged T-year return frequency rainfall depths for study purposes. Figure 7a show plots of the various County depth-area curves involved, for several design storm peak rainfall durations, as well as other depth-area curves, developed by U.S. Army Corps of Engineers and other Agencies, for comparison purposes.

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Table 8. Ratio of Design Storm Time-to-Peak versus Total Storm Duration

| County | | Ratio |
|---|---|---|
| San Bernardino[1] | | 0.67 |
| Maricopa | | 0.67 |
| Clark[2] | | 0.62 |
| Riverside[3] | | 0.91 |
| San Diego[4] | | 0.63 |
| | (mean) | (0.70) |

Notes:

[1] Peak 6 hours of 24-hour storm pattern considered.
[2] For the selected storm patterns, Clark County storm characteristics are identical to COE (1988).
[3] Riverside County 6-hour storm pattern considered.
[4] Storm pattern is of near uniform intensity from hours 3.5 to 4.0.

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The Maricopa County storm pattern set, and the corresponding 6-hour depth-area curve, are based upon a single storm event that occurred on August 19, 1954 over the Queen Creek area, Arizona. The Clark County 6-hour set of storm patterns and 6-hour depth-area curve, are a subset of that used in COE (1988), for the greater Las Vegas area, Nevada. The San Bernardino County short duration depth-area curves come from a 3-hour duration 1943 thunderstorm in Sierra-Madre, California and, for 6- and 24-hour curves, from NOAA Atlas II (the storm pattern construction follows HEC Training Document #15 (1982), which also uses NOAA Atlas II). The Riverside County 3- and 6-hour storm patterns are from a 1939 Indio, California thunderstorm; the depth-area curves follow NOAA Atlas II for all durations. The San Diego County storm pattern and depth-area curve is for "arid and semi-arid climates", and references the SCS.

Table 9. Total Design Storm Rainfall Mass Prior to Rainfall Time-to-Peak

| County | | Mass (percent) |
|---|---|---|
| San Bernardino[1] | | 67 |
| Maricopa | | (62.7-83.4)[2] |
| Clark[3] | | 78[2] |
| Riverside [4] | | 95.6 |
| San Diego[5] | | 60.0 |
| | (mean) | (75) |

Notes:

[1] Peak 6 hours of 24-hour storm pattern considered.
[2] Total rainfall mass decreases as catchment area increases.
[3] Characteristics are identical to COE (1988).
[4] Riverside County 6-hour storm pattern considered.
[5] Storm pattern is of near uniform intensity from hours 3.5 to 4.0.

Table 10a. Comparison of 100-Year Rainfall Depth-Duration Estimates

| | San Bernardino County | Maricopa County | Clark County | Riverside County | San Diego County |
|---|---|---|---|---|---|
| Rainfall Duration | Amboy[1] | Phoenix Metro[2] | McCarran Airport[3] | Desert Hot Springs[4] | Crawford Ranch[5] |
| 5-minute | .52 (25)[6] | 0.75 (20)[6] | 0.63 (21)[6] | 0.47 (11)[6] | 0.52 (11)[6] |
| 30-minute | 1.14 (54) | 2.00 (52) | 1.79 (60) | 1.25 (28) | 1.33 (29) |
| 1-hour | 1.32 (62) | 2.50 (65) | 2.06 (70) | 1.59 (36) | 1.67 (36) |
| 3-hour | 1.62 (76) | 3.00 (78) | 2.48 (84) | 2.36 (53) | 2.40 (52) |
| 6-hour | 1.83 (86) | 3.30 (86) | 2.77 (94) | 3.13 (70) | 3.03 (66) |
| 24-hour | 2.12 (100) | 3.84 (100) | 2.96 (100) | 4.45 (100) | 4.61 (100) |

Table 10b. Comparison of 10-Year Rainfall Depth-Duration Estimates

|  | San Bernardino County | Maricopa County | Clark County | Riverside County | San Diego County |
|---|---|---|---|---|---|
| Rainfall Duration | Amboy[1] | Phoenix Metro[2] | McCarran Airport[3] | Desert Hot Springs[4] | Crawford Ranch[5] |
| 5-minute | .29 (25)[6] | 0.49 (20)[6] | 0.35 (19)[6] | 0.26 (11)[6] | 0.29 (11)[6] |
| 30-minute | .63 (53) | 1.25 (52) | 1.01 (56) | 0.69 (28) | 0.73 (29) |
| 1-hour | .73 (62) | 1.60 (67) | 1.15 (64) | 0.88 (36) | 0.92 (36) |
| 3-hour | .90 (76) | 1.89 (79) | 1.39 (77) | 1.31 (53) | 1.33 (52) |
| 6-hour | 1.01 (86) | 2.10 (88) | 1.58 (88) | 1.74 (70) | 1.68 (66) |
| 24-hour | 1.18 (100) | 2.40 (100) | 1.80 (100) | 2.47 (100) | 2.55 (100) |

[1] DWR Gauge No. 176.
[2] From Maricopa County Hydrology Manual, Figure 3.2.
[3] From Clark County Hydrology Manual, Table 505.
[4] DWR Gauge No. 2405
[5] DWR Gauge No. 2139.
[6] Percentage of 24-hour rainfall value.

