

Need for New Rainfall Intensity Atlas Analyses in the West

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Estimates of short-duration rainfall intensities provide critical information for the design of highway drainage systems. Rapid growth of urban population in the arid West has exposed more drivers to the effects of undersized drainage structures. Contemporary stormwater computations on small, semi-arid or urban watersheds require the estimation of rainfall intensities at ten-minute intervals in runoff-producing storms. Earlier methods, such as the rational formula, required less complex rain data. Precipitation-frequency atlases (NOAA-2) for eleven western states were prepared from data prior to 1970 (1). These atlases were used daily rainfall observations, regression against topographic parameters, and hydrometeorological considerations to draw isohyetal maps for 24- and 6-hour intervals. The 24-hour maxima may follow topographic features because they usually occur in winter. Visual observation in Arizona does not confirm this to be true with summer convective storms. These produce design floods on semi-arid watersheds smaller than 100 or 200 square miles. Regional variation of short-duration rainfall may be less sensitive to desert mountains than the 24-hour maps developed in NOAA-2. The shortest duration analyzed for NOAA-2 was one hour, used at about ten percent of the sites. For example, in Arizona only 38 autographic recorders were used, over periods averaging less than 20 years. Re-analysis in that state could consider recording gages from over 100 additional sites, for durations as short as 10 minutes. Two decades of new data at NOAA-2 sites could now reduce the error of estimate at these points. Improved statistical methods are also available. Highway and other engineers in ten Western states would gain from new analyses of short-duration intensity data available from recording rain gages operated by many agencies. This paper attempts to serve administrators, drainage engineers, and others who may consider the implementation of re-studies in a western state. The 16-year-old western-rainfall intensity atlas should be replaced after the short-duration recorder data now available have been analyzed. High intensities for durations as short as 10-minutes are particularly important to Western drainage design. Analysis of such data was absent from NOAA-2.

Urban hydrograph models and modern computer synthesis of flood peaks from small (less than about 100 sq. mi.) desert watersheds depend on rainfall input. Rainfall intensity during flood-producing storms, varies rapidly in time and space. Watersheds are being rapidly urbanized, and heavy urban highway use is increasing during times normally associated with intense rainfall (usually late afternoons).

Many high-priced developments border on highway rights-of-way, and property owners fear that improper highway design will lead to flood damage. Pavement drainage, culvert sizing,

storm drains, channel design, bank protection, and bridging of larger streams could all be improved by better rainstorm data. Regional flood-frequency studies for large non-urbanized watersheds also require rainfall intensity as an independent variable when regressing stream gage flood estimates against environmental parameters.

COMMUNITY INTEREST IN RESTUDY THROUGHOUT THE ARID WEST

Surveys of the need to improve rainfall-intensity manuals are becoming common in southwestern communities. Phoenix, Arizona, had such an investigation (2) performed at the same time that Maricopa County, in which it is located, commissioned another engineering firm to perform a similar investigation (3). In a Clark County, Nevada, study (4), frequency plots suggested a 45-percent increase in short-duration rainfall. The study recommends that "NOAA should periodically update the atlases where the period of records is short." Re-analysis of 45 years of National Weather Service (NWS) data at Billings, Montana, showed that 5- to 15-minute estimates for 5- to 100-year frequencies were 1.6 to 1.3 times greater than NOAA-2 values respectively (5). Many more examples could be given of the concern felt by local communities in relying entirely on NOAA-2 for small-watershed designs.

A rash of independent studies poses other problems. Many cities or counties have more rain gages than they are able to analyze, but one Arizona county comprising over 10,000 square miles has not even one gage! Very few small jurisdictions have the specialized personnel to either select or adequately supervise a consultant for this work. Analysis of data from a single gage, even if performed correctly with appropriate statistical methods, lacks the validation provided by a regional study. Individual point values may reflect unfortunate sampling error. A state-wide approach would overcome this problem and facilitate standardized data collection and processing. This scale of effort should engender close cooperation with other agencies with data sources, including the NWS, and be able to achieve the necessary conformity at state boundaries.

