NOAA Technical Memorandum NWS HYDRO-40

DEPTH-AREA RATIOS IN THE SEMI-ARID SOUTHWEST UNITED STATES

Silver Spring, Md.
August 1984

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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ESSA Technical Memorandums

WBTM HYDRO 2 Annotated Bibliography of ESSA Publications of Hydrometeorological Interest. J. L. H. Paulhus, February 1967, 20 pp. (Superseded by WBTM HYDRO 8)

WBTM HYDRO 3 The Role of Persistence, Instability, and Moisture in the Intense Rainstorms in Eastern Colorado, June 14-17, 1965. F. K. Schwarz, February 1967, 21 pp. (PB-174-609)

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WBTM HYDRO 10 Flood Warning Benefit Evaluation--Susquehanna River Basin (Urban Residences). Harold J. Day, March 1970, 42 pp. (PB-190-984)

WBTM HYDRO 11 Joint Probability Method of Tide Frequency Analysis Applied to Atlantic City and Long Beach Island, N.J. Vance A. Myers, April 1970, 109 pp. (PB-192-745)

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NWS HYDRO 12 Direct Search Optimization in Mathematical Modeling and a Watershed Model Application. John C. Monro, April 1971, 52 pp. (COM-71-00616)

NWS HYDRO 13 Time Distribution of Precipitation in 4- to 10-Day Storms--Ohio River Basin. John F. Miller and Ralph H. Frederick, July 1972, 41 pp. (COM-72-11139)

NWS HYDRO 14 National Weather Service River Forecast System Forecast Procedures. Staff, Hydrologic Research Laboratory, December 1972, 7 chapters plus appendixes A through I. (COM-73-10517)

NWS HYDRO 15 Time Distribution of Precipitation in 4- to 10-Day Storms--Arkansas-Canadian River Basins. Ralph H. Frederick, June 1973, 45 pp. (COM-73-11169)

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DEPTH-AREA RATIOS IN THE SEMI-ARID SOUTHWEST UNITED STATES

Raymond M. Zehr and Vance A. Myers

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UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
John V. Byrne, Administrator

National Weather Service
Richard E. Hallgren,
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List of Symbols

A	area
b	coefficient used in equations that model the data (see Appendixes II and III)
C_x	calibration factor used to place final curves between bounds
cv	coefficient of variation (see Appendix I)
cov	covariance between precipitation amounts at two stations (see Appendix I)
DA	depth-area ratio
d	distance
d_s	distance separating exponential model (inner) from linear model (outer)
f	frequency (reciprocal of return period)
K_t	coefficient in Chow's equation, depends on return period
M	coefficient used in equations that model the data (see Appendixes II and III)
N	number of observations
P_5	5-station average precipitation
s	standard deviation of precipitation amounts
$\bar{X}$	average of precipitation amounts
y	fitted value of model statistic

Subscripts

A, B	designate annual maxima at particular stations associated with station-pair statistics
a, b	designate precipitation amount at second station that is concurrent with the annual maximum at the first station b is also used to designate the statistic for station-pair totals made up of the annual maximum at one station and the concurrent amount at the second station
L	designates "final" statistic fit between bounding values with the aid of the calibration constant (C_x)
m	designates annual maximum of station-pair total
in	designates smaller distances where exponential model is used

out designates larger distances where linear model is used

t designates specific return period, i.e., "t" years

Superscripts

The prime (') is used to designate relative values, that is individual values normalized by maxima. Any primed quantity has a value ranging from 0 to 1.

DEPTH-AREA RATIOS IN THE SEMI-ARID SOUTHWEST UNITED STATES

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ABSTRACT Geographically fixed depth-area ratios are estimated for Arizona and western New Mexico. While the study relies on a methodology for computing depth-area ratios from dense network data, modification of the approach was necessary to extend the results to data sparse regions. Available data indicate that reductions of point rainfalls for area size in the semi-arid Southwest are greater than previously published nationwide average depth-area curves.

1. INTRODUCTION

1.1 Purpose and Definition of Depth-Area Ratios

A knowledge of rainfall frequencies is basic to the design of many runoff carrying structures and to decisions on flood plain occupancy. Rainfall frequencies for these purposes are published as maps of point rainfalls for specified durations. For many problems the design engineer or investigator needs the corresponding frequency values for depth of rainfall averaged over a basin. To meet this need, nomograms are published giving the conversion factor necessary to estimate areal average depths at a particular location based on published point rainfall-frequency values. These adjustment factors are geographically fixed depth-area ratios. They are defined as ratios of two rainfalls, point values and areal average values with the same return periods. They are not

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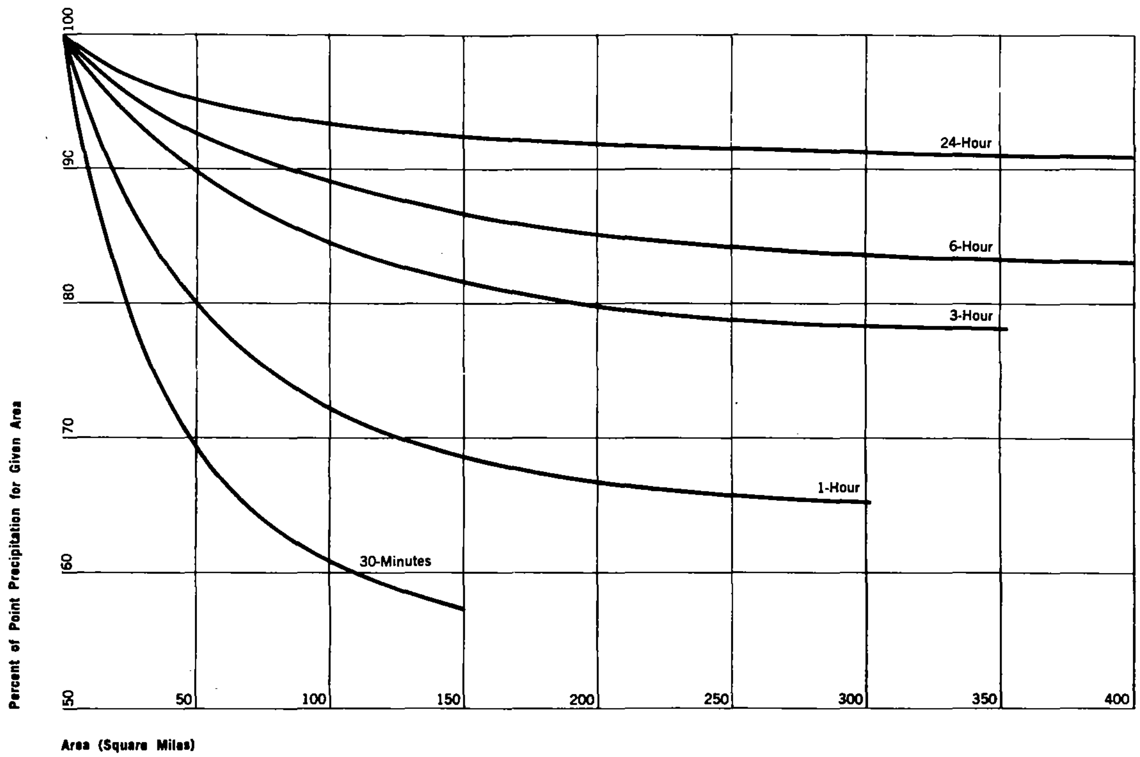

Figure 1.--Depth-area ratios from NOAA Atlas 2 (Miller et al. 1973).

necessarily dependent on the same set of storms, i.e., specific values in both the numerator and denominator may come from different precipitation events. Similar ratios based on the morphology of individual storms are termed storm-centered depth-area ratios.

1.2 Previous Work

A nomogram of geographically fixed depth-area ratios was first published by the U.S. Weather Bureau (now the National Weather Service, NWS) in the late 1950's in U.S. Weather Bureau Technical Paper No. 29 (U.S. Weather Bureau 1957-60). Such nomograms were based on data from dense networks of recording gages. Only a limited amount of such data is available. All data was pooled to produce a national-average depth-area nomogram (fig. 1). Reanalysis of basic data for various subsequent atlases indicated no evidence that would warrant changes in the nationwide average nomogram.

Osborn et al. (1980) analyzed 20 years of dense network recording raingage data from the Agricultural Research Service experimental watershed at Walnut Gulch in southeast Arizona to develop geographically fixed depth-area ratios. Data from this network are not routinely published and only recently have been available in a computer compatible form. (They were not available for the earlier atlases.) The results of this analysis for durations from 30 min to 6 hrs are reproduced in figure 2 and show significant differences from the national average curves. At Walnut Gulch, the depth-area ratios decrease more rapidly with increasing area than those published in NOAA Atlas 2 (Miller et al. 1973).

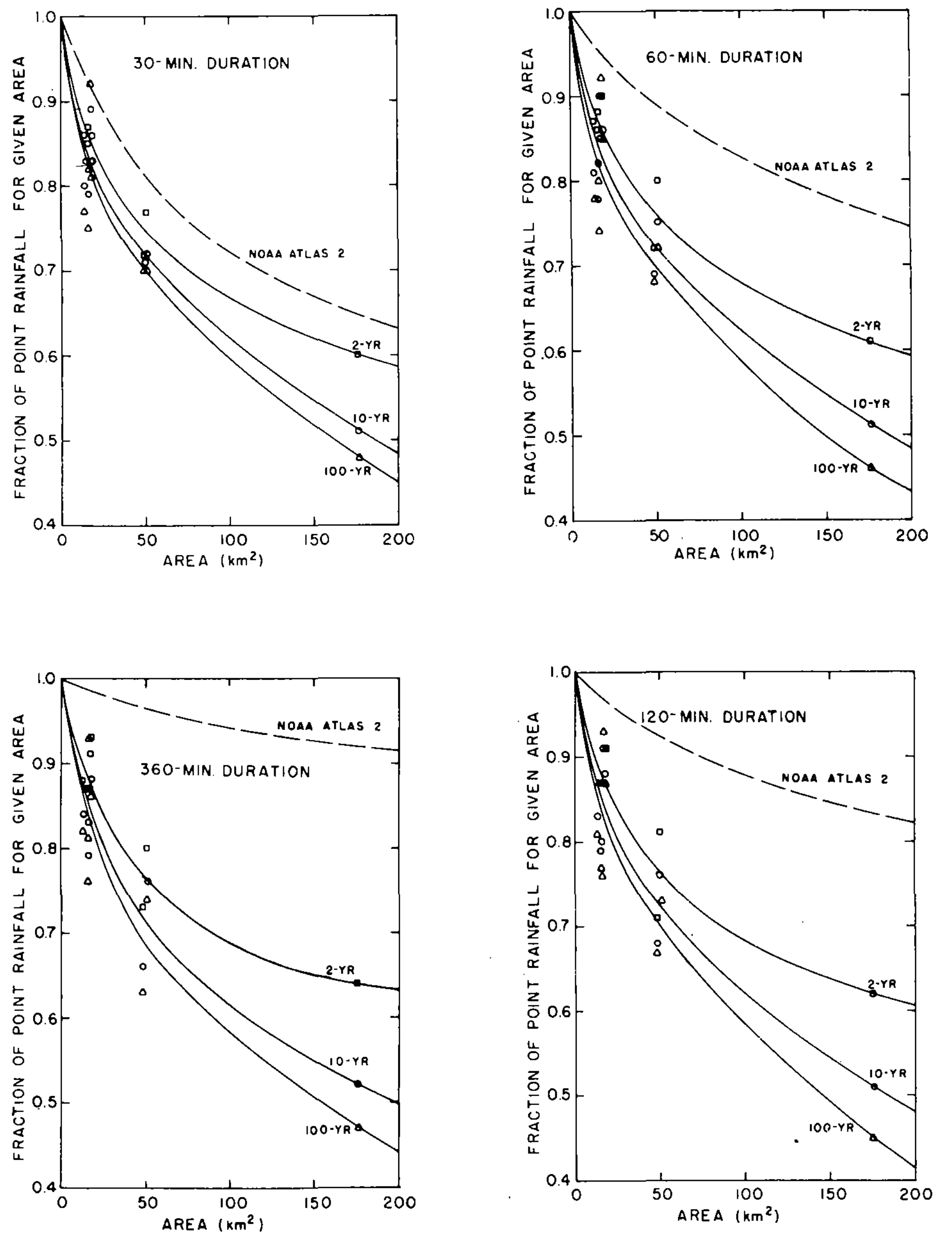

Figure 2.--Depth-area ratios at Walnut Gulch, Arizona, for durations of 30-min, 1-, 2-, and 6-hr (Osborn et al. 1980).

In NOAA Technical Report No. 24 (Myers and Zehr 1980), the methodology for computing geographically fixed depth-area ratios was extended and a model developed that permitted the estimation of upper and lower bounds on depth-area ratios from simultaneous rainfall records at station pairs, with calibration of the specific curve within these bounds using a few 5-station groups. There is considerable reliance in the present work on that study, hereafter referred to as TR 24. Some familiarity with that report will be assumed and the references to it will be concise.

1.3 Objective of Present Study

The objective of this study is to derive depth-area ratios in a form suitable for engineering use for a substantial portion of Arizona and New Mexico. This involves, a) developing depth-area ratios for Walnut Gulch for 24 hr, a duration not included in the study by Osborn et al. (1980), b) extending the Walnut Gulch ratios to areas larger than the original 79.5 mi^2 (200 km^2), and c) defining a region over which the Walnut Gulch curves apply and additional regions over which they apply with modification.

The 24-hr duration is necessary for maximum utility in hydrologic procedures of the Soil Conservation Service which uses 24 hr as a basic duration, and as the vehicle for exploring within-region and inter-region depth-area ratio variations. For reasons related to storm characteristics to be discussed later, the geographic variation of depth-area ratios is greater at 24 hr than at shorter durations.

2. WALNUT GULCH, ARIZONA, 24-HR DEPTH-AREA RATIOS

2.1 Data

Precipitation data are archived at the Agricultural Research Service experimental watersheds by accumulations at break points, i.e., precipitation accumulation and time and date at selected points on a recorder trace. Connecting these points by straight lines approximates the recorder trace (precipitation mass curve). These data cannot be processed directly for frequency analysis. Amounts for successive standard durations, such as an hour or a day must be abstracted by interpolation for an entire period of record.