Only a 6-hour depth-area adjustment is used by Clark, Maricopa, Riverside (for the 6-hour storm), and San Diego Counties which implies that, from the use of rigid 6-hour storm patterns, all the storm pattern smaller interior durations are being adjusted by the same 6-hour duration adjustment. In contrast, the San Bernardino County method uses an adjustment for each duration. It is noted, however, that the use of a set of storm patterns (e.g., five patterns used by Maricopa County), with each pattern being selected based on catchment area, is somewhat analogous to the use of a set of depth-area reduction curves, in that the smaller interior durations are being adjusted by virtue of the defined storm pattern shape selection. Using the set of five storm patterns of Maricopa County, shorter duration depth-area reduction curves can be synthesized which include the effects of both the overall 6-hour depth-area reduction, as well as the changing storm pattern shape. Included in the one- and three-hour depth-area curves, of Figs. 7b and 7c, are depth-area curves synthesized from the Maricopa County storm pattern set of five storms, using the small area storm pattern as the base storm (i.e., no depth-area adjustment).

## Comparison of Depth-Area Reduction Curves

Figure 7a examines peak 30-minute rainfall depth-area curves, and indicates that the San Bernardino curve is an approximate average of the Walnut Gulch (Arizona) and the synthesized Maricopa County depth-area curves, for areas less than 50 square miles; otherwise, the San Bernardino curve provides more depth-area reduction. Hence, for catchments where short duration storms of 30-minutes have a significant impact on flooding, the runoff estimates will generally vary in magnitude according to the shown depth-area curves.

Figure 7b shows several peak one hour depth-area reduction curves. Generally, the one hour depth-area curve will have a considerable influence on storm runoff estimates for small catchments that have time-of-concentration values less than about one hour. From Fig. 7b, the San Bernardino County curve provides the most depth-area reduction for catchment areas less than 60 square miles, while the synthesized Maricopa County depth-area curve provides significantly less adjustment for catchment areas greater than 60 square miles. The synthesized Maricopa County depth-area curve provides less reduction than the San Bernardino County curve for areas greater than about 15 square miles; otherwise, the two curves are comparable. Use of the one hour San Bernardino depth-area curve will result in lower runoff estimates than by use of the synthesized Maricopa County one hour curve. The Riverside County one-hour depth-area curve agrees with the NOAA Atlas II curve, and provides considerably less reduction than the other depth-area curves.

Table 11. Depth-Area Adjustment Procedures

| County | Method |
|---|---|
| San Bernardino | Compute T-year area-averaged rainfall depths for peak 5-, 15-, 30-minute, 1-, 3-, 6-, 24-hour durations. Modify each depth per appropriate depth-area curve. |
| Maricopa[1]<br>Clark[2,3]<br>Riverside[4]<br>San Diego | Compute T-year area-averaged rainfall depth for 6-hour duration. Use single 6-hour depth-area curve, and adjust 6-hour rainfall depth. |

Notes:

[1] Maricopa County uses a set of five storm patterns, based on catchment area.

[2] Clark County uses a set of two storm patterns, based on catchment area.

[3] Six-hour depth-area curve also used in COE (1988).

[4] Riverside County's procedure is similar for the 1-, 3-, and 24-hour storm patterns, respectively.

Figure 7c considers three-hour depth-area reduction, and shows that the San Bernardino curve approximates an average between the Tucson, Arizona depth-area curve and the synthesized Maricopa County curve. Depth-area curves from the National Weather Service HYDRO-40 publication are also included, which indicate a relative maximum depth-area reduction for three-hour durations. The three-hour depth-area curves show a considerable dispersion in reduction values that were not evident in the 30- and 60-minute depth-area curves. Note that the Tucson depth-area curve significantly disagrees with the HYDRO-40 curves, which also apply to the Tucson area. Also note that Maricopa County uses depth-area curves that are significantly higher in value than the HYDRO-40 curves for that region. Again, Riverside County uses a 3-hour curve that agrees with NOAA Atlas II, and provides significantly less reduction than the other curves.

Figure 7d considers 6-hour depth-area adjustment. Again, considerable dispersion and uncertainty in reduction values is seen. The San Bernardino curve follows NOAA Atlas II (as does Riverside County) in a philosophy that "general storms" may influence 6-hour rainfall depths, whereas the other depth-area curves address thunderstorm effects. The Maricopa County curve approximates an average of the NOAA Atlas II and HYDRO-40 curves. The San Bernardino reduction values are 9-, 10-, and 14-percent higher in values than the Maricopa County values for 50-, 100-, and 150-square miles, respectively. The 6-hour depth-area curve would impact runoff volume estimates in detention basin design and planning, and peak flow estimates for catchments with time-of-concentration values typically in the 3- to 6-hour range (which infrequently occur for areas less than 150-square miles). Generally speaking, use of the NOAA Atlas II 6-hour depth-area curve (used by San Bernardino and Riverside Counties) would result in larger detention basin requirements than by use of the 6-hour Maricopa County curve. The Maricopa County depth-area curve is significantly higher in value than the HYDRO-40 curve for that region. In contrast, the Clark County curve approximates the HYDRO-40 curve. The Clark County curve provides considerable depth-area reduction; at 150 square miles, the Maricopa County curve is 47-percent higher in value than the Clark County curve. The San Diego County depth-area curve provides reduction comparable to Clark County. Thus, considerable uncertainty is evident as to which 6-hour depth-area curve is appropriate for a region.