JUSTIFICATION FOR STUDY OF NEWLY-ACQUIRED RAIN DATA

Accelerated urbanization in the southwest is constantly increasing driver-exposure to hazards associated with high rainfall intensities. The urgency was much less serious when NOAA-2 was planned, almost two decades ago. At that time

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the rational formula prevailed, and urban hydrology was in its infancy. Investigations of flash floods, as well as the short duration and the compact aerial extent of desert convective storms, were at an early stage.

In the past twenty years, design engineers have become equipped with powerful hydrology software for personal computers. Runoff computations can now use data comprising spatially and temporally varied rainfall intensities for durations far shorter than one hour, the period used for the NOAA-2 atlases. Highway-drainage engineering for the future justifies new analyses of the large pool of break-point rainfall data that has accumulated in the last three decades. Deterministic runoff models might lull users into a false sense of security, if used with the short-duration rainfall estimates derived from NOAA-2. Today's technology deserves updated regional analyses of the increased number of recording rain gages and years of data. A recent pre-print (6) indicated possibilities. The number of stations for individual states included: Arizona, 5; New Mexico, 2; Nevada, 4; and Utah, 5. The authors of a similar study promulgated a finer delineation by dividing California into eight regions (7). It used 250 stations, averaging more than 27 years.

RE-STUDIES OF OLD DATA, ONGOING NWS CONTRIBUTIONS

The eastern portion of the United States did receive a re-study (8), although its previous database (9) was much more substantial than is presently available for the arid west. Likewise, California updated NOAA-2 three years after its release. In fact, that State produced its own three-volume study (10). Other restudies are more numerous than generally known. Many western small watershed hydrologists only know of NOAA-2. Some are aware of Hershfield's (9) "Rainfall Frequency Atlas of the United States" (TP-40). Recently, NWS published a very useful Technical Memorandum, which confusingly also has the number "40" in its title HYDRO-40 (11). It extends some of the depth-area work of the Agricultural Research Service (12) across all of Arizona and the western half of New Mexico. NOAA Technical Report, NWS 27, deals with inter-duration storms, between one and 24 hours (13). Most highway drainage designs in the arid West involve durations of less than 60 minutes.

OPPORTUNITY TO AUGMENT NWS DATABASE

Except for California, the eleven western states are poorly equipped with recording rain gages. Consequently, data shortage was a basic problem when NOAA-2 was prepared for the U.S. Soil Conservation Service using pre-1970 data (1). Some western states have fewer recording rain gages than others. The NWS maintains fewer than 40 recording rain gages in each of Utah, Nevada, and Arizona. Most intense summer rainstorms in the Southwest cover very small areas. Fortunately, longstanding experimental rangeland and desert watershed research has been pursued for many decades by the Agricultural Research Service (ARS), the U.S. Forest Service (USFS), and several universities. These scientific endeavors have included operating dense networks containing many recording rain gages spaced only a few miles apart. Most

of these dense networks are located at higher elevations than the rain gages in the NWS network. They contain information on areal and temporal characteristics of short-duration, flood-producing storms that should be analyzed and presented to designers. Some of these data fill regional voids in the statewide NWS networks, and there is a need to process it in a consistent format.

Arizona, for which a state-of-the-art study was recently completed, is used as an example (14). Figure 1 shows the 38 NWS recording rain gages from which 731 station-years of data were used in NOAA-2. Only 29 stations are maintained by the NWS today (fig. 2). Data were limited by being tabulated at the end of each clock-hour. On average, each gage sampled 3,100 square miles. The information shortage is made worse by the rare occurrence and spotty nature of heavy rainfall centers in an arid region. Research in southeastern Arizona showed, for 30 minute rains, that the highest point rainfall can be more than twice the average depth across an 80-square-mile storm (15). NOAA-2 was limited by a gross spatial network, which missed many larger point values. Moreover, the average record length of less than 20 years produced unreliable estimates at each gage site, particularly for less-frequent events such as a 50-year storm.

