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FLOOD FREQUENCY ESTIMATES IN SOUTHEASTERN ARIZONA

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ABSTRACT: The effect of the October 1983 floods in southeastern Arizona, on a previously established generalized envelope for floods expected once in 100 years (Q_{100}), is studied. The design envelope is found to produce more conservative estimates of Q_{100} than individual data sets find. The design envelope for Q_{100} is revised to correct for some longer periods of record now available, and to be consistent with floods on a wider range of drainage area than previously considered. Additional design envelopes for floods expected once in 2 years (Q_2) and once in 10 years (Q_{10}) are prepared, and the three envelopes are used to provide conservative estimates of flood frequencies on ungaged watersheds in southeastern Arizona with drainage areas between 0.01 km^2 and 10,000 km^2. A procedure is presented for developing regional flood frequency estimates that could be used in geographically and climatically homogeneous areas.

INTRODUCTION

In the period from September 29 to October 2, 1983, Tropical Storm Octave, off the west coast of Baja, California, produced widespread rain in southern Arizona. In Tucson, 3.58 in. (91 cm) of rain fell in 29 hours; this storm produced about a 25-year return-period rainfall. Severe flooding occurred in many watersheds in southern Arizona, but the most damage was caused by bank erosion. The magnitude of the damage has been documented by the Pima County Department of Transportation and Flood Control District (no date).

The Santa Cruz River, at Congress Street, in Tucson, peaked at 1,490 m^3/s (52,700 cfs). This flood flow exceeds, by more than a factor of two, any other flood recorded at that station. It exceeds, by a factor of 1.75, the magnitude of the 1-in-100-year flood as established by the Federal Emergency Management Agency Flood Insurance Study (Federal Emergency Management Agency 1982; Saarinen, et al., 1984).

In a study prior to the 1983 event, Boughton and Renard (1984) analyzed the flood frequency characteristics of 18 watersheds in southeastern Arizona, and produced a design envelope for Q_{100} for watersheds between 0.02 and 10,000 km^2. The 1984 study considered the results of several earlier studies, but was undertaken before the 1983 floods. In the 1983

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TABLE 1. Details of Watersheds Used to Establish Design Envelope (Q_{100ENV}) in 1984 Study

Watershed (1)	Watershed identification (2)	Area (km²) (3)	Period of record (4)	Estimated Envelope		
				Q_{100} (m³/s) (5)	(Q_{100ENV}) Ratio (6)	Q_{100} envelope (7)
Walnut Gulch[a]	63.112	0.0186	1962–79	0.68	0.71	0.96
Walnut Gulch[a]	63.104	0.0453	1963–79	1.59	1.78	0.89
Safford	WS 1	2.10	1939–68	16.8	53.2	0.32
Safford	WS 5	2.93	1939–67	24.8	68.0	0.36
Cemetery Wash[a]	Tucson	3.37	1966–78	22.7	75.3	0.30
Walnut Gulch[a]	63.011	8.24	1963–80	110	139	0.79
Walnut Gulch[a]	63.003	8.99	1958–80	59.5	147	0.40
Rodeo Wash	Tucson	15.3	1970–79	33.1	206	0.16
Walnut Gulch[a]	63.008	15.5	1963–80	111	207	0.54
Sabino Creek[a]	Tucson	91.9	1933–79	317	546	0.58
Tanque Verde Creek[a]	Tucson	111	1960–79	198	600	0.33
Willow Creek	Point of pines	264	1945–67	124	875	0.14
Eagle Creek	Double circle above pumping plant	976	1944–67	544	1,400	0.39
Eagle Creek[a]		1,588	1944–75	1,130	1,620	0.70
San Carlos R.[a]	Peridot	2,660	1930–75	1,650	1,850	0.89
Santa Cruz R.	Tucson	5,750	1915–79	572	2,180	0.26
Gila R.[a]	Virden	8,296	1927–75	832	2,330	0.36
Gila R.[a]	Clifton	10,390	1911–17 and 1928–75	748	2,420	0.31

[a] These stations were operational in 1985, and were used to update the earlier study.

event, 3 of the 18 watersheds used in the study recorded the largest floods in the period of record. Floods in the Santa Cruz River, at Tucson, and in Tanque Verde Creek, were more than double the previously recorded highest flood.