Annual maxima, used for depth-area ratio evaluation, can then be abstracted for the standard durations or combinations of them.

In the analyses for the various National Weather Service atlases, the 24-hr annual maxima depict the greatest precipitation amounts for any consecutive 1440-min interval. When using either hourly or daily observations, at least a few annual maxima will be less than those for 1440 consecutive minutes because the fixed observation time can cause the 1440-min amount to be partitioned. An empirical factor, applied to the precipitation-frequency values, is used to adjust for this effect in NWS atlases. The Walnut Gulch 24-hr depth-area ratios derived here are based on a fixed clock time without adjustment. The Southwest Watershed Research Center abstracted 15 yr of 24-hr 2 a.m. to 2 a.m. MST rainfall data at twenty Walnut Gulch gages (fig. 3) and furnished these data to this project. The 2 a.m. time was chosen as most often falling between, rather than during storms. In comparison to other uncertainties, it seems unlikely that dimensionless ratios of areal-to-point values for these 24-hr periods would differ significantly from 1440-min data.

2.2 Station Groups

The TR 24 method of depth-area ratio analysis was followed with these Walnut Gulch data. The approach involves deriving basic statistics from pairs of stations distributed over available interstation distances, and statistics from five-station sets. The selected pairs are listed in table 1 and the five-station groups in table 2. The latter are chosen as being most like the desired configuration of a single center station and four outer stations with uniform spacing. Two examples are depicted in figure 4.

2.3 Depth-Area Ratios

The first step in determining depth-area ratios, using the TR 24 method, required the determination of $\overline{X}'_m$, s'_m, $\overline{X}'_b$, s'_b, and cov'_{Ab} using the station pairs. Formal mathematical definitions of these statistics are found in Appendix I. The notation here is identical with that in TR 24. $\overline{X}'_m$ and s'_m are the relative mean and standard deviation of the annual maximum series of two-station total precipitation. They are expressed as ratios of the station-pair statistics to the individual station statistics, and thus, are termed relative. $\overline{X}'_b$, s'_b and cov'_{Ab} are the relative mean, standard deviation and

Table 1.--Walnut Gulch station pairs for 24-hr analysis

Pair no.	Stations		Distance (mi)	Pair no.	Stations		Distance (mi)
41	1	3	0.9	51	1	30	7.7
42	56	54	1.1	59	33	70	8.3
43	66	68	1.3	57	23	68	8.8
44	29	30	1.6	53	8	56	9.1
45	3	8	1.9	54	9	60	9.6
32	3	9	2.1	40	11	66	10.1
31	1	9	2.4	64	3	56	10.7
39	30	33	2.8	69	18	68	10.7
46	44	60	3.0	66	8	66	11.4
47	30	44	4.1	60	18	70	11.7
48	33	56	5.0	61	1	60	12.3
50	47	54	5.1	68	9	70	12.8
56	18	44	5.6	67	8	70	13.0
55	11	47	6.3	65	3	68	13.8
52	3	29	6.7	62	1	68	14.5
58	30	66	7.4	63	1	70	15.3
49	1	29	7.5				

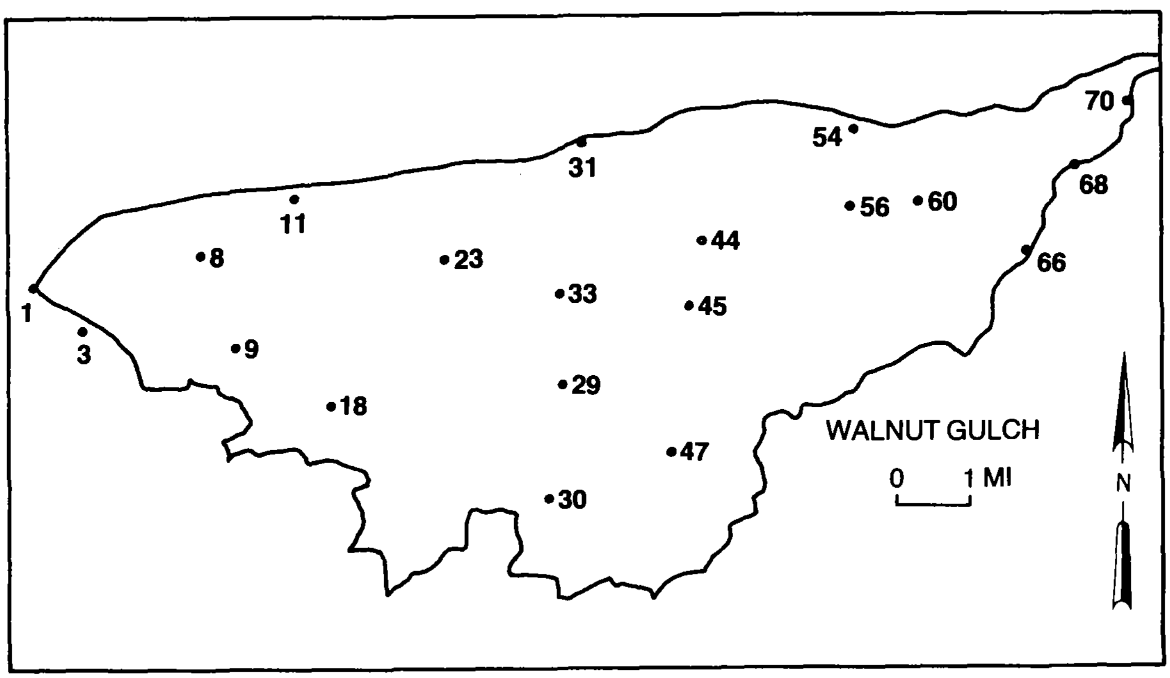

Figure 3.--Walnut Gulch, Arizona, basin and rain gages used for 24-hr analysis. Numbers are station identifiers.

Table 2.--Walnut Gulch 5-station groups for 24-hr analysis

Group no.	Center station	Surrounding stations				$\bar{d}$(mi)
13	33	23	29	31	45	1.70
11	29	18	30	33	45	2.03
16	60	44	54	66	68	2.03
14	33	18	30	31	44	2.15
19	8	1	3	11	18	2.15
12	29	18	23	45	47	2.33
15	45	29	31	47	56	2.35
10	23	11	18	29	31	2.40
17	33	11	18	47	56	3.78
18	45	18	30	54	66	4.10

$\bar{d}$ = average of the four distances from the center station to the surrounding stations.

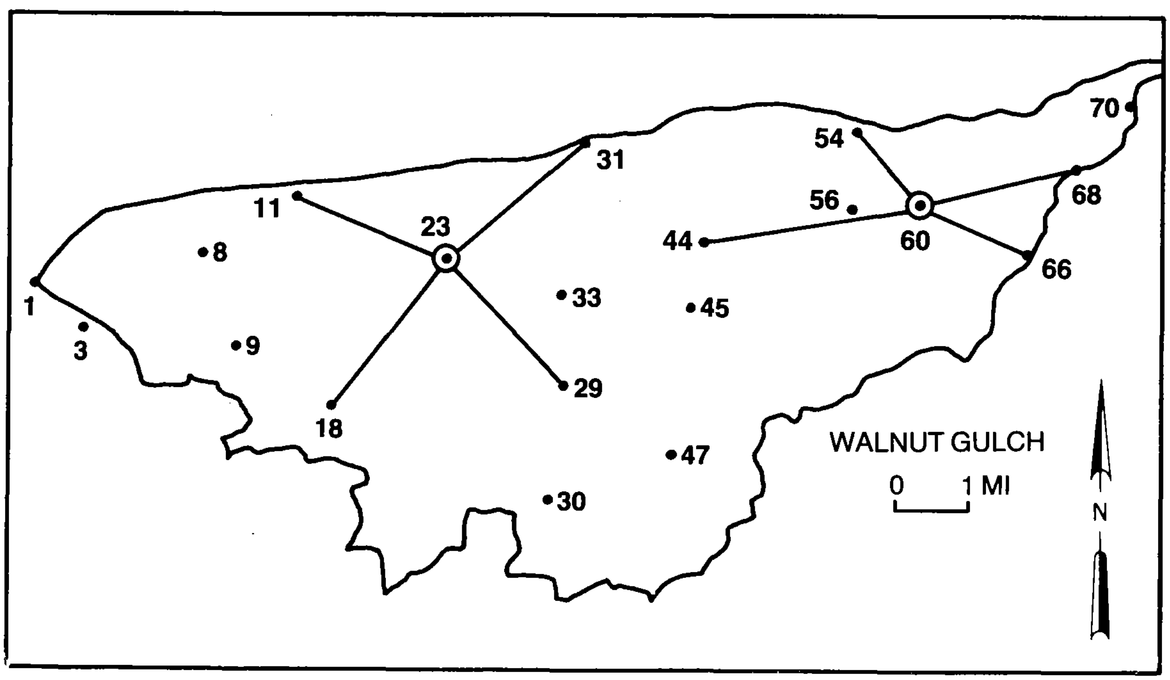

Figure 4.--Typical examples of two of the ten five-station groups listed in table 2.

covariance of rain falling at one member of a station pair simultaneous with annual maximum rainfall at the other member of the pair. These statistics were fit to analytic curves in a manner similar to that used in TR 24. The fitting coefficients and formula are included in Appendix II.

The TR 24 method combines curves fit to station-pair statistics vs. interstation distance and theoretical considerations to estimate bounds for the relative mean, $\overline{X}'_L$, and the relative standard deviation, s'_L, of the annual series of areal average rainfall. Five-station statistics are then used as a calibration to place $\overline{X}'_L$ and s'_L curves vs. area between the bounds. Values from these curves are used to compute depth-area ratios as functions of area and return period.

The results of this methodology applied to 24-hr Walnut Gulch data are shown in figures 5 and 6. The 24-hr depth-area curves for 2-, 10-, and 100-yr return periods calculated from the adopted $\overline{X}'_L$ and s'_L appear in figure 5. Combining 24-hr results with the 30-min to 6-hr depth-area ratios from Osborn et al. (1980) produced the depth area ratio vs. duration curves in figure 6. It is noted that the 24-hr Walnut Gulch results are a reasonable complement to the curves of Osborn et al., which were derived by an independent method. A limited comparison of these two methods for developing depth-area curves revealed small differences in results. The technique of Osborn et al., produced curves with a somewhat greater reduction for area than those developed by the TR 24 method. The differences were not considered significant and were well within the range of differences expected from analyzing the data by different methods.

3. EXTENSION BEYOND WALNUT GULCH

More widely spaced precipitation data and other clues were used in an attempt to define the area for which the Walnut Gulch depth-area ratios are valid, and other areas where they may be applicable with some modification. The intent was to delineate zones with climate sufficiently homogeneous to justify using a common set of depth-area ratios in engineering applications. Zone definition was necessarily based on inferences from limited information.

3.1 Data Types

Ideally, data would be available at closely spaced intervals throughout the study area and would be suitable for direct calculation of depth-area ratios.

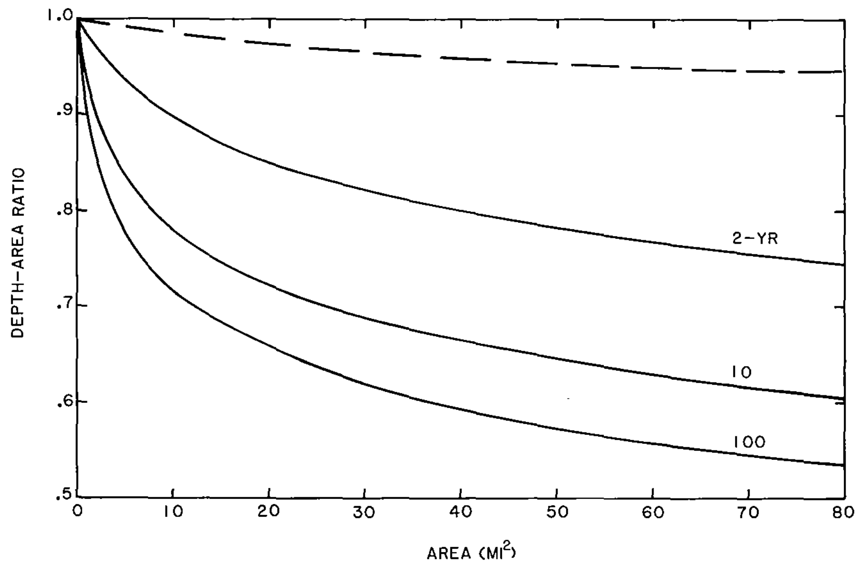

Figure 5.--24-hr depth-area ratio at Walnut Gulch for 2-, 10-, and 100-yr return periods. The dashed line is the NOAA Atlas 2 (Miller et al. 1973) 24-hr depth-area curve.

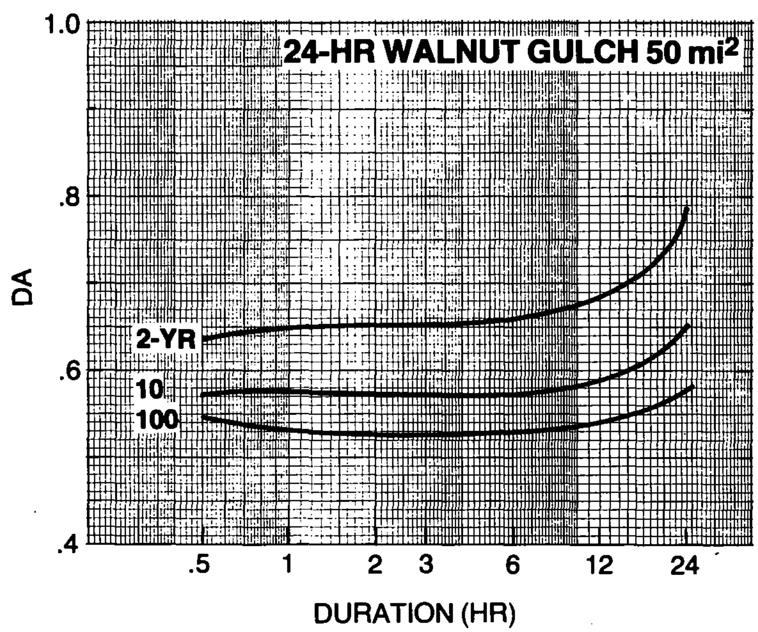

Figure 6.--Depth-area ratio vs. duration at 50 mi^2 (129.5 km^2) for 2-, 10-, and 100-yr return periods. The 24-hr Walnut Gulch results are combined with the Walnut Gulch depth-area ratios for 30 min, 1-hr, 2-hr, and 6-hr from Osborn et al. (1980).

