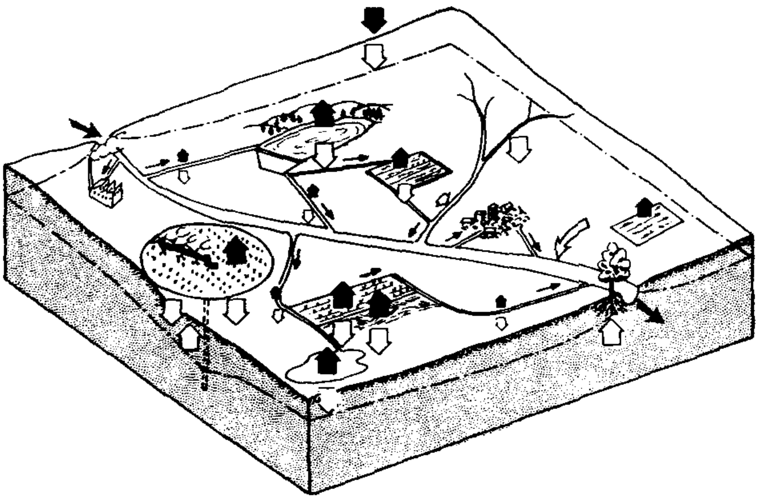
Proceedings
of Twelfth Annual
American Geophysical Union

HYDROLOGY DAYS



March 31 - April 3, 1992
Colorado State University
Fort Collins, Colorado

HYDROLOGY DAYS PUBLICATION

Hubert J. Morel-Seytoux

Proceedings

of

American Geophysical Union

Twelfth Annual

HYDROLOGY DAYS

March 31 - April 3, 1992

Colorado State University

Fort Collins, Colorado

Published by

HYDROLOGY DAYS Publications

57 Selby Lane

Atherton, California 94027-3926

A Review of Hydrologic Models for Arid Southwest United States

T.V. Hromadka[1]

ABSTRACT

Recently, hydrologic 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, San Diego County, and Riverside County, California. 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. In this paper, these hydrology manuals are compared as to modeling approaches, and the individual modeling components are examined for similarities.

I. RATIONAL METHOD 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.

II. UNIT HYDROGRAPH METHOD TECHNIQUES

II.1. Unit Hydrograph

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).

[1] Principal Engineer, Boyle Engineering Corporation, Newport Beach, California 92658

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.

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.

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.

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.

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

II.2. Unit Hydrograph Shape

The remaining consideration, regarding the unit hydrograph methods, is the unit hydrograph shape. Figure 1 compares 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

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)

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.

III. DESIGN STORM INPUT

III.1. 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.

III.2. Design Storm Areal Extent

Several counties address catchment sizes according to the storm size area limits shown in Table 5. Beyond the area limits of the table, several county manuals recommend special consideration of other approved hydrologic estimation techniques.

Table 5. 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.

III.3. 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 6, 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. 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.

III.4. 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.

Table 7. 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.

III.5. Desert Rainfall Intensity-Duration Characteristics

Table 9 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 Table, 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.

III.6. 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. Each of the hydrology manuals use area-averaged T-year return frequency rainfall depths for study purposes. Figure 2 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.

Table 8. 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 9. 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)

III.7. Comparison of Depth-Area Reduction Curves

Figure 2a 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 2b 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. Figure 2c 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. Figure 2d considers 6-hour depth-area adjustment. Again, considerable dispersion and uncertainty in reduction values is seen.

Figure 2e 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. 2, 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 depth-area relationships.

IV. DESIGN STORM RAINFALL RETURN FREQUENCIES

The several counties that use a fixed design storm pattern are not transferable between regions due to the differing rainfall intensity-duration relationships; however, the San Bernardino storm pattern (excluding depth-area curves) is transferable due to its construction using local rain gauge data. Table 10 provides a comparison of the several counties 100-year design storm patterns, for interior duration return frequencies, using respective county local rainfall data.

V. EFFECTIVE RAINFALL DETERMINATION

V.1. Loss Rate Estimation Methods

All the Agency design storm methods first modify the design storm rainfalls according to depth-area relationships, and then subtract (from the adjusted

rainfalls) rainfall losses, in order, to develop effective rainfall quantities. The effective rainfalls are then convoluted with the catchment unit hydrograph. In this section, the several loss rate estimation techniques are compared for the unit hydrograph applications. The several loss rate methods are itemized in Table 11.