This paper reviews the effects of the 1983 floods on the results of the earlier study (referred to hereafter as the 1984 study), and demonstrates the stability of the design envelope approach. The design envelope method is modified to obtain conservative estimates of flood frequency characteristics for ungaged watersheds whose drainage areas are between 0.01 and 10,000 km² in southeastern Arizona.

DESIGN ENVELOPE FOR Q_{100} IN 1984 STUDY

Table 1 lists the 18 watersheds used in the 1984 study to develop an envelope of Q_{100} for ungaged watersheds. Details of the watersheds are contained in Boughton and Renard (1984).

Estimates of Q_{100} were obtained by fitting the log-Boughton distribution (Boughton 1980; Boughton and Shirley 1983) to each data set. These estimates were used with the results of earlier studies (Osborn and Laursen 1973; Roeske 1978; Reich, et al. 1979; Malvick 1980) to produce the design envelope for Q_{100}, shown in Fig. 1. Using the same form of equation that had been used in two of the earlier studies (Reich, et al. 1979; Malvick 1980), Boughton and Renard (1984) produced the following equation to define the envelope shown in Fig. 1:

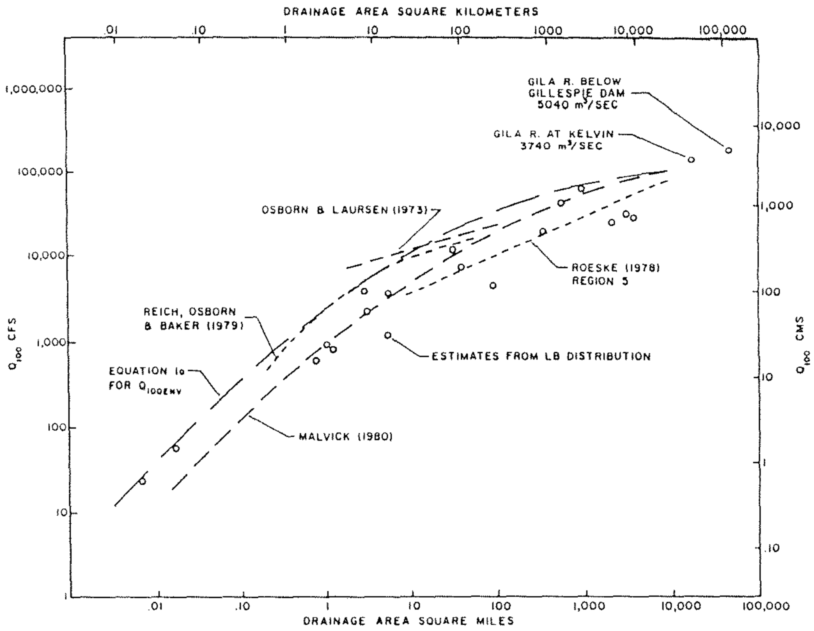

FIG. 1. Regional Flood Frequency Relationships for Peak Flow Estimation in Southeastern Arizona [Modified after Boughton and Renard (1984)]

$$Q_{100ENV} = 2{,}200\ D^{(0.736 - 0.082 \log D)} \quad \text{(1a)}$$

where Q_{100ENV} = envelope value, in cfs; and D = drainage area in sq. miles. Eq. 1b shows the same equation converted to m³/s and km² units:

$$Q_{100ENV} = 29.9\ D^{(0.803 - 0.082 \log D)} \quad \text{(1b)}$$

where Q_{100ENV} = envelope value, in m³/s; and D = drainage area in km².

EFFECTS OF 1983 FLOODS ON ENVELOPE

The data used in the 1984 study did not cover the same period of record on all watersheds. Some of the stream-gaging stations had ceased to operate in 1967 and 1968, but the flood data were used in the study because the watersheds provided information for particular sizes of drainage area for which other data could not be obtained. Six of the original eighteen stations were not in operation during the 1983 flood event, and could not be updated for the current study.