Figure 7e examines 24-hour depth-area curves, (only Riverside and San Bernardino Counties employ a 24-hour design storm). It is noted that the HYDRO-40 curves suggest that the 24-hour depth-area reduction values may increase as one approaches the arid regions of San Bernardino and Riverside. Zones A & C are closest to San Bernardino and Riverside, and there is approximately a ten-percent variation in depth-area reduction values between HYDRO-40, San Bernardino, Riverside Counties, and NOAA Atlas II.

From Figs. 7a,b,e, there is significantly closer agreement in depth-area reduction values for 30-, 60-minute, and 24-hour depth-area relationships than for 3-, 6-hour (see Figs. 7c,d) depth-area relationships. Perhaps the widest disparity and uncertainty occurs for the 6-hour set of depth-area curves (see Fig. 7d). For catchments under 150 square miles, the 6-hour depth-area curves would generally have a significant impact on runoff volume estimates as considered in detention basin design. Additionally, 100-year storm desert rainfall data indicates that 90-percent or more of the 24-hour rainfall depth occurs in the peak 6-hours. Because failure mode for detention basins and dams are usually more damaging than peak flow channel failures, further research is needed in order to ascertain which depth-area curve set is most appropriate for a region, especially longer duration depth-area curves that significantly impact runoff volume estimates, such as the 6-hour curve.

## CONCLUSIONS

Upon comparison of the several hydrology manuals prepared for the Southwest United States, several similarities exist. Based on these similarities in methodologies, a unified method may be developed for the entire region. Such a uniform procedure would afford many advantages for the practicing engineer and in government policy development.

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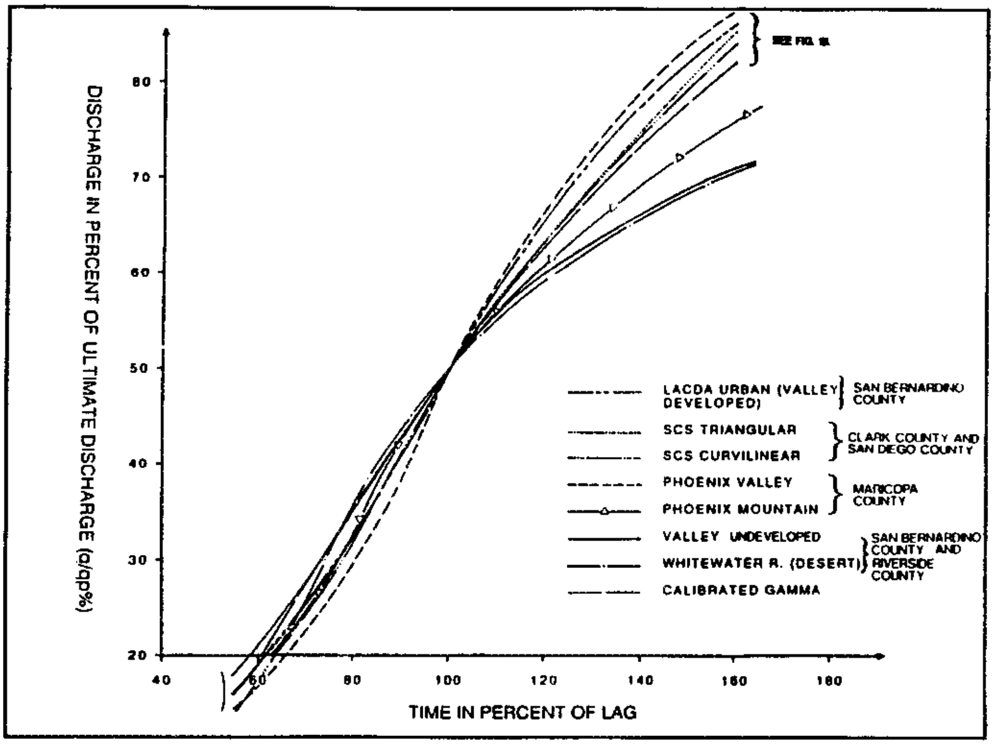