Such data do not exist. Inferences are made from each of the following data sources or types. They progress in sequence from data of greatest to least direct applicability, and from least to greatest coverage of the study area.

3.1.1 Dense Networks

The dense network at Walnut Gulch has been described. Osborn et al. (1980) also published depth-area ratios for the Alamogordo Creek, NM, Experimental Watershed. The location in eastern New Mexico is shown as "AC" in figure 7b. Statistics from recorder pairs (section 3.1.2 below) indicate that depth-area ratios in the upper Rio Grande basin near Albuquerque are similar to those for Walnut Gulch and different from those at Alamogordo Creek, though the distance between Albuquerque and Alamogordo Creek is much less than that between Albuquerque and Walnut Gulch. Storms in eastern New Mexico depend heavily on moisture flow from the Gulf of Mexico that is not disrupted by orographic barriers. Cold fronts that approach from the northeast and lodge against the mountains and minimally modified tropical storms are often associated with heavy rainfall on the Alamogordo Creek Watershed (Osborn et al. 1980). Both situations differ from conditions that usually accompany heavy rainfalls in the Walnut Gulch area. Alamogordo Creek data are not used further in this study because of these meteorological differences. The eastern boundary to the present investigation (dashed line in figure 7b) is placed at the crest of the Sangre de Cristo in northern New Mexico and along the major easternmost ridges to the south near 105° 45'W. The mountains along the eastern boundary in central and southern New Mexico have lower elevations and are less continuous than the Sangre de Cristo. Therefore, the previously mentioned characteristic storm differences are less applicable in southern New Mexico than along the Sangre de Cristo crest.

3.1.2 Recorder Pairs

Simultaneous rainfall at a pair of gages allows the estimation of the covariance of point rainfall at the interstation distance, and thus is related to depth-area ratios over corresponding area sizes. Recording gage pairs with 12 or more years of simultaneous record during 1948-75 and with interstation distances of 50 mi or less were identified in Arizona and western New Mexico. The pairs are listed in table 3 and the locations of midpoints between paired stations are depicted in figure 7. The pair numbers in the tables and on the map are

Table 3.--Arizona and New Mexico station pairs

Pair no.	Stations*		Dist (mi)	Yr of record	Pair no.	Stations*		Dist. (mi)	Yr of record
	Arizona					New Mexico			
710+	8940	9534	2.2	18	810	0903	4366	4.7	20
711	6481	6486	3.1	14	815	4719	7827	4.7	18
712+	0966	8409	13.6	17	817	1286	4009	15.7	25
713+	8810	8820	14.4	14	818	3374	8518	16.1	15
714+	8409	9279	15.0	17	820	1138	7423	18.3	15
715	6676	6801	16.7	19	821	0234	0903	18.8	26
716	8264	8940	17.2	18	824	1138	8387	21.8	16
717	8264	8348	18.2	15	826	4426	8535	23.0	16
718	8264	9534	18.5	19	828	0234	4366	23.4	21
720+	0768	2659	23.7	21	835	6435	9686	28.0	24
721	7741	8940	24.0	15	836	7423	8387	29.9	22
722+	7593	8820	24.6	24	838	3374	4366	32.9	17
723	0808	9271	26.7	22	839	0640	7423	33.1	18
724+	6546	8409	27.6	16	840	1286	3225	33.9	25
725+	0966	1870	27.8	15	841	4426	9686	34.0	21
727+	9066	9279	28.5	17	842	0903	3374	34.4	17
728	7741	8264	28.9	12	844	0903	8518	34.6	17
729+	5921	7593	29.0	22	845	3225	4009	34.8	23
730+	6546	9279	29.1	17	846	4366	8518	35.3	17
731	1314	8348	34.8	13	847	0818	5800	35.7	17
733+	6119	8820	35.3	24	853	0234	8518	37.7	18
734+	0966	6546	36.4	16	856	1286	4426	38.3	23
735	8348	9534	36.4	13	858	6435	8535	38.6	16
736	6323	8940	37.1	20	862	4426	6435	40.3	22
737	6323	9534	37.3	19	863	4436	8072	41.2	15
738+	7593	8810	38.6	12	868	2024	3225	42.5	21
740	0487	6801	39.2	18	870	3225	8535	44.1	16
741	1314	6481	40.9	20	873	0234	4719	44.4	21
742+	1870	8409	41.4	14	875	0903	8072	44.5	20
743+	0768	1870	42.5	18	876	0234	3374	44.8	18
744	1314	6486	43.8	19	879	3225	4426	45.6	20
745+	6119	6546	44.7	13	881	0640	8387	46.0	22
746	0487	3010	46.6	23	884	8535	9686	47.7	16
747+	0808	6546	47.1	17	885	0818	4009	48.2	19
748+	0808	9279	48.1	18					
749	0808	7741	48.7	16					
750	6468	9439	49.6	25					

* Station index numbers are published in "Hourly Precipitation Data," Environmental Data Service, 1951-1975.

\+ "Southeast Arizona" station pairs

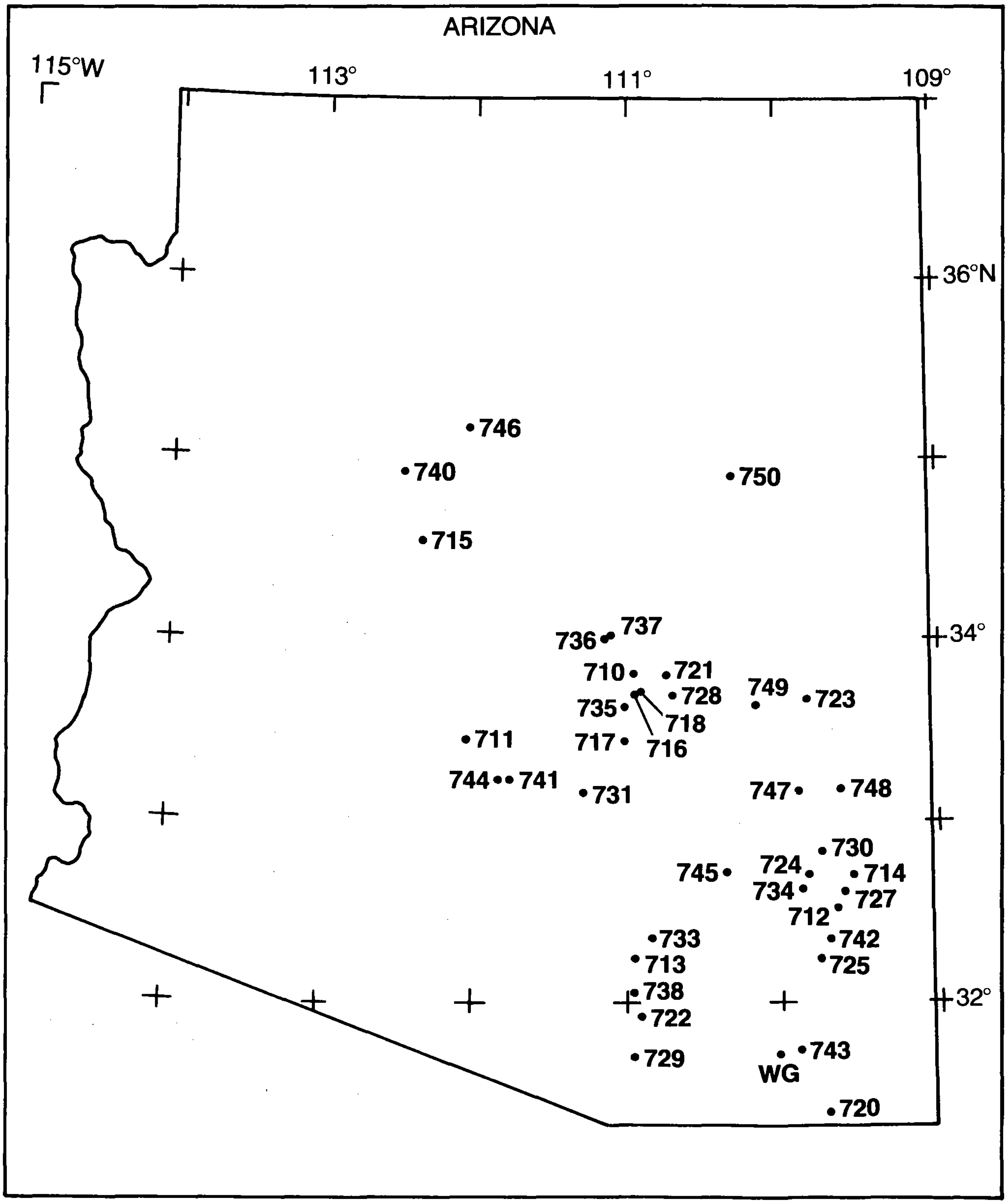

Figure 7a.--Locations of midpoints between Arizona recorder pairs. Identification numbers are from table 3. Point labeled WG is Walnut Gulch.

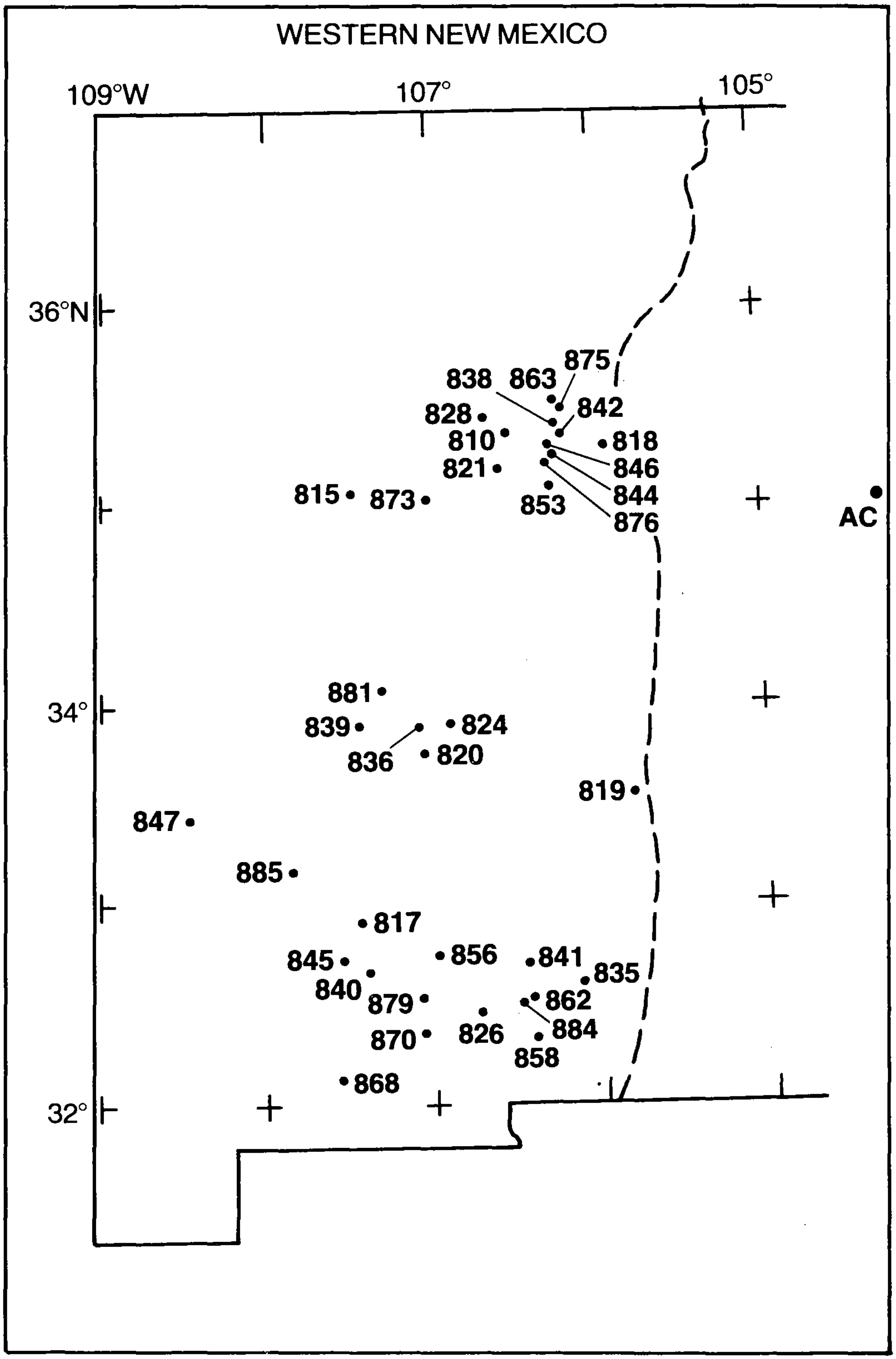

Figure 7b.--Locations of midpoints between New Mexico recorder pairs. Identification numbers are from table 3. Point labeled AC is Alamogordo Creek.