Table 10. Design Storm Interior Duration Return Frequencies[1] for 100-year Storm Event

Peak Storm Duration	San Bernardino	Clark	Maricopa	Riverside	San Diego
30-minutes	100	19	60+	12	45
1-hour	100	29	100+	30	50
3-hour	100	50	100-	90	80
6-hour	100	100	100	100	100
(mean)[2]	(100)	(36.4)	(96)	(52.2)	(61.5)

Notes:
1 Based on respective County local rain gauge data, with depth-area effects neglected.
2 Mean computed for durations 30-minutes to 3-hour, using linear interpolation.

In order to compare loss estimation techniques, a 100-year return frequency event 6-hour design storm rainfall (appropriate for Phoenix Metro area, Arizona) is considered of 3.3-inches for the peak 6-hours (3.6-inches for the 24-hour duration). A SCS soil group B designation with Curve Number CN=75, and AMC II is assumed. For western desert urban areas, pervious area natural desert landscaping have SCS curve numbers (e.g., Clark County hydrology manual, 1990) of 63, 77, 85, 88, for SCS soil groups A, B, C, D, respectively, with a mean curve number of about 78. Artificial desert landscaping have a curve number of CN=96. Because rainfall losses decrease as CN increases, the use of CN=75 in the example problem demonstrates a reasonable comparison of loss rate techniques. Runoff comparisons are given in Table 12, neglecting depth-area effects.

Table 11. Loss Rate Methods

Agency	Loss rate, f(t)
San Bernardino[1]	$f(t) = \min\{\phi_1, \overline{Y}\, I(t)\}$
Maricopa[2]	f(t): method #1: $\min\{K_s\,(1 + \frac{\psi\theta}{F}),\ I(t)\}$ method #2: $I(t)$, for $\int_{s=0}^{t} I(s)\,ds$ £ STRTL; ϕ_2, for $\int_{s=0}^{t} I(s)\,ds$.> STRTL
Clark, San Diego	SCS Curve-Number Technique[3]
Riverside[4]	$f(t) = \min(\phi_3, kI(t))$
COE[5] (1988)	$f(t) = \phi_4$

Notes:

1 (i) ϕ_1 = phi index; as a function of SCS Curve Number.
(ii) $\overline{Y}$ = (1-yield); yield computed from SCS Curve Number based on 24-hour storm rainfall depth (or total storm).
(iii $I(t)$ = rainfall intensity, at time $t>0$.

2 (i) Either method may be used.
(ii) Green-Ampt model, with K_s = hydraulic conductivity;
ψ = wetted soil capillary suction;
θ = soil moisture deficit;
F = depth of infiltrated rainfall since storm time t = 0.
(iii) STRTL = initial infiltration + surface retention loss.

3 See Hromadka et al (1987), or McCuen (1983).

4 Phi-Index, ϕ_3, is used for 3- and 6-hour storm patterns; k is a low-loss constant, usually 0.8 to 0.9.

5 Reconstituted phi index, ϕ_4, is 0.40 in/hr for dry catchment.

Table 12. Example Problem Loss Rate Comparisons

Agency	Constant loss or phi-index (in/hr)	Total runoff (inches)
San Bernardino	0.47	2.28 (2.25)[1]
Maricopa[2]	0.25	2.28
Clark[3], San Diego[3,5]	--	1.16
Riverside[4]	0.30	2.33
COE (1988)[6]	0.40	1.99
(mean)[7]	(0.36)	(1.87)

Notes:

1 24-hour rainfall value used to estimate storm runoff yield. Value in parenthesis is total runoff volume, based on 6-hour rainfall.
2 Method 2 used. (Surface retention loss assumed to be 0.18 inches (average non-agricultural value); normal initial loss = 0.3 inches.)
3 Loss rates are per standard SCS methods
4 Low-loss rate assumed as 0.85 (i.e., mig-range of 80- to 90-percent of rainfall).
5 Low-loss rate of 0.05 in/hr neglected.
6 Reconstituted loss rate shown.
7 Mean based on six samples.

REFERENCES

1. Randerson, D., Meteorologist, National Weather Service, Nevada.
2. French, R.H., Precipitation in Southern Nevada, ASCE Journal of Hydraulic Engineering, Vol. 109, No. 7, 1983.
3. U.S. Corps of Engineers, 1988, Feasibility Study, Clark County, Nevada, Los Angeles District.
4. Miller, J.F., Frederick, R.H., Tracey, R.J., 1973, NOAA Atlas II, Vol. IX, California, NWS.
5. U.S. Army Corps of Engineers HEC Training Document No. 15, Hydrologic Analysis of Ungauged Watersheds Using HEC-1, 1982.