Data from the 12 stations that were in operation during the 1983 event were brought up to date to include the 1983 flood, and new estimates of Q_{100} were obtained by fitting the log-Boughton distribution to the annual maxima flood series in the same way as in the earlier study.

The new estimates of Q_{100}, obtained after including the additional flood data (up to, and including, the 1983 flood), were not all greater than the earlier estimates. Seven of the new estimates of Q_{100} were greater than the old estimates, while five were smaller. Only one of the new estimates of Q_{100} (from the smallest of the 18 watersheds, the 1.86-ha Walnut Gulch watershed number 63.112) exceeded the old envelope value of Q_{100ENV}. Only 18 years of data were available for the original study, and the additional 5 years of data increased the estimate of Q_{100} from 0.68 m³/s to 0.92 m³/s. It should be noted that the 1983 flood on this watershed was only the 13th highest ranking flood with an estimated return period of 1.85 years. It was the additional accumulation of record, not the 1983 event, that caused the new estimate of Q_{100} to exceed the envelope value on this watershed.

The main effect of the 1983 flood event was to increase the estimates of Q_{100} on some watersheds whose earlier estimates were significantly low in relation to the design envelope. In general, the envelope proved to be much more stable than the estimates of Q_{100} based on individual data sets, even on watersheds with long periods of record, such as the Santa Cruz River at Tucson.

REVISION OF ENVELOPE

The stability of the envelope, outlined in the preceding section, prompted further work that goes beyond the 1984 study, and extends the envelope approach into a complete method for obtaining a conservative estimate of flood frequency characteristics on ungaged watersheds in southeastern Arizona. In the course of this additional work, a study was made of the equation that is used to define the design envelope.

Eq. 1b has a maximum value of Q_{100ENV} at a particular value of drainage area. The value of Q_{100ENV} then decreases as drainage area increases beyond that particular value (see Fig. 2). The size of drainage area at which the maximum Q_{100ENV} value occurs is found by converting Eq. 1b into Eq. 2, differentiating, and then setting the differential to zero:

$$\log Q_{100ENV} = \log 29.9 + 0.803 \log D - 0.082 \log^2 D \qquad (2)$$

$$\frac{d(\log Q_{100ENV})}{d(\log D)} = 0.803 - 0.164 \log D = 0 \qquad (3)$$

Thus, the maximum Q_{100ENV} = 2,764 m³/s (97,600 cfs) occurs at D = 78,800 km² (30,412 sq. mi).

The rational method for flood flows from small watersheds assumes them to vary in direct proportion to drainage area size. It is also generally accepted that flood flows from medium to large watersheds vary in proportion to D^n where the exponent n is less than 1.0. There would be little justification for any relationship in which flood flows increased at a faster rate than drainage area, i.e., $n > 1.0$.

Fig. 2 shows a straight line with Q_{100ENV} proportional to $D^{1.0}$ fitted to become tangential to the envelope curve at the point where

$$\frac{d(\log Q_{100ENV})}{d(\log D)} = 1.0 \qquad (4a)$$

$$\text{Solving} \quad D = 0.063 \text{ km}^2 \text{ and } Q_{100ENV} = 2.47\ m^3/s \qquad (4b)$$