**Figure 1A.** S-Graph Comparisons.

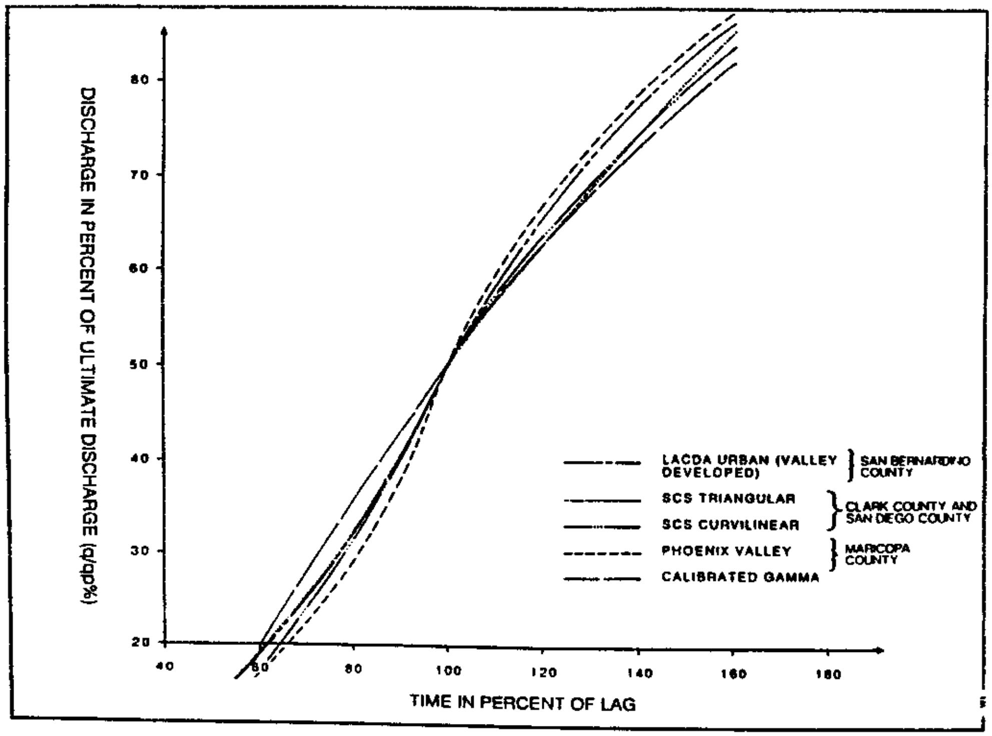

**Figure 1B.** S-Graph Comparisons.

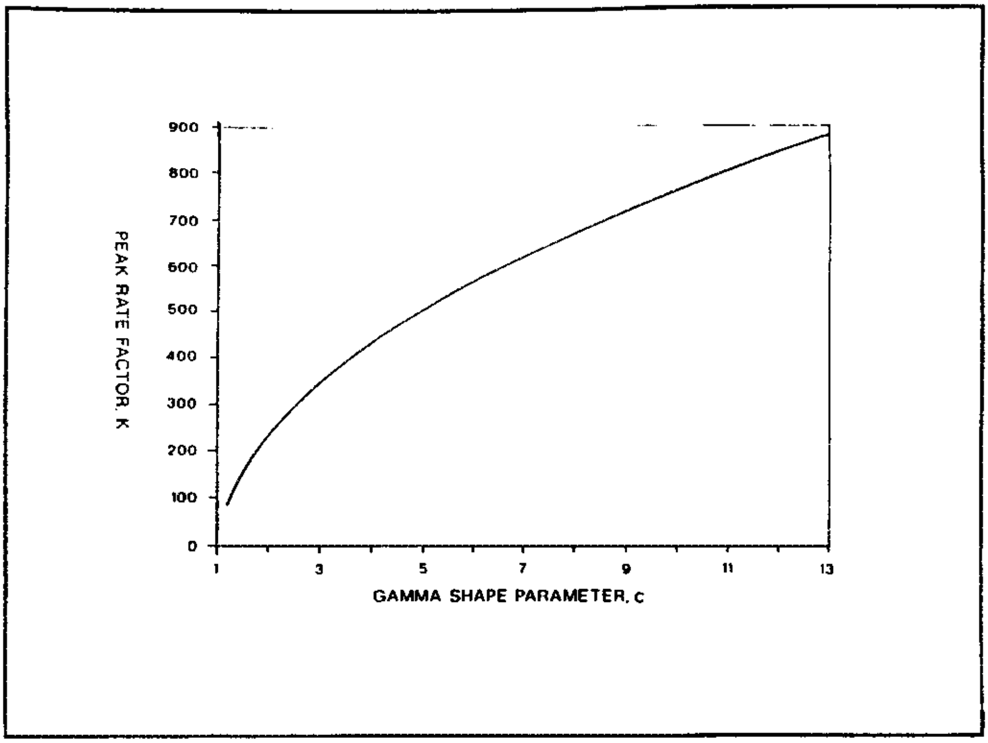

Figure 2. Relationship Between the Peak Rate Factor and the Gamma Shape Parameter.