Today, 104 recording gages are operated by agencies throughout Arizona (fig. 3 and table 1). Some of these data are digitized each time storm intensity changes (break-point data). This is the type of information needed by designers. Future analysis should focus on processing data in "break-point" format. Longer histories and additional sites add up to about 3,000 station-years of additional data in Arizona alone. The longer records will provide more reliable 100-year point estimates.

NWS has added, or replaced weighing-bucket chart recorders with, Fisher & Porter punched paper-tape gages at 17 sites (indicated by closed circles in fig. 2). Table 1 shows that other agencies have increased the number of recording gages in Arizona markedly. Many are located in areas that supplement the NWS network, such as the Mogollon Rim (an extensive topographic feature with relatively high annual rainfall) and southeastern Arizona closer to the Gulf of Mexico moisture source. Since some of the older records were fairly long before they were terminated, an Arizona re-study could use about a hundred recording rain gages (fig. 3).

ANTICIPATED RESULTS OF NEW RAINFALL INTENSITY STUDIES

In addition to providing western states, counties, and local government agencies with updated analyses from an expanded database of short-duration rainfall measurements, the contemplated investigation should yield additional design tools to those found in TP-40 or NOAA-2. Research in Arizona has shown that flood peaks and flood hydrographs are heavily influenced by the high-intensity rainfalls that last for thirty minutes or less (12). With expanding urbanization in the desert southwest, these flash floods may become more frequent and severe. Expanding population means that more people will suffer the effects of mudflows and floods. Therefore, financial and societal benefits will result from regional studies of rainfall recorded autographically during the last few decades.

Second, the dichotomy which presently exists between the

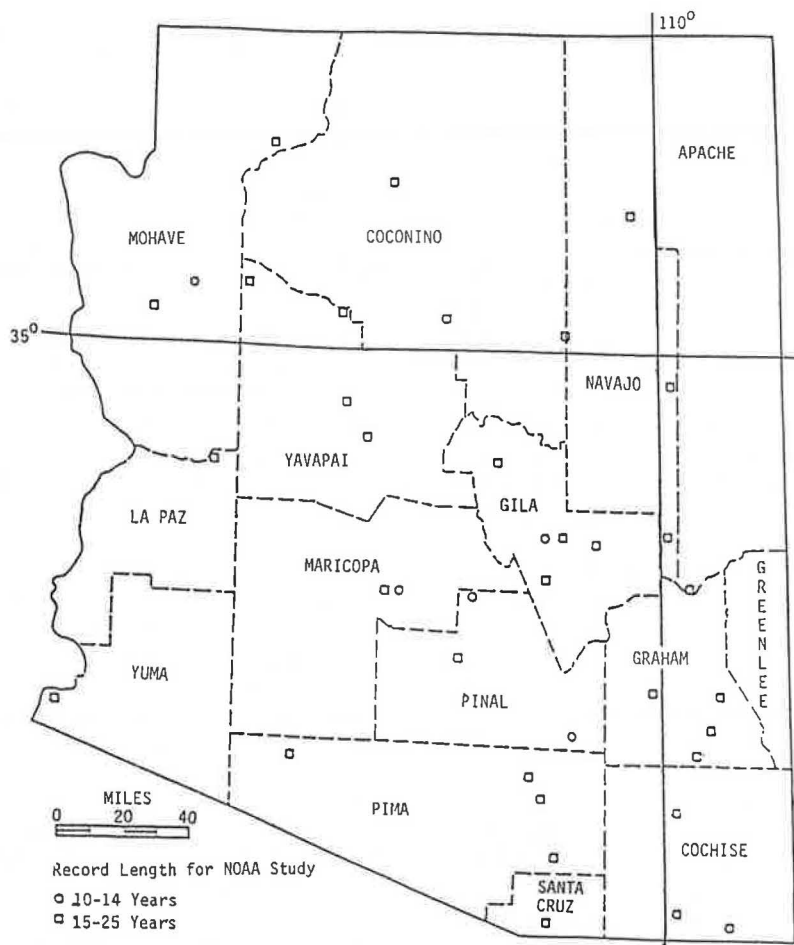


FIGURE 1 Arizona sites of NOAA-2 clock hour data use.