6. Zehr, R.M., Myers, V.A., 9184, Depth-Area Ratios in the Semi-Arid Southwest United States, NWS HYDRO-40, NOAA.
7. McCuen, R.H., Hydrologic Analysis and Design, Prentice Hall, 1989.
8. Sabol, G.V., Desert Rainfall Study, Report Nos. 1 and 2, Sept. 14, 1990 and Oct. 26, 1990.
9. Hydrology Manuals for Counties of Riverside (1978), San Diego (Addendum, 1985), San Bernardino (1986), Clark (1990), Maricopa (1990), Kern (1992).
10. State of California, Department of Water Resources, Rainfall Depth-Duration-Frequency for California, Short Duration Data, revised June 1988.
11. Hromadka II, T.V., McCuen, R.H., and Yen, C.C., 1987, Computational Hydrology in Flood Control Design and Planning, Lighthouse Publications.
12. Hromadka II, T.V., and Whitley, R.J., 1989, Stochastic Integral Equations in Rainfall-Runoff Modeling, Springer-Verlag.
13. U.S. Geological Survey, Water-Resources Investigations 77-21, Magnitude and Frequency of Floods in California (1977).
14. U.S. Geological Survey, Water-Resources Investigations Report 84-4142, Estimation of Magnitude and Frequency of Floods in Pima County, Arizona, With Comparisons of Alternative Methods (1984).
15. U.S. Geological Survey, ADOT-RS-15-121, Methods for Estimating the Magnitude and Frequency of Floods in Arizona (1978).