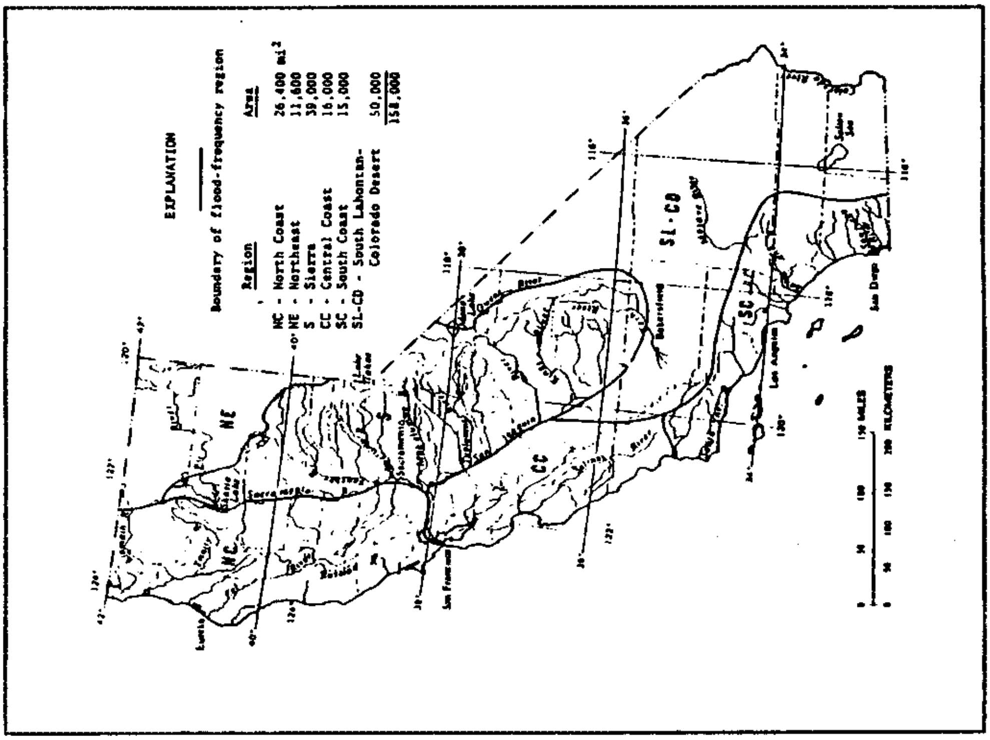

Figure 3. Flood Frequency Regions of California.

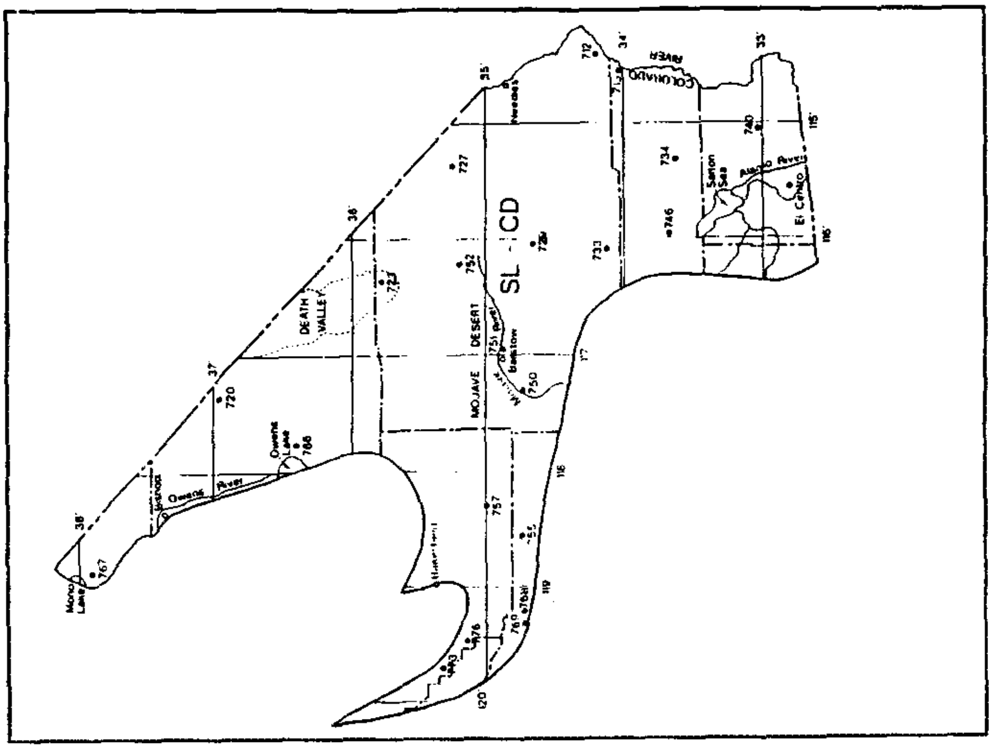

Figure 4. Location of 21 Stream Guaging Stations Used to Calibrate Peak Rate Factor, K.