two latest NWS IDF-atlases, TP-40 and NOAA-2, can be resolved. Reference is made to the introduction in NOAA-2 of complex isolines (fig. 4), which suggest large differences in rainfall intensities switching back and forth many times over small distances, even within a county. Application of these contorted isolines requires considerable time, and enhances the opportunity for error in engineering or hydrologic design. Paucity of short-duration data in the NOAA-2 study, coupled with the apparently random spatial occurrence of thunder storms, leads observers of desert phenomena to question NOAA-2's high, short-rainfall maxima on lone desert mountains. Some engineers prefer TP40's smoothed user-friendly maps (fig. 5).

Third, statewide studies would reduce the tendency for smaller communities to re-analyze update records of one local gage.

A fourth benefit of a unified study is that it would provide an opportunity to consolidate the expert knowledge of scientists whose missions are other than highway design (16). These researchers might offer valuable advice and possibly solve some highway design problems. One component of the proposed projects would be to develop hydrology/hydraulic engineering manuals from research results that might otherwise be only partially reported in scientific journals.

A final benefit to highway engineers from the proposed research is a digital database, allowing instant site-specific

answers to be obtained from a personal computer. This would greatly reduce time and errors in executing drainage calculations.

PRIME REFERENCES AND CONCEPTS OF DESIGN RAINFALL

A scientific review recently reported 137 papers dealing with the analysis of storm rainfall and hydrometeorology (14). About one-third of the references included Arizona data. A similar proportion concerned other parts of the arid, western United States. The non-arid United States and overseas studies comprised a quarter of the documents, and the remainder dealt with selected topics in hydrometeorology—primarily the interaction of rainfall with regional topography in the interpretation of statistically anomalous results. This body of physical science can provide essential help in drawing isolines among the sparse network of recording rain gages (17-19).

Time Distribution Within Storms

State-side, unified studies would also provide new methods for estimating intensities within design storms situated over small watersheds. Sequences of rainfall increments within a

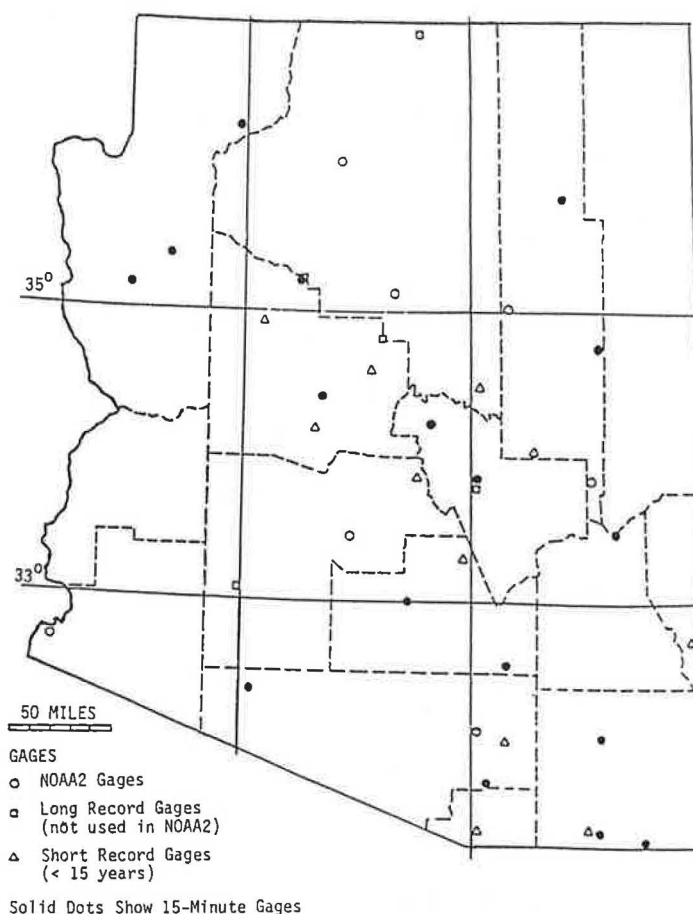


FIGURE 2 Various types of Arizona NWS recording raingages, 1987.