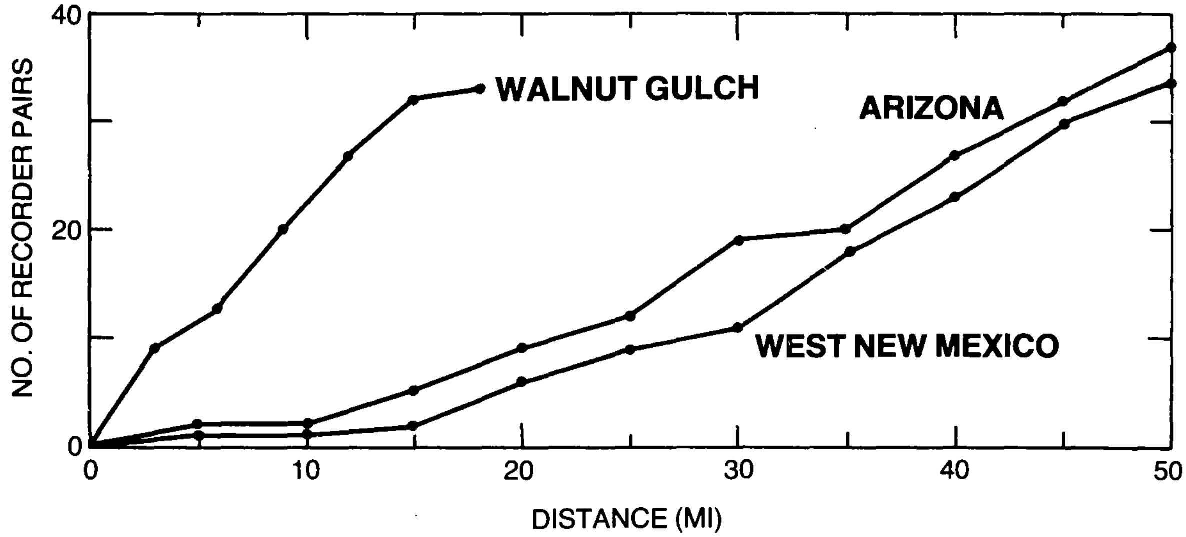

Figure 8.--Distribution of recorder-pair interstation distances for Arizona, western New Mexico, and Walnut Gulch 24-hr data. Points denote total number of pairs with interstation distance less than or equal to the plotted distance.

arbitrary identifiers. Figure 8 depicts the distribution of interstation distances. Most distances exceed 15 mi and are large for optimum relevance to area sizes of 500 mi^2 and less, our greatest interest. For the area sizes of greatest interest, the recorder-pair statistics are most useful as indices of regional and interdurational variations of depth-area ratios.

3.1.3 Daily Precipitation Stations

The study area is covered more densely and uniformly by daily reporting precipitation stations (Environmental Data Service 1951-76) than with recorder stations (see figs. 9 and 10). The percentage of annual maximum daily rainfalls at each station that occur in the cool season was used as an indicator of the contribution of general vs. local storms to the 24-hr annual series. A zone with more cool-season storm influence on the annual series could be expected to have larger depth-area ratios than a zone with less cool-season influence.

An attempt was made to use daily reporting station pairs in the same manner as recorder pairs to evaluate station-pair statistics for the 24-hr duration. The effect of varying observation times could not be overcome and this attempt was not successful.

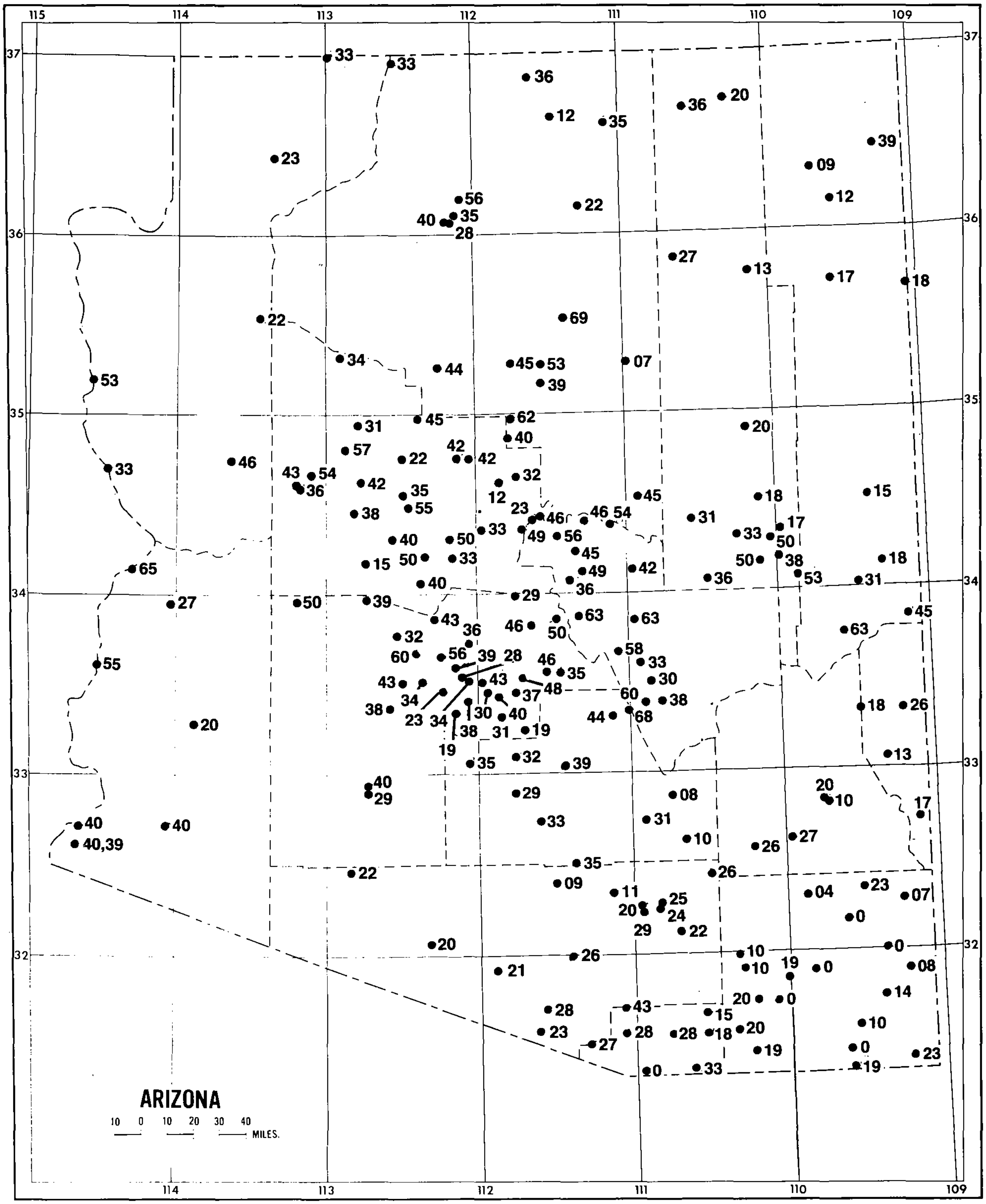

Figure 9.--Percentages of daily annual maxima in the "cool-season" (November through April) for Arizona.

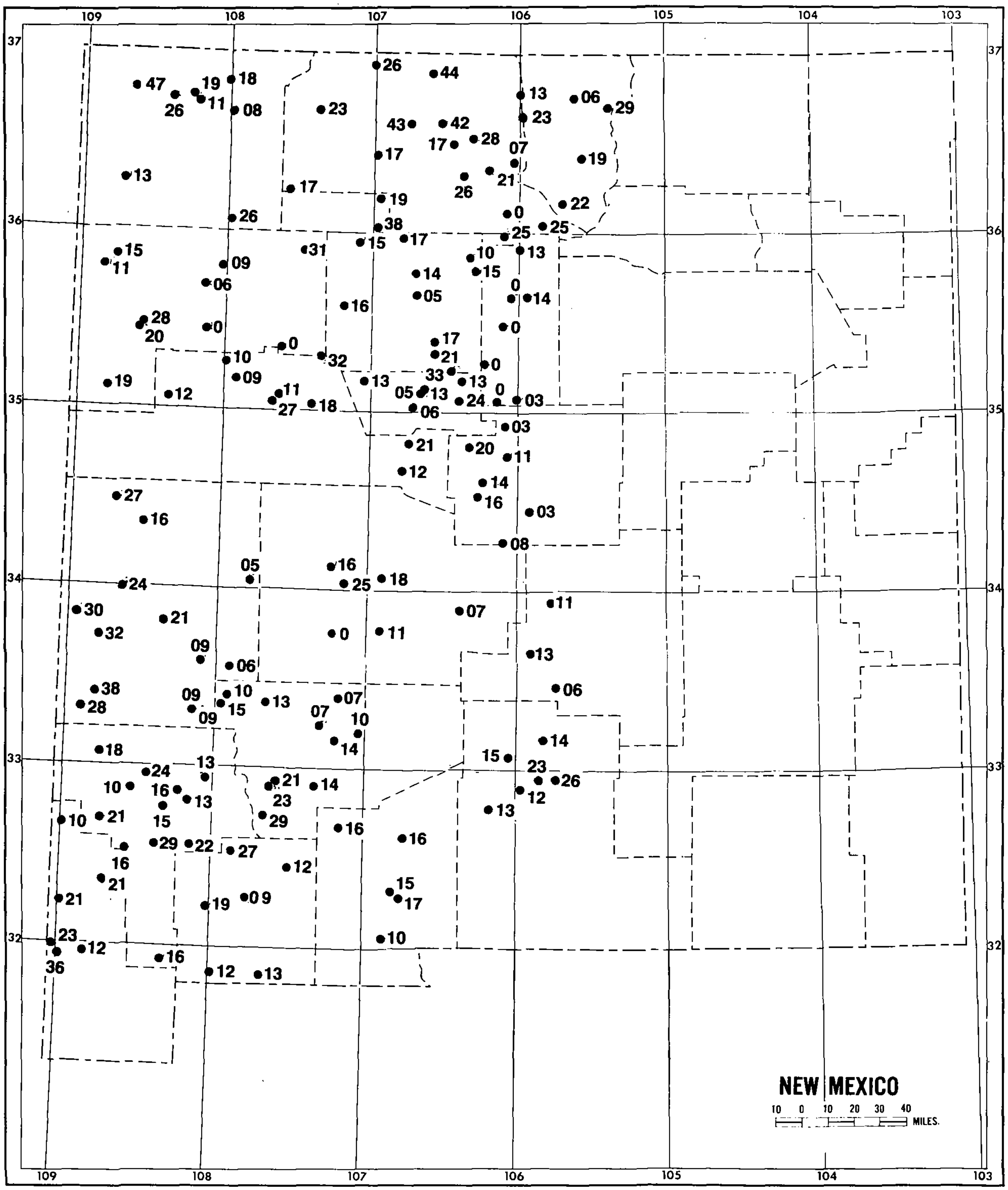

Figure 10.--Same as figure 9, except for western New Mexico.

3.1.4 Topography and Synoptic Factors

Landforms and elevations are defined everywhere on topographic maps at all scales of variation relevant to present purposes. Topographic information is the least direct of the data used. However, judicious use of topographic information in combination with knowledge of meteorological factors can provide useful insights into the spatial variation of generally "noisy" quantitative data, such as that discussed above.

3.1.5 Rainfall-Frequency Values

Rainfall-frequency values are also defined everywhere in map form in NOAA Atlas 2. It would be of great utility if station-pair statistics, measured at a limited number of points, could be predicted from parameters that are more universally available, such as these rainfall-frequency values. As outlined in Appendix II, the TR 24 approach was used to fit the station-pair data to analytic equations. The deviations at each station pair midpoint from this curve of best fit were used in a regression with the 2-yr 24-hr rainfall (determined from NOAA Atlas 2) as a predictor. The results yielded a low correlation with large scatter. A possible explanation for the poor relationship is that there are insufficient data to compensate for the relatively large amount of "noise" in the $\bar{X}'_m$ deviations. No further attempt was made to use the rainfall-frequency values.

3.2 Station-Pair Statistics

The data used for the paired recorder phase of the project are hourly precipitation values on Office of Hydrology, National Weather Service, magnetic tapes (Peck et al. 1977). These contain the data published in Hourly Precipitation Data (Environmental Data Service 1951-75). For quality control, it was possible to take advantage of work from another project (Frederick et al. 1981) which tabulated periods of missing data and accumulated data. Years of record with data of poor quality were eliminated, with criteria similar to those used in TR 24.

The quantities $\bar{X}'_m$, and $\bar{X}'_b$ (defined in Appendix I) were calculated for all station pairs and normalized to a 20-yr record by the TR 24 method. At each pair, values at 1, 2, 3, 6, 12 and 24 hr were first smoothed over duration, fitting the data to eq. (3-5) of TR 24. These duration-smoothed values were then fit over interstation distance, again using the TR 24 approach. Arizona and New Mexico data were fit separately.

3.3 $\overline{X}'_b$ Statistic vs Interstation Distance

With increasing distance between recorder-pair stations, a distance is approached at which there is practically no relationship between simultaneous rainfalls at the stations and no information applicable to depth-area ratios is obtainable. This distance is determined by the space and time scale of the meteorological systems which produce the annual maximum rainfalls, and varies with duration, storm type, and topography. The statistic $\overline{X}'_b$ becomes quite small at large interstation distance. However, by definition it cannot be negative. Thus, when curves are fit to $\overline{X}'_b$ with interstation distances distributed from zero to very large values, a theoretical curve will be asymptotic to a small positive value.

Table 4 lists the number of recorder pairs with $\overline{X}'_b < 0.1$ within intervals of interstation distance for each duration (0.1 is an arbitrary value and has no explicit physical significance). Based on table 4 and careful inspection of $\overline{X}'_b$ plots (not shown), the following decisions were made with regard to the applicability of these recorder-pair statistics to depth-area evaluation:

1. 1-hr and 2-hr recorder-pair data may produce unrepresentative results and are not used.

2. 3-hr pairs are limited to those with interstation distances less than 35 mi.