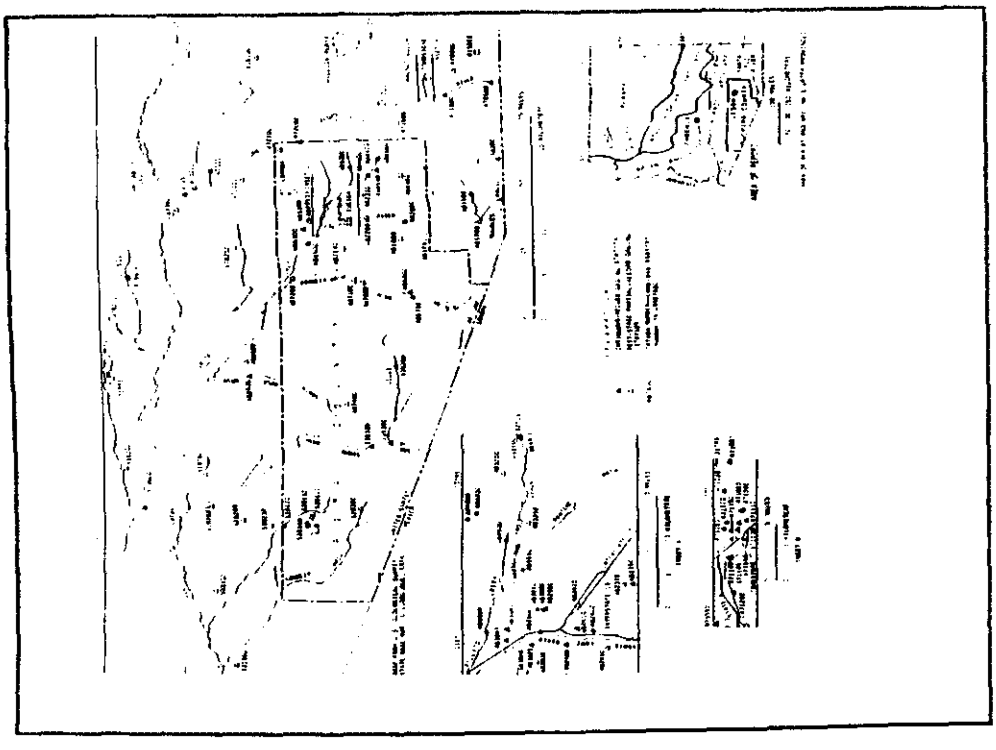

Figure 5. Location of Stream Gauges Used to Verify Peak Rate Factor, K.

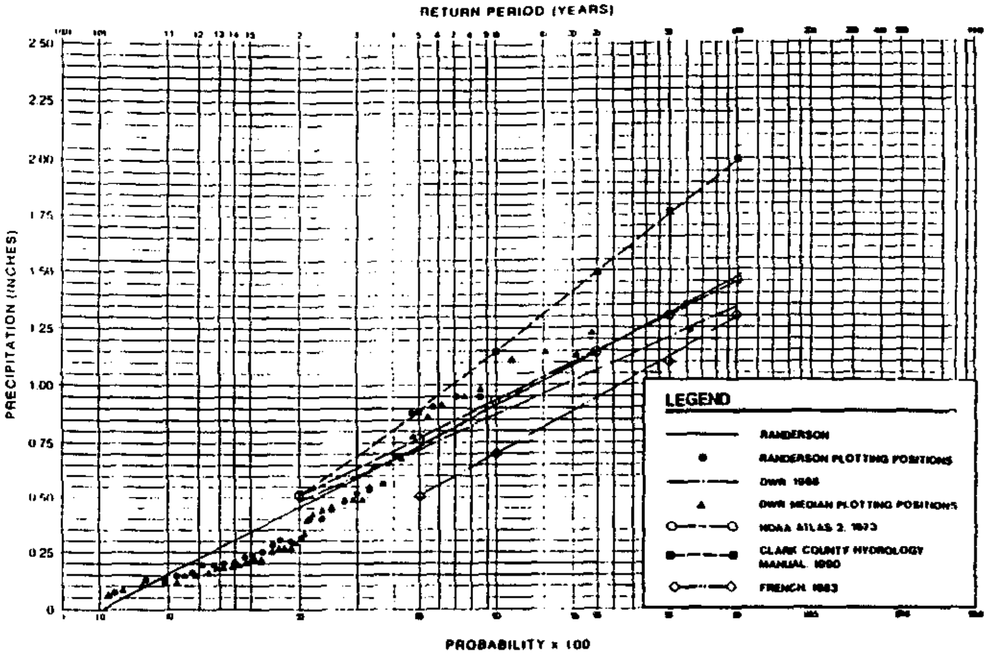

Figure 6A. 1-Hour Precipitation Data Las Vegas, McCarran Airport.

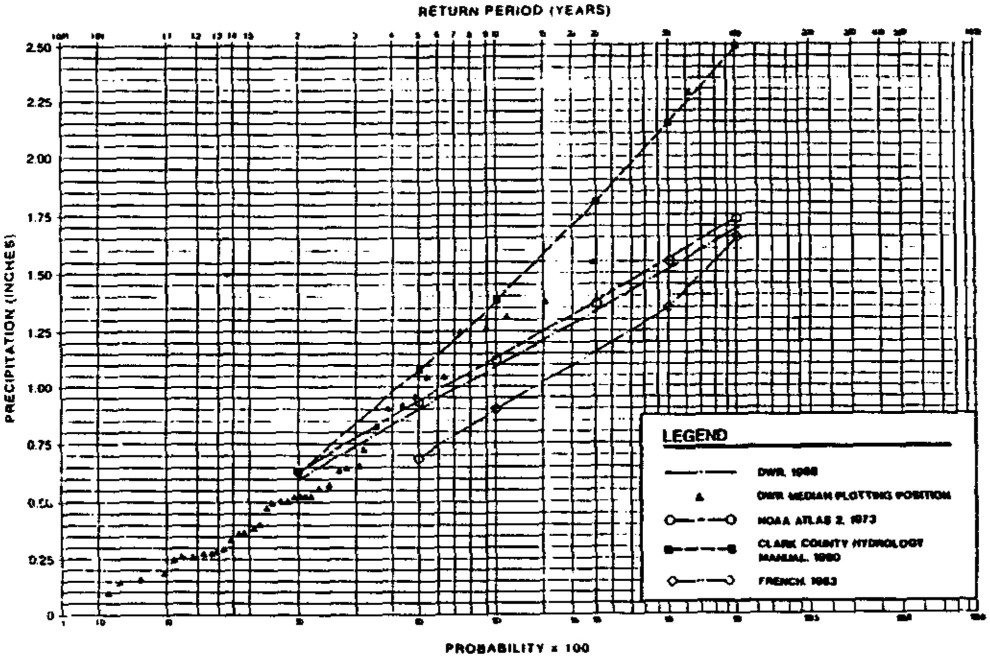

Figure 6B. 3-Hour Precipitation Data Las Vegas, McCarran Airport.