runoff-producing storm provide necessary input for deterministic hydrograph models. Such sequences may be used on ungaged urban or rural watersheds to predict flood volumes, flood peaks, and flood forecasting algorithms, as well as for predicting scour or deposition via computerized sediment transport models. A recently produced national design storm involved data from only five Arizona sites (20). The design storm values were based on an average of 30 rains per year at each site. The time-distribution of many small events represents an entirely different universe from the few flood-producing storms of interest to the highway designer. New investigations of flood-producing storms, based on the large pool of break-point data available from various agencies, are needed in the west.

It seems appropriate to take advantage of the additional number of rain gages and their longer records. State-wide or regional efforts to digitize the many unprocessed rainfall recorder charts for 10- through 60-minute and 2-, 6-, and 24-hour annual maximum series should begin. In Arizona, the database has quadrupled since NOAA-2 was developed. NOAA-2 analysis was restricted largely to daily observations, supplemented by clock-hour accumulations at a few short-record stations in all western states, except California. Today, investigations could analyze much more short-duration data in the ten western states.

TP40: An Early National IDF Atlas

In 1961 the Weather Bureau of the U.S. Department of Commerce published Technical Paper No. 40 (TP40), "Rainfall Frequency Atlas of the United States, for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years" (9). For its time, this was a monumental effort. For the entire country, it used 2,081 stations that had clock-hour data. The records were for the period 1938 through 1957, none being less than 5 years. The Arizona subset comprised 38 stations. A nationwide subset of 200 stations was used to interrelate rainfall intensities for intervals as short as 30 minutes by establishing average relationships to clock-hour amounts. Sixty-minute amounts are distinguished from clock-hour amounts in that the former represent the maximum 60-minute depth regardless of when the continuous period occurred. A relationship was developed between the 1-hour depth and the 6- and 24-hour depths for return-periods from 1- to 100-years.

Mapping relied on a larger network of 6,185 daily gages nationwide. Maximum annual rainfall data for selected durations at each of these sites yielded a series. Each of these was then fitted by an extreme value (EV) probability distribution (21). Thereafter, generalized relationships between the daily estimates and those for durations of 30-minutes, 1-, 2-, 3-, 6-, 12-, and 24-hour estimates and 1-, 2-, 5-, 10-, 25-, 50-, and

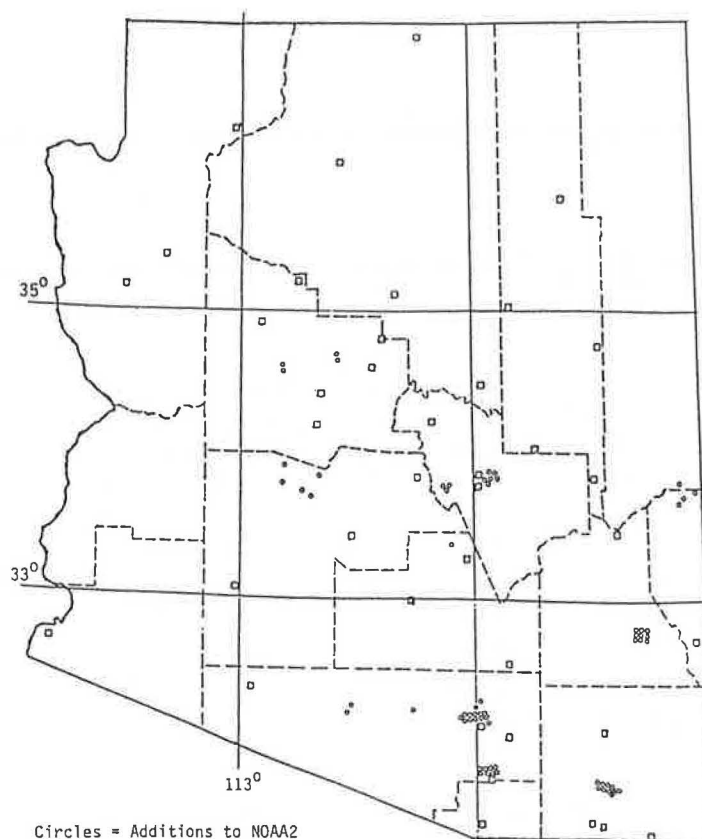


FIGURE 3 Recording raingages in Arizona available for a new study.