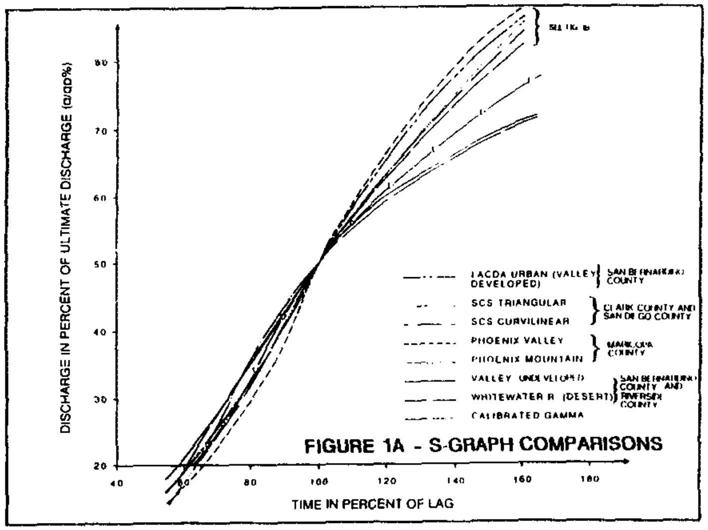


FIGURE 1A - S-GRAPH COMPARISONS

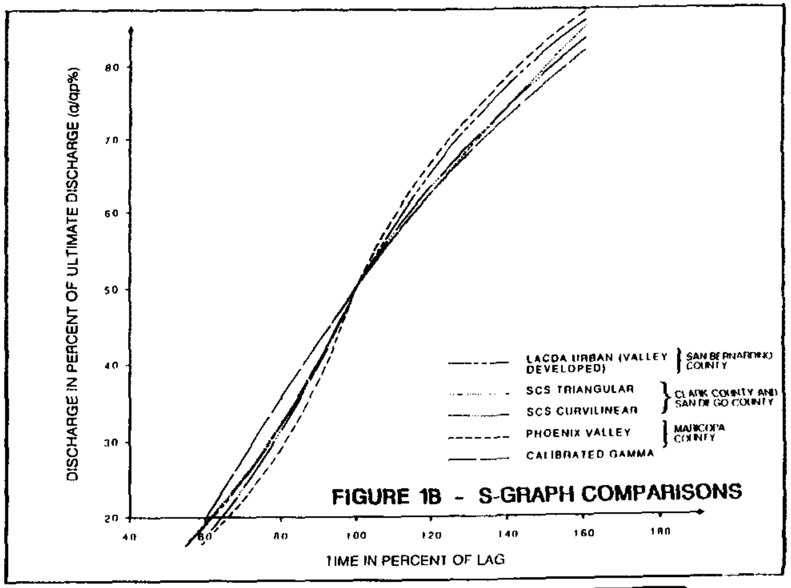


FIGURE 1B - S-GRAPH COMPARISONS

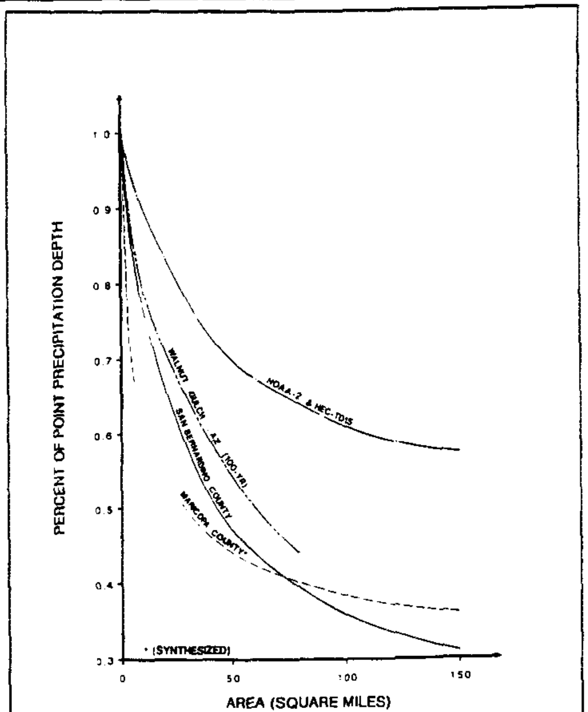


Figure 2A - Design Storm (30-min) Depth Area Curves

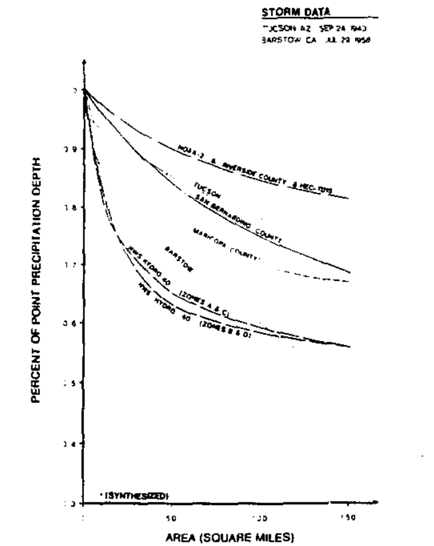


Figure 2C - Design Storm (3-hr)
Depth Area Curves

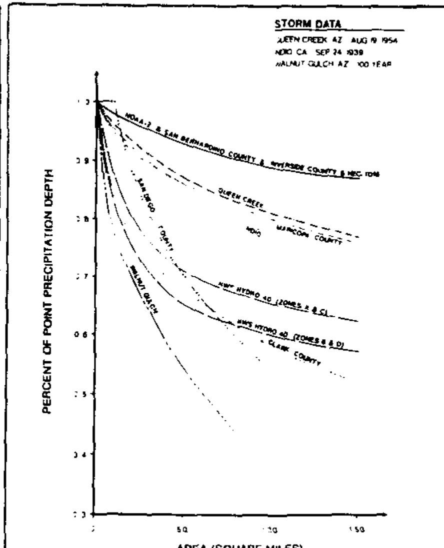


Figure 2D - Design Storm (6-hr)
Depth Area Curves

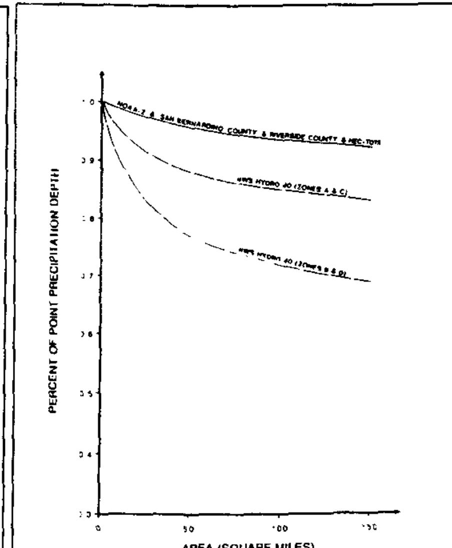


Figure 2E - Design Storm (24-hr)
Depth Area Curves