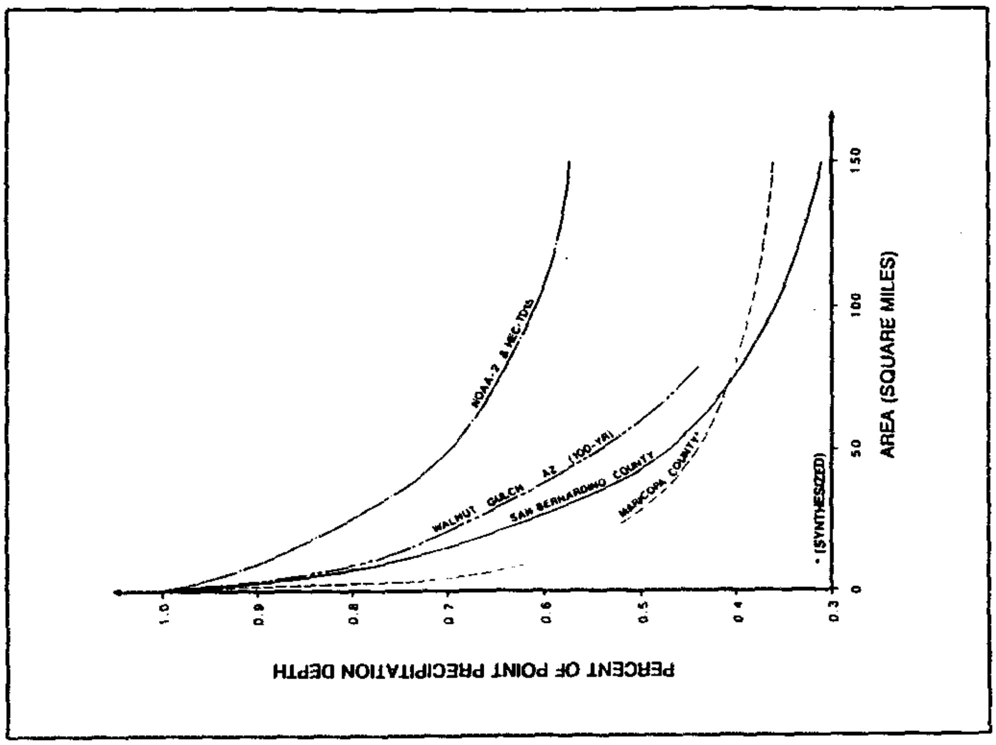

**Figure 7A. Design Storm (30-min) Depth Area Curves.**

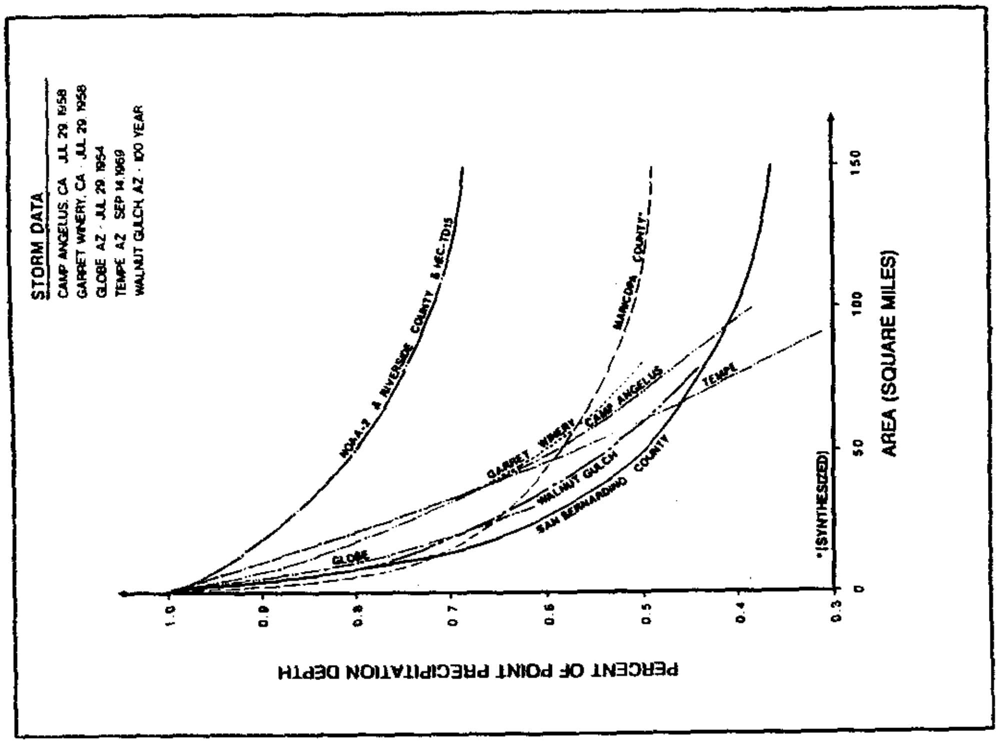

**Figure 7B. Design Storm (60-min) Depth Area Curves.