100-year frequencies were used to complete the atlas. The isolines were smoothed through the national network of daily rain gages.

Arizona was represented on the completed maps by about five square inches. For example, the 100-year 1-hour (P100y1h) isoline for 3, 2.5, 2, and 1.5 inches depicted four smooth, continuous, concentric areas (see fig. 5). This early report provided a useful, user-friendly design manual. In the pre-computer era, it extracted a high level of information from a minimal history of short-duration rainfall-intensity measurements. The transition of storm estimates across Arizona was sufficiently gradual that most counties were contained within a pair of isolines. For example, the 1-hour 100-year return period changes gradually from 2 inches on Maricopa County's

western boundary to 3 inches at its eastern extremity. The isoline trends are north-south, with very gentle curvature.

NOAA-2: Computer Attempt to Synthesize Inside Same Gages

NOAA-2 had the advantage of mainframe computers and about ten years of additional records in developing maps for eleven western states. In a similar manner to TP40, this study provided some benefits to each state from stations beyond its borders. The NOAA-2 study developed relationships between 24-hour maxima and the following factors: terrain slope, annual moisture, location, and roughness. The equations were applied to a dense grid on topographic maps. This information was subsequently fitted by tight, contorted isolines for every two-tenths of an inch. NOAA-2 presented a set of very detailed synthetic maps for selected return periods (2-year to 100-year) for both 6- and 24-hour durations. The maps of each state were about 110 square inches in area. The effect of this high degree of preciseness on potential users can be appreciated by examining figure 4 for P100y6h. Hydrologists who endeavor to determine floods from NOAA-2 are confronted with averaging among the intricately scalloped isolines for P100y6h or similar maps from the atlas. Nevertheless, some of the overall trends that are apparent despite the detail have been explained elsewhere on hydrometeorological grounds (17). For instance, the decrease in isohyetal rise in the northeast quarter of Ari-

TABLE 1 RECORDING
RAINGAGES IN ARIZONA
WITH ADEQUATE DATA
FOR ANALYSIS IN 1987

| Agency | No. of Raingages |
|---------|---------------------|
| NWS | 38 |
| USFS | 17 |
| ARS | 26 |
| UOA | 14 |
| Various | 9 |
| Total | 104 |