3. Pair statistics with interstation distances up to 50 mi are applicable for durations of 6 hr and greater.

3.4 Search for Geographical Variations

To search for meteorologically homogeneous zones, for each station-pair, deviations of each statistic at each duration from the corresponding curve fit using all station pairs were plotted on maps. The clearest geographical pattern of deviations was for $\overline{X}'_m$ at 24 hr in Arizona (fig. 11a). There is a preponderance of negative values southeast of the dashed line, while positive

Table 4.--Number of recorder pairs with $\bar{X}_b' < 0.1$

Distance (mi)	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr	Total no. of pairs
			Arizona				
0-5	0	0	0	0	0	0	2
5-10	0	0	0	0	0	0	0
10-15	2	1	0	0	0	0	3
15-20	3	0	0	0	0	0	3
20-25	3	2	0	0	0	0	3
25-30	6	4	2	0	0	0	7
30-35	1	0	0	0	0	0	1
35-40	5	4	4	0	0	0	6
40-45	4	3	2	0	0	0	4
45-50	5	4	4	0	0	0	5
0-50	29	18	12	0	0	0	34
% of total	85	53	35	0	0	0	
			New Mexico				
0-5	0	0	0	0	0	0	1
5-10	0	0	0	0	0	0	0
10-15	0	0	0	0	0	0	1
15-20	3	0	0	0	0	0	4
20-25	3	1	1	0	0	0	3
25-30	2	1	0	0	0	0	2
30-35	7	5	1	0	0	0	7
35-40	5	4	2	0	0	0	5
40-45	7	6	5	0	0	0	7
45-50	4	3	3	2	0	0	4
0-50	31	20	12	2	0	0	34
% of total	91	59	35	6	0	0	

values are dominant northwest of this line. There is less suggestion of this difference at 6 hr and it virtually disappears at 3 hr (figures not shown). Inspection of the New Mexico deviations (fig. 11b) suggests no consistent variation over the region.

On the basis of this tentative separation, the station pairs in Arizona were divided into two sets, "southeast Arizona," southeast of the line of figure 11a and "central Arizona," the remaining pairs. Curves were fit again to each statistic in these two sets: the curves for 3, 6 and 24-hr for $\bar{X}_m'$ appear in figure 12 along with the New Mexico curve. Due to the paucity of data at

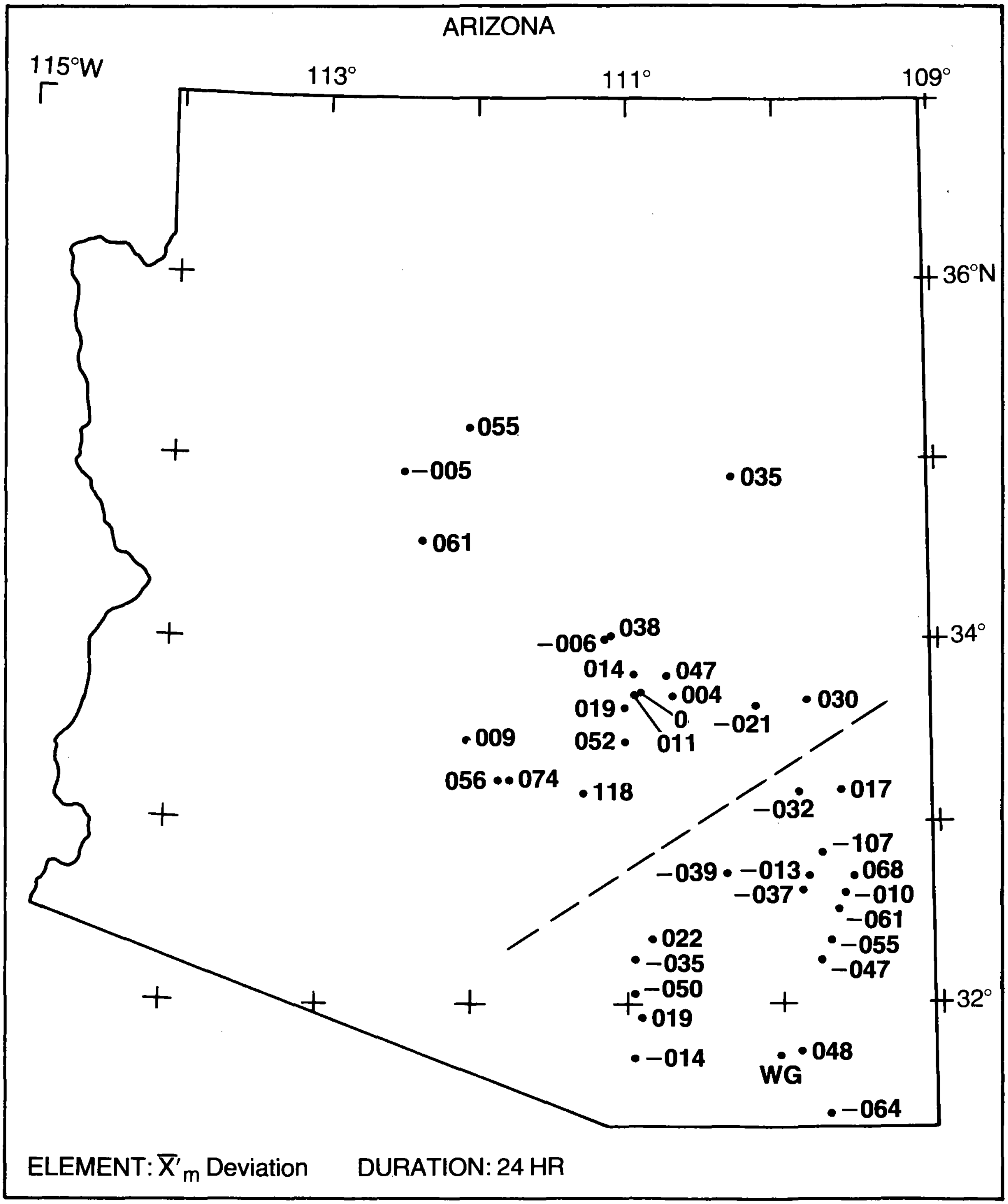

Figure 11a.--Deviation ($X10^{-3}$) of $\bar{X}'_m$ from the fitted curve for the 24-hr duration in Arizona.

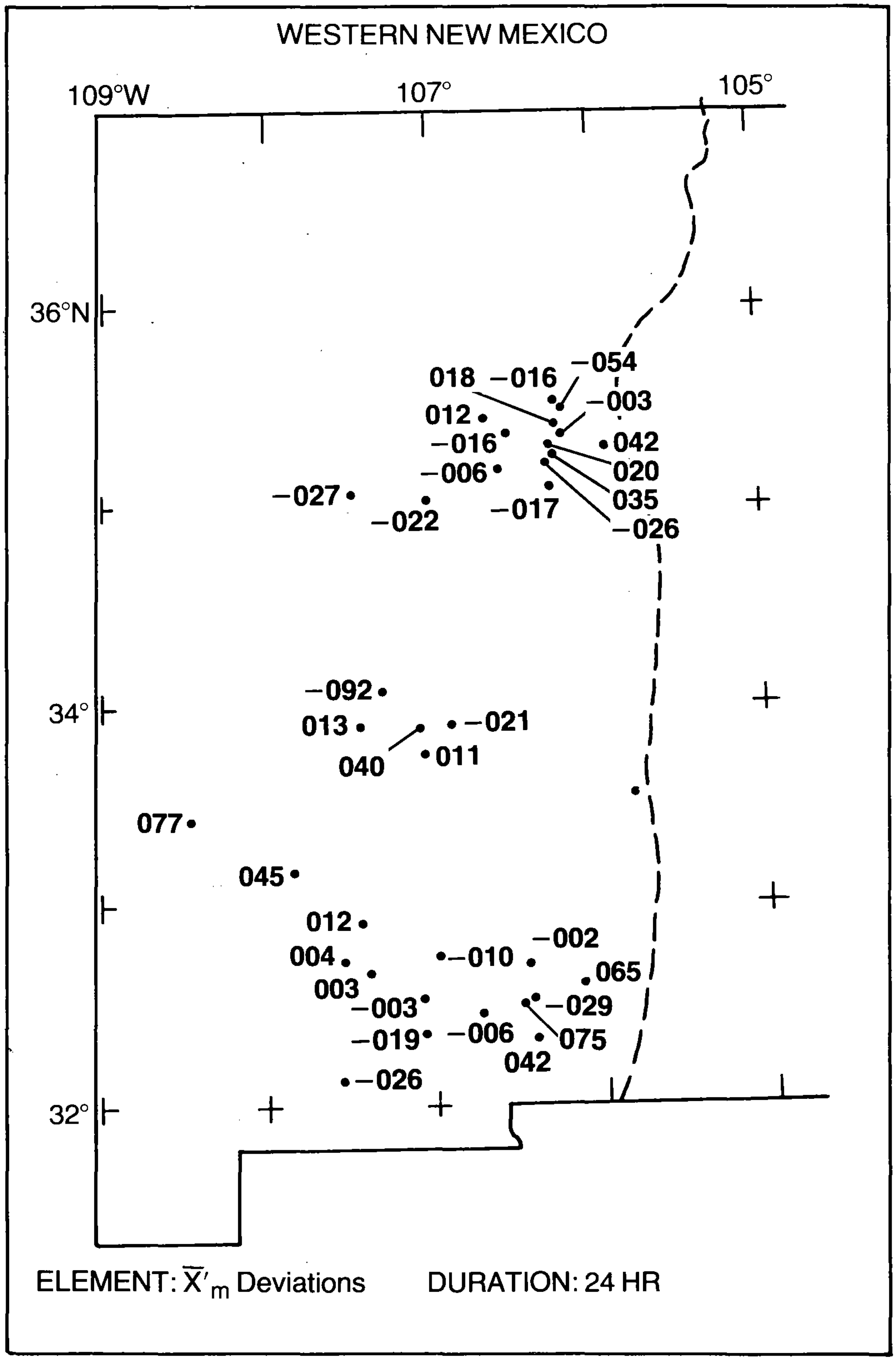

Figure 11b.—Deviation ($X10^{-3}$) of $\bar{X}'_m$ from the fitted curve for the 24-hr duration in New Mexico.

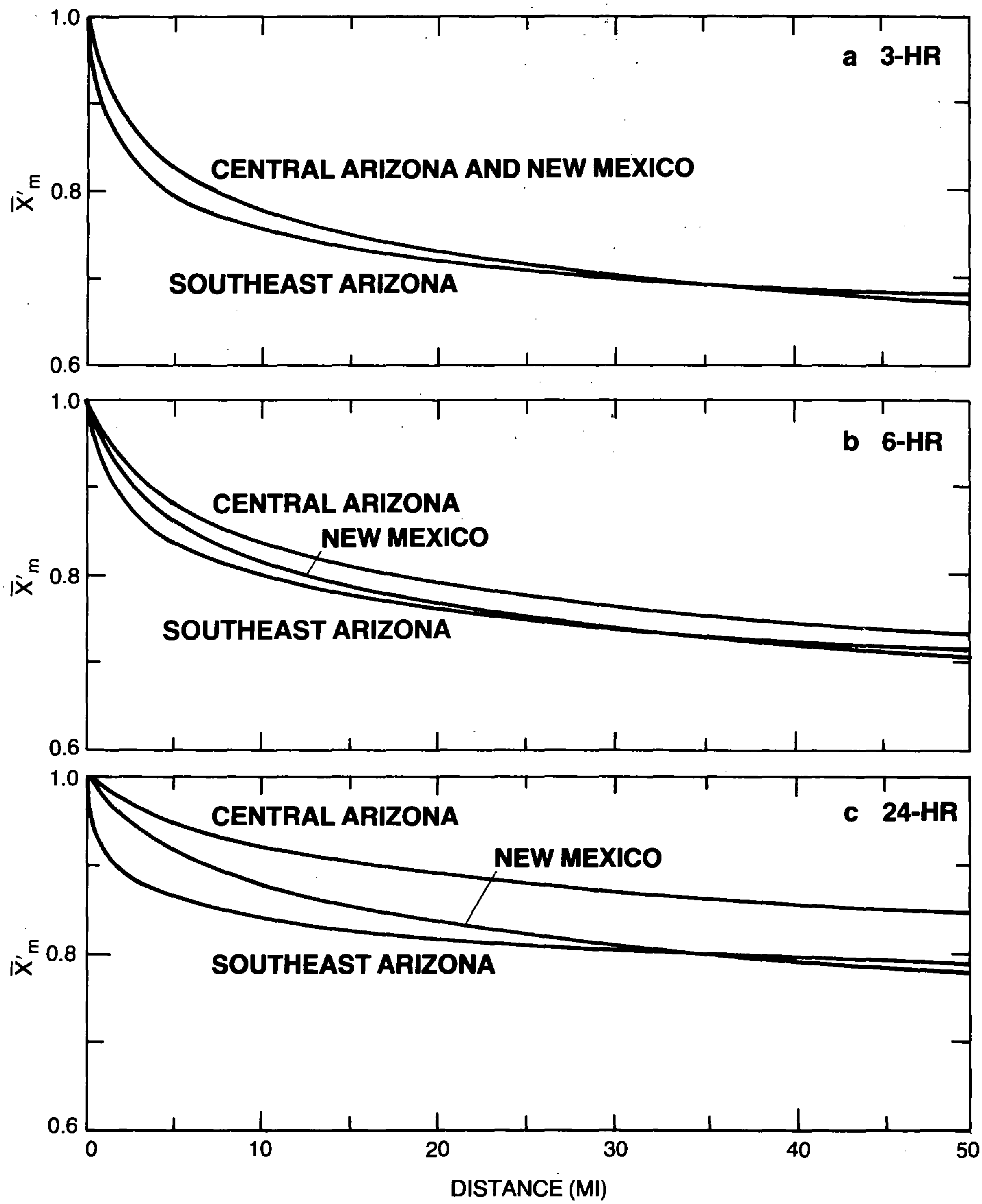

Figure 12.-- $\bar{X}'_m$ curves for southeast Arizona, central Arizona, and western New Mexico. a) 3-hr, b) 6-hr, c) 24-hr.

distances less than 15 mi (see table 3 and fig. 8), a valid comparison among regions should be restricted to the 15-50 mile range. Essentially no difference appears at 3 hr, small differences at 6 hr, and marked differences at 24 hr. $\overline{X}'_m$ in central Arizona is larger than in southeast Arizona and western New Mexico where the values are quite similar. To a lesser degree, the other station-pair statistics exhibited similar differences among regions and durations.

A depth-length ratio defined in TR 24, chapter 3, can be derived from data at a pair of stations. With the Gumbel fitting of Fisher-Tippett Type I Distribution as the frequency distribution model, $\overline{X}'_m$ is identical with the depth-length ratio for the 2.54-yr return period (see sec. 4.2). Thus, basic decisions on zonal variation of depth-area ratios were made from $\overline{X}'_m$ statistics, with the other statistics used as supporting information.