**

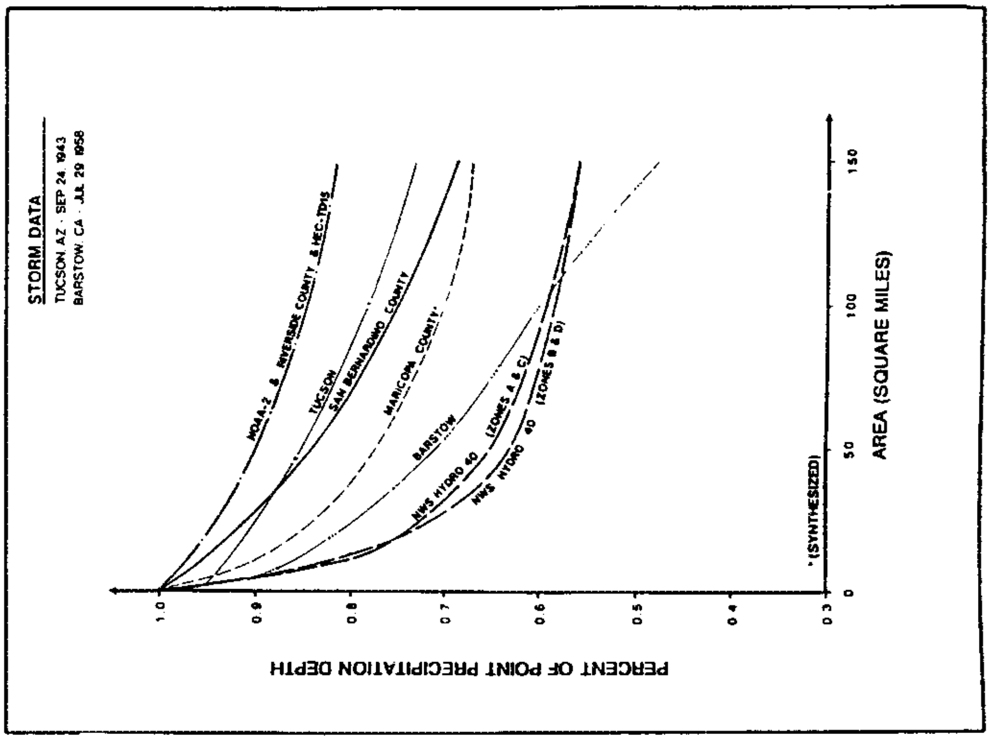

Figure 7C. Design Storm (3-hr) Depth Area Curves.

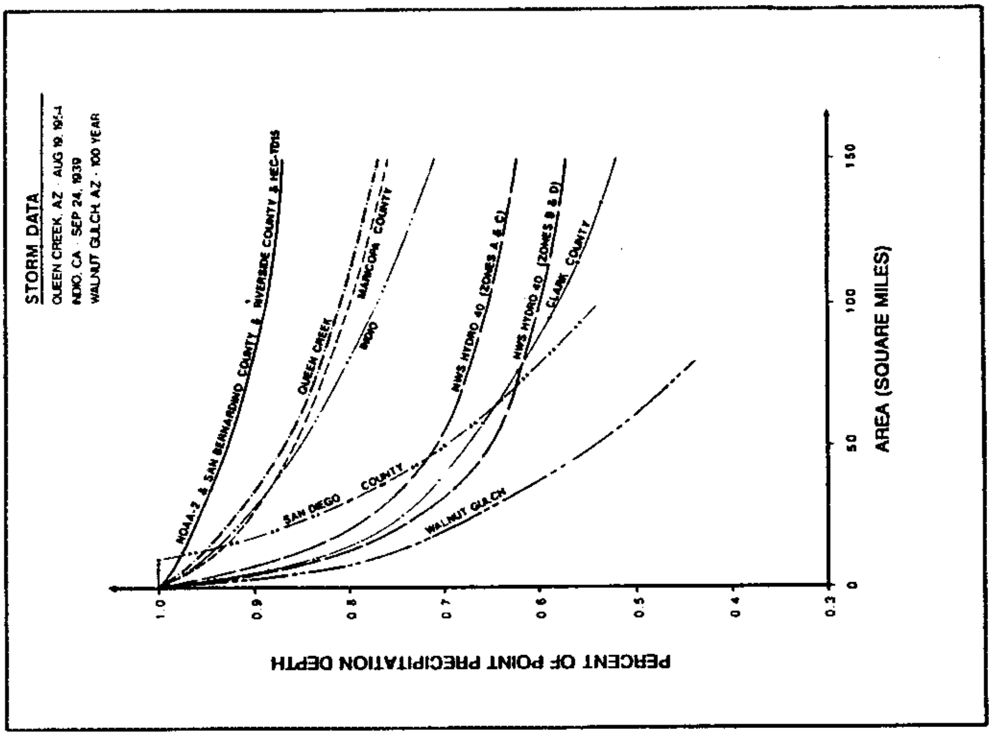

Figure 7D. Design Storm (6-hr) Depth Area Curves.