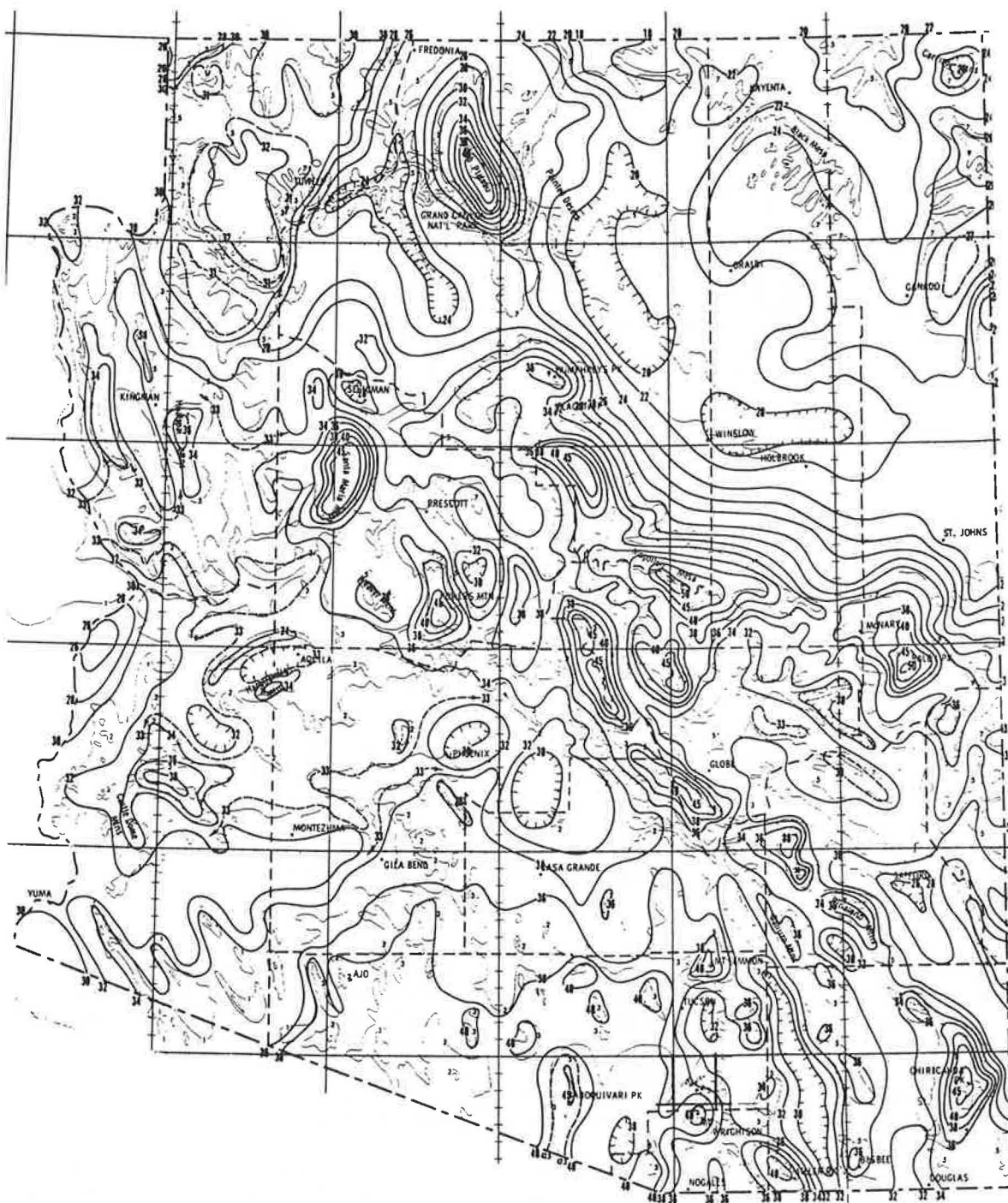


FIGURE 4 NOAA-2 map for 100-year 6-hour rainfall, tenths of an inch.

zona on the lee of the Mogollon Rim is caused by atmospheric moisture depletion.

Hydrometeorology

Excellent descriptions of the physical processes responsible for major storms were also given in Hydrometeorological Report 49 (17). That report included 26 major parts of five states. Of most importance to the highway program is the

section describing ideal storms, which are defined as "heavy rains, exceeding 3 inches in 3 hours or less, that are reasonably isolated from surrounding rains." It is very unlikely for such a local storm, much less its epicenter, to occur in a rain gage of the sparse NWS network gages. One of these storms produced 8 inches within 45 minutes near Fort Mohave, Arizona. This HMR 50 (18) also discussed "cloud mergers," where synergistic effects produce far greater rain than the sum of the water from separate clouds that do not collide. These complex mechanisms produce very heavy short-duration rain