3.5 Seasonal Variation as an Indicator

Inspection of the tabulated dates of 24-hr annual maxima revealed that central Arizona experienced more winter occurrences than southeast Arizona. This is taken as another clue that general storms have more influence on rainfall-frequency values in central Arizona than in southeast Arizona, and that at least at the 24-hr duration, depth-area ratios could be expected to be higher in central Arizona. The seasonal variation of 24-hr annual maxima at individual precipitation stations, both daily and recorder, was used to refine the boundary between these regions and to compare other regions not covered by station pairs (recorders) within these regions.

With some experimentation, the year was divided into two seasons, May-October and November-April, hereafter termed the warm and cool seasons. The percentage of 24-hr annual maxima that occur in the cool season are plotted on maps of Arizona and New Mexico in figures 9 and 10. Thirty percent appears to be about the break point on figure 9 between the southeast Arizona type of climate and the central Arizona type. These data do not suggest any substantial zones of climate different from both of these.

3.6 Topographic and Synoptic Indications

Topographic features and known synoptic meteorological characteristics of storms suggest some explanations for the detected regional differences in $\overline{X}'_m$ and the other statistics. Locations along and west of the Mogollon Rim in central Arizona are exposed to a relatively unimpeded flow of air from the Gulf of California and the Pacific Ocean. Moisture inflow into southeast Arizona and most of New Mexico is reduced by both distance and the sheltering effect of the Sierra Madre in Mexico. The importance of the flow of air from the south and west lies in its warm moist character which affects areal coverage as well as intensity of precipitation. Topographic features that tend to favor storm occurrence in particular locations increase both the temporal persistence and the areal coherence, thus, a positive correlation between these two features is expected. Similarly, storm types that persist for 24 hr tend to yield more uniform areal coverage of precipitation than short duration local storms. Short duration storms tend to be due to small scale convective cells that vary little from one location to another. Hence, greater regional variation for 24-hr than for shorter durations is expected.

3.7 Definition of Zones

Compositing all of the clues and information suggests dividing Arizona and western New Mexico into the four depth-area ratio zones in figure 13. Zone A is the portion southwest of a generalized 3,000-ft elevation contour, readily exposed to moist inflow from the Gulf of California and the Pacific Ocean, but with rather smooth terrain. B is the portion northeast of a generalized drainage divide from the Kaibab Plateau to Humphrey's Peak, and along the highest elevations of the Mogollon Mesa to Baldy Peak. C is along the Mogollon Rim and lies between zones A and B. Zone D includes the higher elevation region of southeastern Arizona that is at least somewhat shielded from the Gulf of California by the Sierra Madre in Mexico, and is the southeast Arizona zone that has been referred to previously. The northern part of the study portion of New Mexico is an extension of zone B, and the southern part is an extension of zone D. While the available data provide no conclusive support for this extension, it was nevertheless made because it was felt that the shielding influence indicated in southeastern Arizona would extend into New Mexico in a fashion related to the prevailing moisture inflow.

Using the 30-percent break point on figure 9 between the southeast Arizona type of climate and the central Arizona type and additional insight from the above analysis, it was concluded that zones D and B are best represented by the Walnut

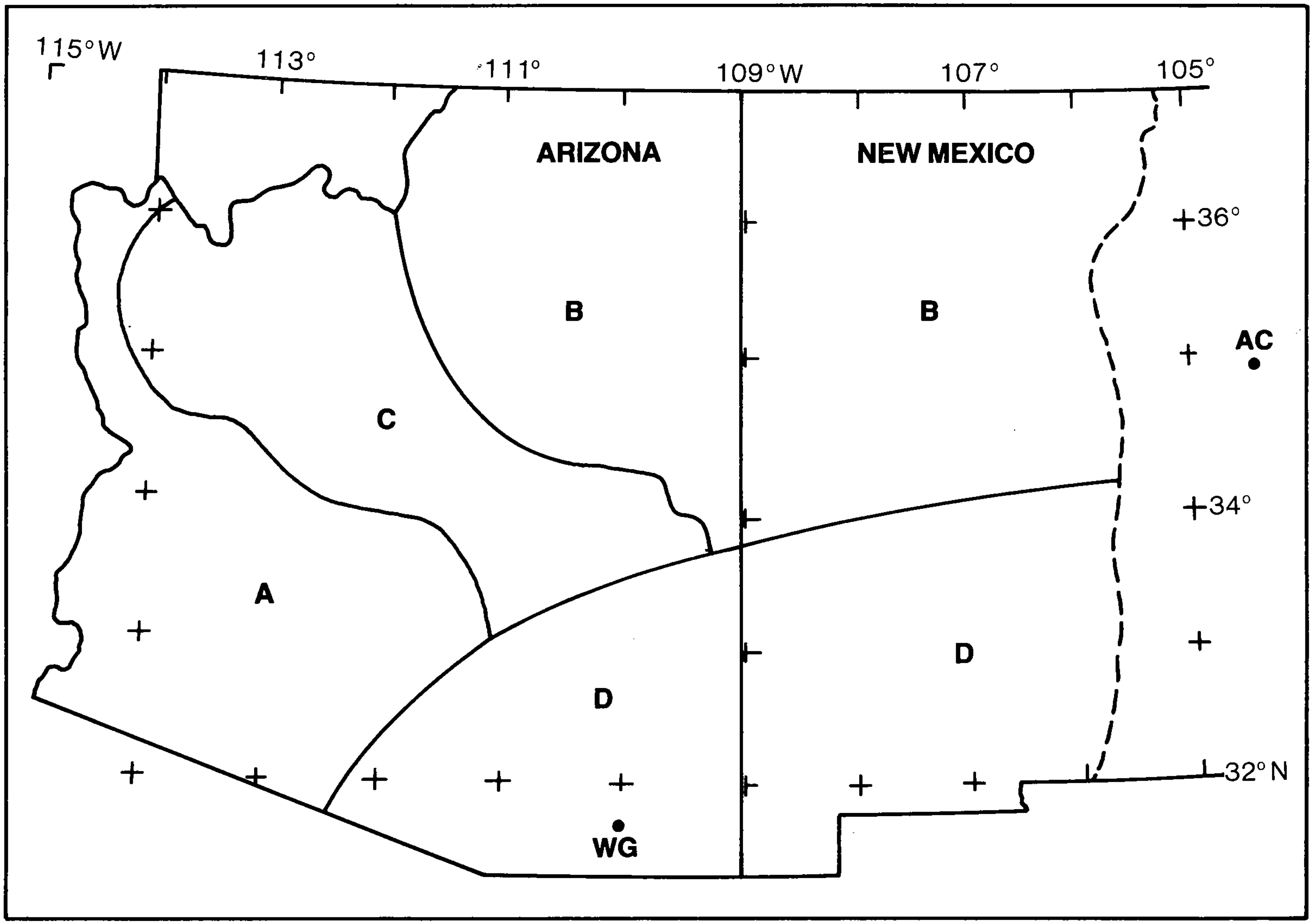

Figure 13.--Map of study area and depth-area zones.

Gulch depth-area ratios, while adjusted values should be applied to zones C and A, for durations of 6, 12, and 24 hr. The higher percentages of cool-season maxima are a principal reason for associating lower elevation, less rugged zone A with Zone C. (Very few recorder pairs are available in zone A.) The shorter distance from the Gulf of California and Pacific Ocean moisture sources may have a similar effect as the topography and elevation of zone C in favoring cool-season storms.

4. DEPTH-AREA RATIOS

The Arizona recorder pairs (table 3), the Walnut Gulch pairs (table 1), and the 5-station groups (table 2), were used to derive two separate sets of depth-area curves for 6-, 12-, and 24-hr durations. Pair statistics for locations southeast of the dashed line on the map in figure 11a comprised the southeast Arizona data set (these pairs are noted in table 3), while the group of remaining pair statistics were termed central Arizona.

In view of the lack of clear geographical pattern of $\overline{X}'_m$ deviation from a fitted curve for 3 hr (see sec. 3.4) and the convergence of depth-area curves going from 24 hr to 6 hr (see fig. 12), a single 3-hr depth-area curve was derived from all Arizona recorder pairs with interstation distances less than 35 mi.

Southeast Arizona depth-area curves are presented as representative of zones B and D and the central Arizona curves as representative of zones A and C (fig. 13), as discussed in chapter 3. It should be emphasized that these are best estimates based on limited data and information. The only dense network data available to this study are from Walnut Gulch. If additional dense networks were available in the study area, it is likely that both the definition of zones and depth-area ratio curves could be refined. However, in spite of uncertainties, we believe that a valid step toward regionalization has been accomplished with the depth-area curves presented.

4.1 Curve Fitting

The problem of the lack of recorder pairs at interstation distances of less than 15 mi was mentioned previously. The problem was minimized for the 24-hr southeast Arizona data set by including the 24-hr Walnut Gulch data. The resulting data set contains 50 recorder pairs with a reasonable distribution over interstation distance for this duration.

With the available data, the fitting procedure of TR 24 was found to be inadequate for $\overline{X}'_m$ and $\overline{X}'_b$ statistics for other durations, because of the paucity of data at distances of less than 15 mi. An alternative procedure was devised. The data points beyond a distance d_s (10–20 mi), were fit to a straight line. The data points at distances less than d_s were fit using the TR 24 approach, imposing the slope and intercept of the straight line at (d_s, y_s). The details of this curve splicing procedure are outlined in Appendix III. Comparisons of the results of the unmodified TR 24 curve fitting procedure and the curve splicing technique are shown in figure III-1. The complete sets of coefficients for the 2-station statistics curves used in developing the depth-area curves are listed in Appendix IV.

4.2 2.54-Year Depth-Area Ratios

Chow's generalized frequency equation (Chow 1951) relates a return value of (X_t) to the mean ($\overline{X}$) and standard deviation (s_x) of the annual series: $X_t = \overline{X} + K_t\, s_x$. The standard deviation is multiplied in the equation by a frequency factor, K_t, dependent on frequency (return period) and the statistical distribution assumed. For the Gumbel fitting of the Fisher-Tippett Type I Distribution used in this study, $K_t = 0$ occurs at a return period of 2.54 yr. (Equations for deriving K_t for this distribution are found in Appendix I of TR 24.) Thus, the frequency value at this particular return period is independent of the standard deviation and is equal to the mean of the annual series. The 2.54-yr depth-area ratios for Walnut Gulch may be immediately equated to the relative mean of the annual series of areal average annual maximum rainfalls, $\overline{X}'_L$. This fact is used in the following sections.

4.3 Relative Mean of Areal Average Annual Maximum Rainfall, $\overline{X}'_L$

The TR 24 method applies theoretical considerations and areal integration to obtain estimates of upper and lower bounds of $\overline{X}'_L$ from curves fit to $\overline{X}'_m$ and $\overline{X}'_b$. $\overline{X}'_L$ values between the bounds are obtained by interpolation based on calibration with a mean data point obtained from 5-station relative areal means. This procedure was followed for the 24-hr duration for southeast Arizona

Table 5.--Calibration constant, C_x.

Duration (hr)	Radius (mi)	Calibration point Type	$\bar{X}'_L$	Bounds Upper	Lower	C_x
3	4.65	Areal	0.62	.716	.356	0.73
6	4.65	Areal	0.63	.760	.406	0.63
12	-	-	-	-	-	0.64
24	2.50	5-point	0.825	.873	.736	0.65

with the ten Walnut Gulch 24-hr 5-station groups providing the calibration. The calibration constant, C_x is defined as:

$$C_x = \frac{(\bar{X}'_L)\ \text{calibration} - (\bar{X}'_L)\ \text{lower}}{(\bar{X}'_L)\ \text{upper} - (\bar{X}'_L)\ \text{lower}}$$

At 3 and 6 hr the 2.54-yr Walnut Gulch depth-area ratios from Osborn et al. (1980) at 176 km^2 (68 mi^2) are equated to $\bar{X}'_L$ and are used for calibration. The resulting C_x values are listed in table 5. The 12-hr calibration value was set at 0.64, intermediate between the 6- and 24-hr calibration constants.

Areal or five-point data for calibration are only available at Walnut Gulch. The southeast Arizona Walnut Gulch calibration values were applied in central Arizona to the bounds for that zone.