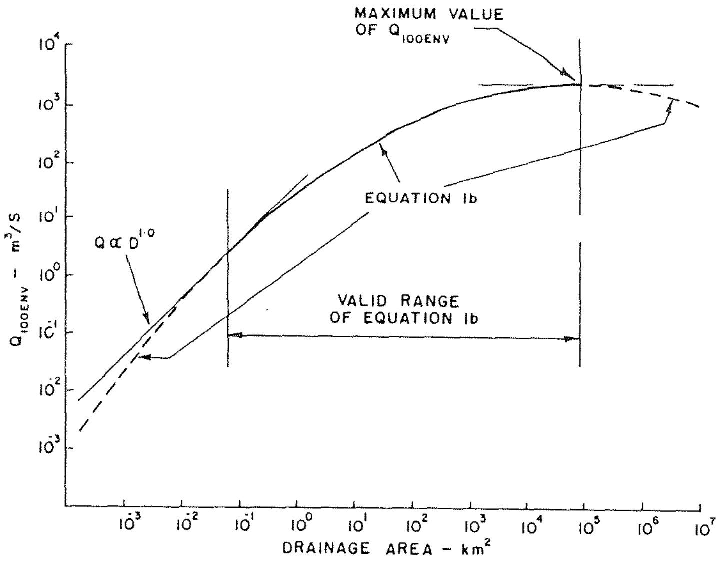

FIG. 2. Procedure Used to Obtain Design Envelope and Define Its Valid Range

$$\text{At this point} \quad Q_{100ENV} = 39.3\, D \qquad (5)$$

which is the equation of the tangential straight line in Fig. 2.

Therefore, the equation used to define the envelope will have an upper limit of applicability given by the point where Q_{100ENV} is a maximum (Eq. 3), and a lower limit of applicability given by the point where Eq. 4 holds.

The upper limit of 2,764 m³/s for a drainage area of 78,800 km² is somewhat low. The Gila River, below Gillespie Dam, with a drainage area of 128,600 km² (49,650 sq. mi), has recorded a flood flow of 5,040 m³/s (178,000 cfs), and the Gila River, at Kelvin, with a drainage area of 46,650 km² (18,010 sq. mi), has recorded a flood flow of 3,740 m³/s (132,000 cfs).

Although the design envelope is not intended for use on watersheds as large as these, it is more satisfactory when the envelope is consistent with flood information from the whole range of watershed sizes. A second reason for revision of the envelope is to incorporate the recent estimate of Q_{100} found on watershed 63.112, as described earlier. For these reasons, the design envelope for Q_{100} was revised. The three pairs of data in Table 2 were used to parameterize the equation of the envelope. Using these values, the constants were evaluated to give the following relationship:

$$Q_{100ENV} = 31.6\, D^{(0.77 - 0.0664 \log D)} \qquad (6)$$

A comparison between the 1984 envelope (Eq. 1b) and the new envelope (Eq. 6) is given in Table 3. It can be seen from Table 3 that the two envelopes are about the same for drainage areas in the range from 1 to 100 km², while the new envelope is about 40% higher at the upper end of the range of drainage area.

The maximum value of Q_{100ENV} in Eq. 6 is 5,395 m³/s, and this occurs at a drainage area of 628,337 km². For design purposes, however, an

TABLE 2. Data Used to Parameterize Equation of Envelope

Drainage area (km^2) (1)	Q_{100ENV} (m^3/s) (2)
0.02	1.00
10.0	160
120,000	5,000

TABLE 3. Comparison of Old and New Envelopes (Q_{100ENV})

Drainage area (km^2) (1)	Old Q_{100ENV} Eq. 1b (m^3/s) (2)	New Q_{100ENV} Eq. 6 (m^3/s) (3)
0.01	0.348	0.495
0.1	3.90	4.61
1	29.9	31.6
10	157	160
100	567	595
1,000	1,400	1,630
10,000	2,380	3,290

appropriate upper limit of applicability of Eq. 6 would be 10,000 km^2, since most of the data were from watersheds smaller than this. The lower limit of applicability occurs at D = 0.0185 km^2, i.e., 1.85 ha, when Q_{100ENV} = 0.927 m^3/s.

ESTIMATING FLOODS ON UNGAGED WATERSHEDS

The new envelope (Eq. 6) provides a conservative estimate of only one return-period flood. In practice, it is more useful if one could estimate the distribution of flood magnitudes for return periods in the range of 2 to 200 years. The design envelope approach has been extended to provide the additional information.

Annual maxima flood data were obtained from six additional stream-gaging stations not used in the original study. The new stations and their drainage areas are listed in Table 4.