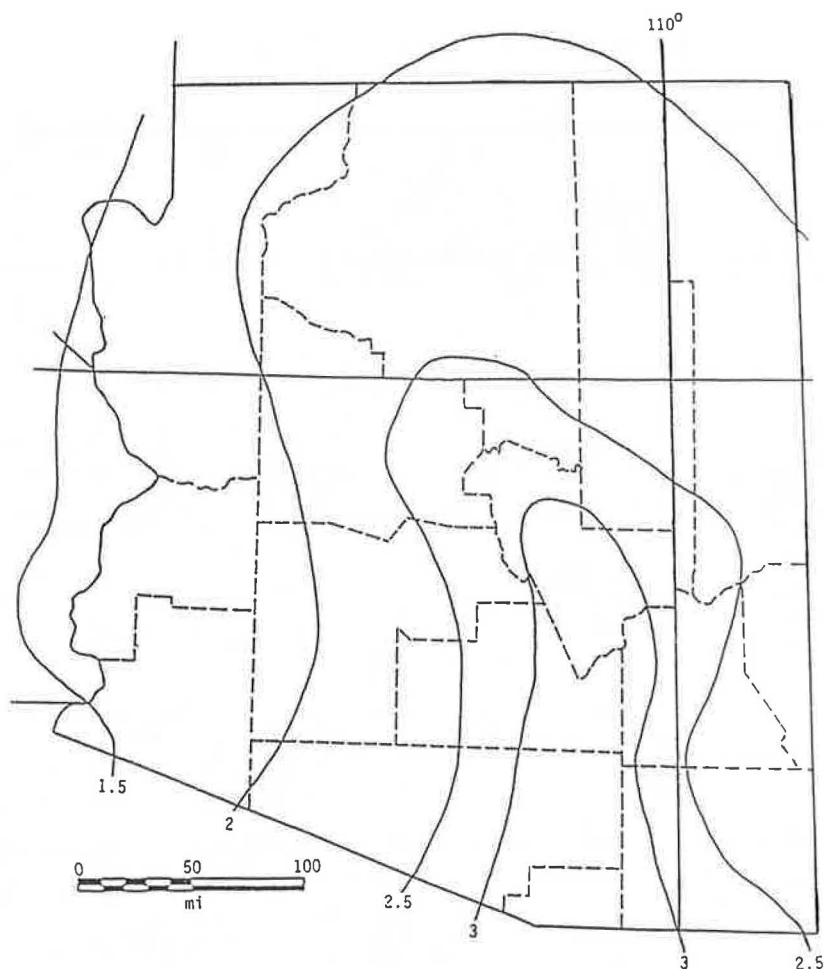


FIGURE 5 TP-40 map for 100-year 1-hour rainfall, inches.

which affects the ever-expanding road network. These violent, local, short-duration storms produce floods in the huge number of watersheds smaller than about 100 square miles (22).

Future analyses should consider hydroclimatological zones for which single values apply. Watersheds straddling a number of isolines can be simply handled as the design point moves close to zonal boundaries. If the proposed Arizona analysis is able to solve these problems, other arid states will be able to plan their re-analyses of short-duration rainfall intensities more effectively.

Time Distribution and Areal Reduction

Studies are also needed that include the interduration variation of rainfall amounts for different durations and frequencies and the reduction of point values to an area. Normally, hydrologic design involves the order in which amounts for selected durations occur, in addition to the average depth of precipitation over a particular drainage area.

The southeastern U.S. was fortunate to get a study (23) that meets such design needs. It suggests that the short-interval interdurational variability of rain storms in the southwestern United

States is critical. Several studies of within-storm rain at Walnut Gulch Watershed in southeastern Arizona have been prepared by the ARS (15). Data from additional small networks in the west should be studied.

CONCLUSIONS

There is a tremendous amount of short-duration rainfall intensity data available today for western states compared with what was available for the NOAA-2 publication in the early 1970s. Moreover, that study relied heavily on daily rain gage data. Today, there is great need for estimating rainfall intensities for the 10-, 15-, and 30-minute durations with which arid-region flood peaks and hydrographs are strongly correlated. Highway hydraulic engineers will be able to enter the microcomputer era of hydrologic design only if the temporal and spatial properties of storm rainfall are described quantitatively. The technology to process and statistically analyze these data is available. It has been estimated that about one-third of a million dollars would be needed in order to perform such a task for Arizona in the next two years (14). Most other western states have less data and may require less funding.

Some economies could be achieved by consolidating studies

for several western states. It is time that this third of the country has an updated rainfall design atlas, such as has been available for the eastern United States for over 10 years (8, 22).

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