Figures 14 and 15 depict the 3-, 6-, 12-, and 24-hr $\bar{X}'_L$ or 2.54-yr depth-area ratio curves for southeast Arizona (zones B and D) and central Arizona (zones A and C), respectively. 3-hr and 24-hr $\bar{X}'_L$ curves for Chicago from TR 24 are shown for comparison. With respect to 24-hr depth-area ratios, the climate in southeast Arizona is different from that in Chicago. The central Arizona curves lie between the Chicago and southeast Arizona curves. A possible explanation is that the typical storm types that predominate at Chicago are different from those prevalent in Arizona for 24 hr. The annual maxima in southeast Arizona are primarily limited area thunderstorms, while in central Arizona annual maxima can

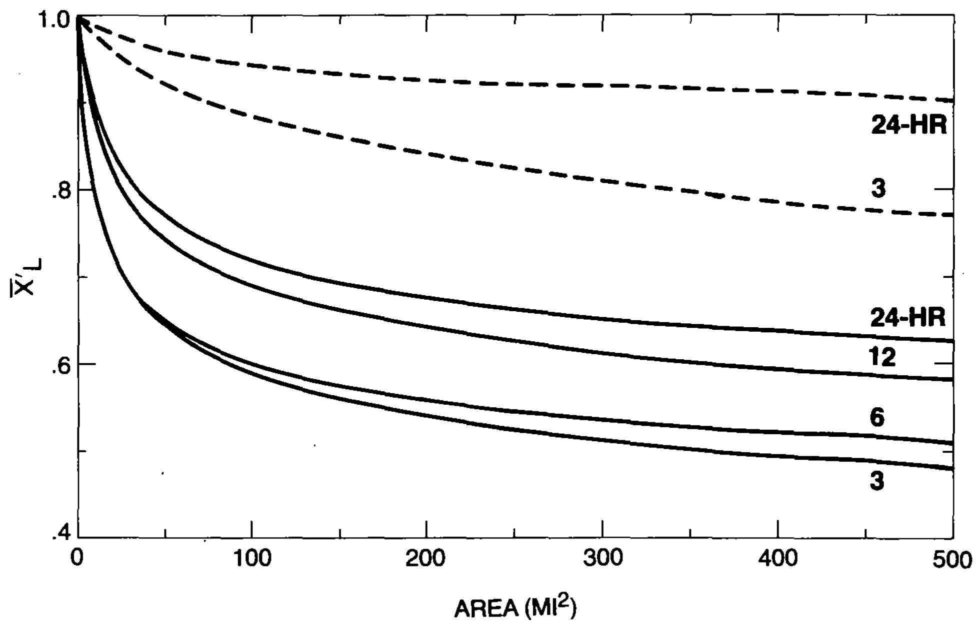

Figure 14.--$\bar{X}'_L$ (2.54-yr depth-area ratio, see sec. 4.3) for 3-, 6-, 12-, and 24-hr in southeast Arizona. Dashed lines are 3-hr and 24-hr Chicago $\bar{X}'_L$ (from TR 24)

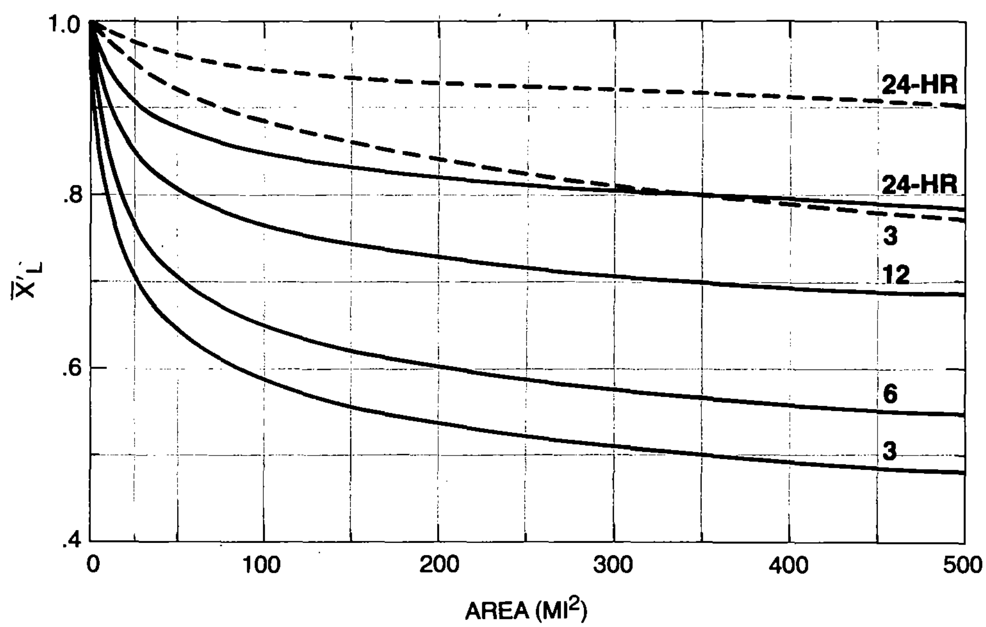

Figure 15.--Same as figure 14, but for central Arizona.

be attributed to a mixture of storm types, but still different from these found in the central Plains.

The recorder-pair data for distances greater than 15 mi contain little information on the structure of 1- and 2-hr storms. This is supported by the low values of $\bar{X}'_b$ at this range for these durations (see table 4). Our attempts to extract guidance from these widely spaced locations proved fruitless. $\bar{X}'_L$ is not defined at these durations in this study. Rather, Walnut Gulch depth-area ratios from Osborn et al. (1980) may be used for these durations up to the area size of the Walnut Gulch network, about 76 mi^2. We were unable to define 1- and 2-hr depth-area ratios for area sizes greater than 76 mi^2.

4.4 Depth-Area Ratios

The two-station variance statistics s'_m, s'_b and cov'_{Ab} (defined in Appendix I), exhibited considerably greater scatter than $\bar{X}'_m$ and $\bar{X}'_b$. To a lesser degree, this was also true for Chicago data in TR 24. Considering the extreme scatter and the previously discussed data limitations, the decision was made to estimate depth-area ratios based only on statistics of the mean. This meant that the possibility of specifying the depth-area variation with return period was lost. Both physical reasoning and the data indicated that any return-period variation would produce lower depth-area ratios for rarer events. It was felt that the limited amount of data and the large amount of scatter precluded quantifying the variation with return period. As discussed in sections 3.4 and 4.2, use of mean quantities is equivalent to determining the depth-area ratios for the 2.54-yr return period. Use of a mean curve for all return periods will lead to conservative estimates for all return periods greater than 2.54 yr. The difference at the 2-yr return period is small, and considering the degree of uncertainty associated with the entire analysis, can be considered negligible.

5. DISCUSSION

5.1 Recommended Depth-Area Ratios

In the Walnut Gulch basin the 24-hr depth-area ratios of figure 5 should be used. For durations of 6 hr and less, the results of Osborn et al. (1980) are appropriate. There are no basin-specific curves for 12-hr amounts. If a 12-hr depth-area ratio is necessary, the curves in figure 14 for southeast Arizona should be used as guidance for interpolation between the 6-hr values found by Osborn et al. and the 24-hr depth-area ratios of figure 5. Use of the depth-area ratios in figure 5 for locations other than Walnut Gulch would depend on the similarity of the meteorological conditions between the other locations and those in the Walnut Gulch basin.

Outside the Walnut Gulch basin, the depth-area ratios in figures 14 and 15 should be used. The curves in figure 14 are most appropriate for use in the zones indicated as B and D in figure 13. The recommended depth-area curves for zones A and C of figure 13 are presented in figure 15. Figure 16, from Osborn et al. (1980), shows depth-area ratios for durations of 30 to 360 min for return periods of 2 and 100 yr. For a given return period, there is little systematic difference among the durations of 3 hr or less. It is likely that the differences are due in large part to sampling variations. For this reason, we recommend that the 3-hr depth-area ratio be used for all durations less than 3 hr. Any error introduced will likely produce slightly conservative estimates of areal rainfall amounts for the shorter durations.

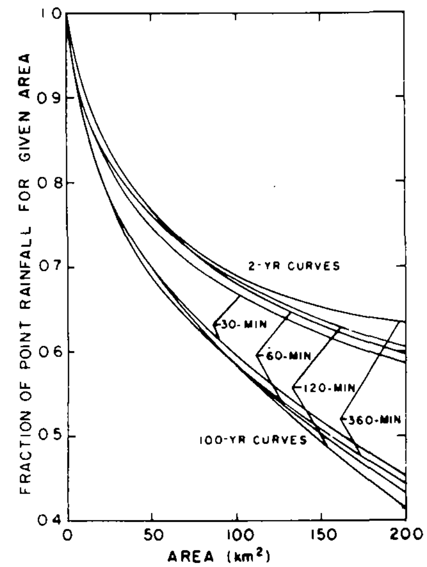

Figure 16.--Point to area rainfall ratios from Osborn et al. (1980).

5.2 Uncertainty of the Depth-Area Ratios

The depth-area ratios shown in figures 14 and 15 are to be applied over the zones shown in figure 13. Examination of figure 7 reveals that there are practically no station-pair data available in zone A, and little data available in the northern portion of zone C. While there does appear to be a definite difference in the deviations from the fitted curves in Arizona that was used to define the separation of zone D from zone C (fig. 11a), no such cleavage was apparent in New Mexico (fig. 11b). In fact, the station-pair data from New Mexico were not used when calculating the depth-area ratios in figures 14 and 15. The conclusion that must be drawn from these observations is that the uncertainty of the depth-area ratios in figures 14 and 15 may vary considerably over the zones shown in figure 13.

The depth-area ratios shown in figure 14 are most accurate for zone D in Arizona. There is a higher degree of uncertainty associated with their use in zone D in New Mexico, as well as in all of zone B. The use of the depth-area curves of figure 15 is most appropriate in the southernmost portion of zone C where almost all of the station-pair data is located. The uncertainty of the curves in figure 15 in the northern portion of zone C is greater than the south simply because of the dearth of data. While the discussion in sec. 3.5 suggests that zone A may be similar to zone C, there is little station-pair data available to support this conclusion. Therefore, there is a higher degree of uncertainty associated with the use of the depth-area values in figure 15 for locations in zone A.

5.3 Comparison of Results

Osborn et al. (1980) have shown that NOAA Atlas 2 (Miller et al. 1973) depth-area curves are conservative for the Walnut Gulch, AZ, watershed. This study confirms and expands on their results. For example, for a 300-mi^2 basin with a 24-hr point rainfall of 2.0 in., one obtains areal rainfalls of 1.32 in. (0.66 X 2.0) if the basin is located in zones B or D and 1.60 in. (0.80 X 2.0) for locations in zones A or C. In contrast, using NOAA Atlas 2, the assigned areal rainfall is about 1.82 in., based on a depth-area ratio of 0.91, regardless of location.

5.4 Determination of Depth-Area Ratios in Data-Sparse Regions

The results of this study demonstrate that the conceptual approach presented in TR 24 can be adopted in data-sparse regions. But data limitations and significant departures from meteorological homogeneity can necessitate modifications to the specific implementation of the approach described in TR 24. The underlying approach is to fit the various statistics, using an exponential model such as in TR 24, using a mixed model such as in the present study, or some other appropriate model which is both consistent with the data and depicts the underlying meteorological situation. In data-sparse areas, the selection of an appropriate model will always require a certain amount of meteorological judgment. The final depth-area curves will be dependent on the suitability of the model selected.

The results of this study highlight two problem areas in data-sparse regions: (1) the requirement of a dense network of raingages or other information to allow the calibration between the theoretical bounds, and (2) the sensitivity of the variance statistics with small data samples. The use of station-pair statistics offers the promise of extracting useful information from previously underutilized data. While these data allow the definition of bounds on the depth-area ratios, the final results require calibration between these bounds. Direct calibration requires a dense raingage network. Indirect calibration, such as using calibration constants from what appear to be meteorologically similar locations, depends on the validity of the assumptions made and introduces an additional level of uncertainty.

Precipitation data is generally characterized by a higher degree of variability than most other meteorological quantities. Higher order moments such as the variance (and, therefore, the standard deviation) and covariance are more sensitive than the mean to noise in the data. As in this study, when there is a limited amount of data, the natural variability can be so large that it may be impossible to adequately quantify the standard deviation or covariance, no matter what model is selected to fit the data. In data-sparse regions, the absence of sufficient amounts of data to compensate for large sampling variability may preclude the quantitative determination of the variation of the depth-area ratios with a return period (or even estimation of the depth-area ratio itself). Both theoretical considerations and other studies where adequate data were available indicate that use of mean values instead of the complete Chow equation (see sec. 4.2) in the TR 24 approach produce conservative depth-area ratios for rarer events (longer return periods).

Finally, in data-sparse areas, the delineation of zones where different depth-area ratios apply will be heavily dependent on the judgment of the individual analyst. This judgment will typically be based on an understanding of the interaction of both synoptic and mesoscale meteorological processes with topographic and other geographic features. The available data can be used to critically assess definition of zones based on the meteorologist's judgment, but definitive evaluation will often be difficult, if not impossible, in data-sparse areas. The final specification of zones will usually require use of auxiliary information, such as use of daily values in this study, to identify areas where cool-season precipitation was most significant. Once zones have been specified, the problem of determining appropriate depth-area ratios for each of the zones remains (see discussion above).

6. SUMMARY

This study develops geographically fixed depth-area ratios for Arizona and western New Mexico. These ratios are required to reduce published point precipitation-frequency values to areal values as part of the basis for design of hydrologic structures. These depth-area ratios, developed specifically for this semi-arid region, are smaller than the national average ratios previously published by the National Weather Service. The new ratios will lead to more economical designs for pre-determined risk levels.

Variation of depth-area ratios over the study region is inferred primarily from various statistics from simultaneous rainfalls at pairs of recording gages. This is done by heavy reliance on the concepts in a previous report of the authors (Myers and Zehr 1980) that develops procedures for fitting surfaces in interstation distance-precipitation duration space to station-pair rainfall statistics and for adjusting the pair statistics to areal average statistics. The previous report treats a dense network of gages, all in the same climate. The present report includes regard for climatological variation that may exist within the overall study area.

Depth-area ratios at the Walnut Gulch Experimental Watershed of the Agricultural Research Service in southeastern Arizona are an essential anchor point for the present study. Walnut Gulch depth-area ratios for durations up to 6 hr are from Osborn et al. (1980). Walnut Gulch ratios for 24 hr are newly calculated and are presented in a chapter 2 of the present report.

There are very few recorder pairs in the study area with interstation distances of less than 15 mi, other than those at Walnut Gulch. Special procedures were applied to extrapolate Walnut Gulch values throughout the study area, with zone adjustments, to cover the corresponding basin sizes of several hundred square miles and less.

Depth-area ratios are presented separately by zones. An original four zones were reduced to two because the data were inadequate to either quantify differences or to determine additional depth-area ratios. Zone to zone variation in depth-area ratios is considered negligible for all durations less than 3 hr and is most pronounced at the longest duration analyzed (24 hr). Zones are defined by a combination of indicators from recorder-pair data, topography, seasonal variation of 24-hr single station annual maxima, and presumed storm types.

The importance of dense networks for anchor points should not be minimized. This report carries out the engineering necessity of extracting practical ratios of importance to design of structures that in the aggregate cost very substantial sums. In regions where expenditures for hydrologic structures are expected, early attention should be given to providing the anchor point dense network depth-area data, either conventionally or by remote sensing techniques, in order to secure a sufficiently long record to average out sampling variation. Such data cannot be secured within the time frames of individual projects.

Refinement and improvement of results and methodologies are always desirable. The procedure for calibrating between bounds detailed in TR 24 is a critical step in the methodology which has not been thoroughly investigated. The variation of the calibration constant, C_x, with duration and with area remains uncertain. Thus far, lack of data has prevented extensive evaluation.

The concept of climatic homogeneity and determination of the maximum interstation distance at which pair statistics are pertinent with regard to depth-area ratios, have been discussed in this report. Additional investigation of these problems is needed. This is especially true for mountainous regions where the effect of elevation and slope on rainfall and depth-area characteristics of storms is greater than in flat terrain regions, such as Chicago.

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APPENDIX I. DEFINITIONS

Variables and statistics discussed previously are explicitly defined here. Additional information is available in TR 24.

Pair statistics

$$\bar{X}'_m = \bar{X}_m/[0.5\ (\bar{X}_A + \bar{X}_B)]$$

$$s'_m = s_m/[0.5\ (s_A + s_B)]$$

X and s are the mean and standard deviation of the annual maximum series. Subscript m refers to the series of pair averages, and A and B refer to the individual stations.

$$\bar{X}'_b = 0.5[(\bar{X}_b/\bar{X}_A) + (\bar{X}_a/\bar{X}_B)]$$

$$s'_b = [(s_b/s_A)(s_a/s_B)]^{1/2}$$

$\bar{X}'_b$ and s'_b denote mean and standard deviation of series "simultaneous with annual maximum." The subscripts on the right signify stations A and B explicitly, with upper case designating annual maximum and lower case, simultaneous with annual maximum.

$$cv'_b = s'_b/\bar{X}'_b$$

This definition is derived from the definition of the coefficient of variation, cv.

$$cov'_{Ab} = 0.5\ [(cov_{Ab}/s_A^2) + (cov_{aB}/s_B^2)],$$

where cov is covariance, and the subscripts on the right refer to specific stations as before.

Five-station statistics

$\bar{X}'_{5m}$ and s'_{5m} are the relative mean and standard deviation of the annual maxima of the 5-station group averages, which are weighted averages.

$$P_5 = .244P_A + .188(P_b + P_c + P_d + P_e)$$

where P_5 is the rainfall of the 5-station group, subscript A refers to the center station, and b, c, d, and e, the outer stations. The stations are normalized to relative form by dividing by the corresponding statistic at the center station, A.

APPENDIX II. CURVE FITTING USING THE TR 24 METHOD

$\bar{X}'_m$ and $\bar{X}'_b$ statistics at durations 1, 2, 3, 6, 12 and 24 hr, for Arizona and New Mexico recorder pairs (table 3) were fit to:

$$y = 1 - M e^{-[ad^{b}]^{-1}},$$

where y is the statistic and d the interstation distance. Coefficients a, b, and M, for various durations are listed in table II-1. Table II-2 contains coefficients for the Walnut Gulch curves.

Table II-1.--Coefficients for Arizona and New Mexico station-pair data

		t(hr)	a	b	M
$\bar{X}'_m$					
	Arizona	1	.9726	.3407	.5
		2	.6148	.3883	.5
		3	.5158	.3891	.5
		6	.4145	.3658	.5
		12	.3532	.3363	.5
		24	.3066	.3162	.5
	New Mexico	1	.7613	.3951	.5
		2	.5666	.4005	.5
		3	.4969	.3981	.5
		6	.4187	.3836	.5
		12	.3683	.3619	.5
		24	.3315	.3394	.5
$\bar{X}'_b$					
	Arizona	1	.8337	.9829	1.0
		2	.6684	.7905	1.0
		3	.5927	.7113	1.0
		6	.5053	.5887	1.0
		12	.4376	.4975	1.0
		24	.3795	.4381	1.0
	New Mexico	1	.0635	2.4464	1.0
		2	.3405	1.0120	1.0
		3	.2826	.9368	1.0
		6	.2421	.8281	1.0
		12	.2397	.7161	1.0
		24	.2502	.6126	1.0

Table II-2.--Coefficients for 24-hr Walnut Gulch pair statistics

Statistic	a	b	M
$\bar{X}'_m$	.3649	.4278	0.50
s'_m	.7546	.4990	0.50
$\bar{X}'_b$	.5014	.6024	1.00
cov'_{Ab}	.8131	.6255	1.24

APPENDIX III. CURVE SPLICING

A curve splicing procedure was devised to obtain a better fit of pair statistics for 24 hr in southeast Arizona. This data set includes the Walnut Gulch pairs (table 1) and southeast Arizona pairs (table 3). The TR 24 curve fitting equations over estimated the data points in the 5-15 mile distance range and underestimated at 0-5 miles for both the $\bar{X}'_m$ and $\bar{X}'_b$ statistics. When the curve splicing procedure was applied, much of this bias was removed. The curves derived from the two fitting procedures and data points are depicted in figures III-1 and III-2 for $\bar{X}'_m$ and $\bar{X}'_b$, respectively.

Implementing the splicing procedure requires that a distance, d_s, be imposed for a splice point, (d_s,y_s). On figures III-1 and III-2 d_s = 15 miles. At distances greater then d_s, designated by subscript "out," data are fit to a straight line. At distances less than d_s, designated by subscript "in," data are fit using the TR 24 procedure.

$$d > d_s: \quad y_{out} = a_{out} + b_{out}\, d \tag{III-1}$$

$$d < d_s: \quad y_{in} = 1 - M\, e^{-[a_{in} d^{b_{in}}]^{-1}} \tag{III-2}$$

Here, y is the statistic, d is distance, and a_{out}, b_{out}, a_{in}, b_{in}, and M are the coefficients which must be determined. a_{out} and b_{out} are evaluated by linear regression for data points, (d, y), $d > d_s$. It is required that the inner and outer portions of the curve join and have equal slopes at (d_s, y_s), as stated by equations (III-3) and (III-4), at d_s,

$$(y_{in})_s = (y_{out})_s \tag{III-3}$$

$$\left[\frac{\partial y_{in}}{\partial d}\right]_s = \left[\frac{\partial y_{out}}{\partial d}\right]_s \tag{III-4}$$

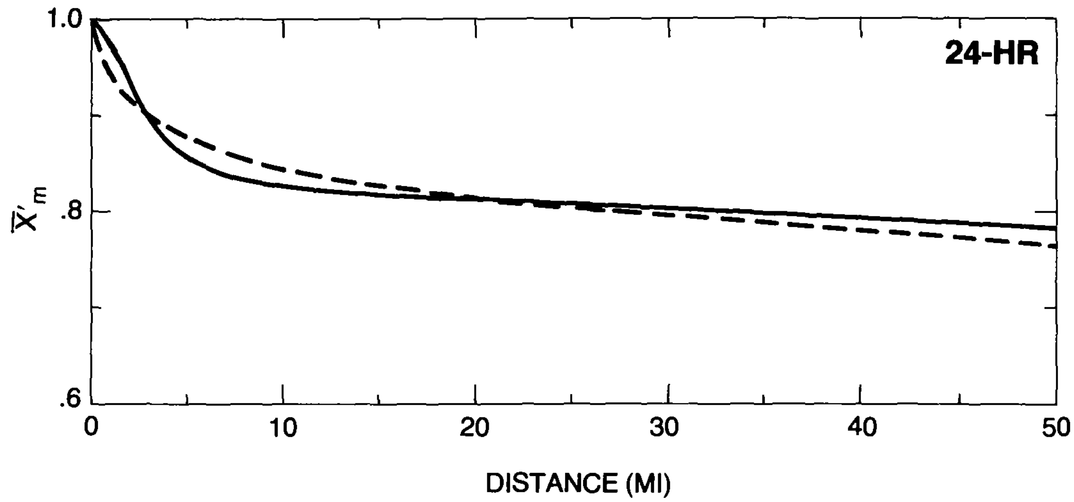

Figure III-1.--24-hr Walnut Gulch and southeast Arizona $\bar{X}'_m$. Solid curve derived by the curve splicing procedure. Dashed curve is derived by the TR fitting method.

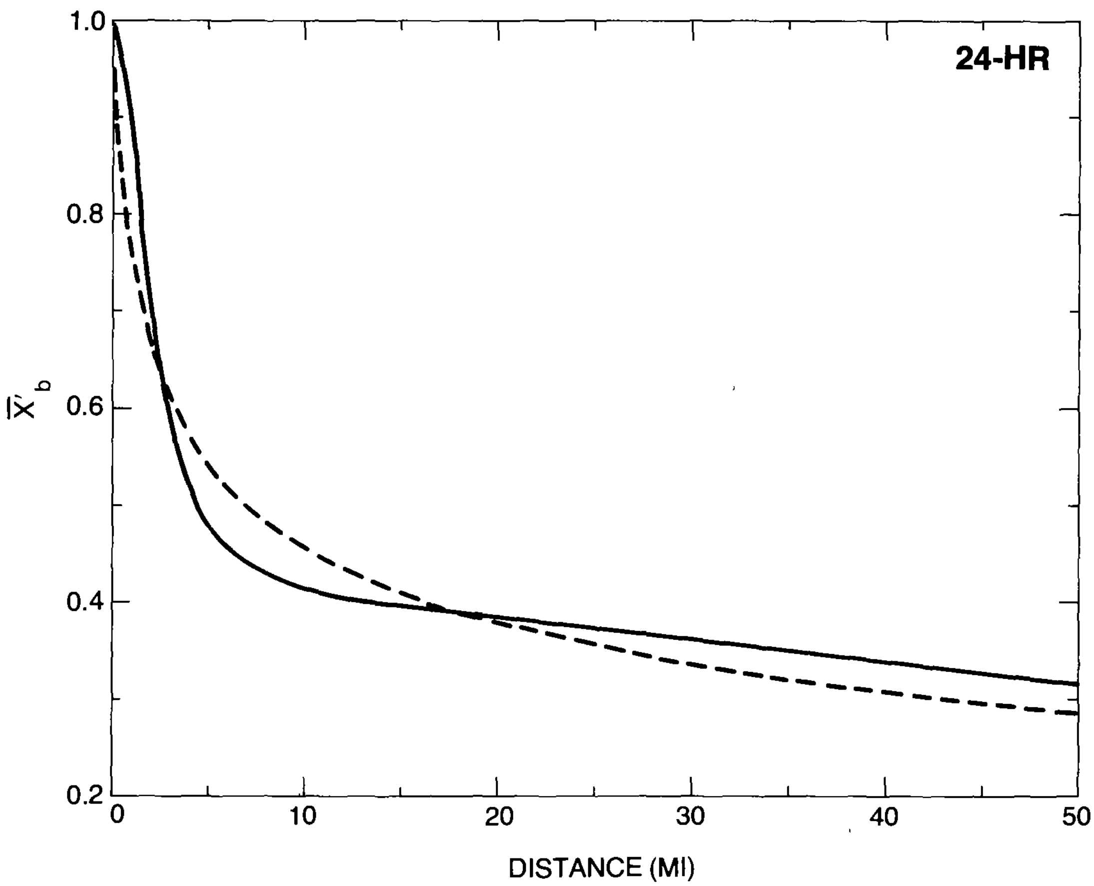

Figure III-2.--Same as figure III-1, except for $\bar{X}'_b$.

Substituting (III-1) and (III-2) into (III-3),

$$1 - M e^{-[a_{in} d_s^{b_{in}}]^{-1}} = a_{out} + b_{out} d_{out} \qquad \text{(III-5)}$$

Substituting (III-1) and (III-2) into (III-4),

$$a_{in}^{-1} b_{in} d_s^{-b_{in}+1} (y_s - 1) = b_{out} \qquad \text{(III-6)}$$

Solving (III-5) and (III-6) simultaneously for b_{in},

$$b_{in} = \frac{-d_s b_{out}}{(y_s - 1) \ln\left[\frac{1 - a_{out} - b_{out} d_s}{M}\right]} \qquad \text{(III-7)}$$

Rewriting (III-2),

$$a_{in} = \frac{-1}{d_s^{b_{in}} \ln\left[\frac{1 - y_s}{M}\right]} \qquad \text{(III-8)}$$

After a_{out} and b_{out} are determined by linear regression, y_s is determined and all quantities on the right side of (III-7) are known except M. To solve for a_{in} and b_{in}, M is initialized to $(1-y_s)$. b_{in} and a_{in} are evaluated with equations (III-7) and (III-8). The sum of squares of deviations of data points at $d < d_s$ from the fitted curve are computed. M is then incremented and iterations performed until the sum of squares of deviations is a minimum. These values of a_{in}, b_{in}, and M, are the "best fit" to the data points at $d < d_s$, with the restriction that the curve pass through (d_s, y_s) with slope, b_{out}, at the splice point. This approach was also used for durations of less than 24 hr.

APPENDIX IV. COEFFICIENTS USED IN CHAPTER 4 DEPTH-AREA RATIO ANALYSES

Coefficients a_{out}, b_{out}, a_{in}, b_{in} and M for the curves of the pair statistics used to derive $\bar{X}'_L$ depicted in figures 14 and 15 are listed in table IV-1.

Table IV-1.--Coefficients for $\bar{X}'_m$, and $\bar{X}'_b$ used in determination of chapter 4 depth-area ratios ($\bar{X}'_L$)

	t(hr)	a_{out}	b_{out}	a_{in}	b_{in}	M	d_s(mi)
$\bar{X}'_m$							
Southeast Arizona							
	3	.7974	-.00287	.7004	.5606	.336	15
	6	.8070	-.00211	.5486	.6090	.316	20
	12	.8323	-.00185	.5479	.6040	.276	20
	24	.8471	-.00141	.5241	.7320	.224	20
Central Arizona							
	3	.7974	-.00287	.7004	.5606	.336	15
	6	.8056	-.00165	.4541	.8570	.269	20
	12	.8815	-.00199	.3581	.6690	.231	20
	24	.9319	-.00196	.2393	.6900	.182	20
$\bar{X}'_b$							
Southeast Arizona							
	3	.2590	-.00373	1.3232	1.3183	.807	10
	6	.3165	-.00326	1.3262	1.3500	.741	10
	12	.3878	-.00315	.4868	1.3500	.695	15
	24	.4442	-.00268	.4914	1.3753	.626	15
Central Arizona							
	3	.2590	-.00373	1.3232	1.3183	.807	10
	6	.4050	-.00429	.8965	1.3500	.671	10
	12	.5336	-.00399	.7661	1.3500	.537	10
	24	.6407	-.00321	.7344	1.3500	.416	10

(Continued from inside front cover)

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