TABLE 4. Data for Six Stations not Included in 1984 Study

New Station (1)	Drainage area (km^2) (2)
Rincon Creek	116
Santa Cruz River at Lochiel	213
Santa Cruz River at Nogales	1,380
San Pedro River at Charleston	3,157
San Pedro River at Reddington	7,610
Santa Cruz River at Cortaro	9,070

Estimates of Q_{100} were made for each station in the same manner as before, and these estimates were checked against the new design envelope (Eq. 6). All of the estimates were found to be less than the envelope, ranging from 0.32 to 0.84 of the envelope value. Estimates of Q_2 and Q_{10} were made for each of the 18 stream-gaging stations used in the 1984 study, and for the six additional stations. Two additional design envelopes were then derived to encompass the Q_2 and Q_{10} values from the 24 stations using the same form of equation as before. Eqs. 7 and 8 are the equations for Q_{2ENV} and Q_{10ENV}, respectively:

$$Q_{2ENV} = 5.44\ D^{(0.703 - 0.0658 \log D)} \quad (7)$$

$$Q_{10ENV} = 15.8\ D^{(0.703 - 0.0662 \log D)} \quad (8)$$

where Q_{2ENV} = envelope value for two-year return period in m^3/s; and Q_{10ENV} = envelope value for 10-year return period in m^3/s.

Table 5 contains the estimates of Q_2, Q_{10}, and Q_{100}, together with the envelope values Q_{2ENV}, Q_{10ENV}, and Q_{100ENV} for each of the 24 stream-gaging stations.

Eqs. 6–8 can be used to obtain estimates of Q_{2ENV}, Q_{10ENV}, and Q_{100ENV} for any given size of drainage area within the range of applicability. These three envelope values can be used to interpolate and extrapolate to other return periods using the average shape of flood frequency distribution for watersheds in southeastern Arizona found in the 1984 study. Boughton and Renard (1984) normalized the logarithms of annual maxima floods in the original 18 data sets by subtracting the mean and dividing by the standard deviation. This gave a set of frequency factors that were related to return period by the following equation:

$$K = 4.3 + \frac{19.8}{\ln\ln\left[\frac{T}{T-1}\right] - 4.3} \quad (9)$$

where K = frequency factor corresponding to a return period of T years.

Eq. 9 was used to construct the probability paper shown in Fig. 3. The probability paper is used to estimate flood frequencies on ungaged watersheds as follows:

1. Using the size of drainage area of the ungaged watershed, estimate Q_{2ENV}, Q_{10ENV}, and Q_{100ENV} from Eqs. 6–8.
2. Plot these three values on the probability paper shown in Fig. 3.
3. By eye, draw a straight line of best fit through the three points.
4. The fitted line gives a conservative (i.e., envelope) estimate of the flood frequency characteristics for the given size of watershed in southeastern Arizona.

An alternative to this procedure is shown in Fig. 4, where values have been calculated and plotted for a wide range of watershed sizes. The envelope flood frequency for any given size of drainage area can be read directly from Fig. 4.

Regardless of whether values are calculated from Eqs. 6–8 and interpolated with Fig. 3 or read directly from Fig. 4, it must be remembered that the flood frequency curve is a design envelope encompassing the data from the 24 watersheds used in the derivation. Consequently, the estimated

TABLE 5. Flood Estimates from Streamflow Records Compared with Envelope Values

Watershed (1)	Drainage area (km²) (2)	Estimates from Data (m³/s) Q_2 (3)	Q_{10} (4)	Q_{100} (5)	Envelope Values (m³/s) Q_{2ENV} (6)	Q_{10ENV} (7)	Q_{100ENV} (8)
Walnut Gulch 63.112	0.0186	0.195	0.555	0.923	0.210	0.608	0.930
Walnut Gulch 63.104	0.0453	0.462	0.926	1.31	0.470	1.36	2.21
Safford WS 1	2.10	2.80	8.75	16.8	9.02	26.2	55.1
Safford WS 5	2.93	3.37	11.9	24.8	11.2	32.5	69.9
Cemetery Wash, Tucson	3.37	8.92	15.2	20.8	12.3	35.6	77.2
Walnut Gulch 63.011	8.24	21.1	64.1	125	21.1	61.2	141
Walnut Gulch 63.003	8.99	5.92	22.5	50.2	22.2	64.4	149
Rodeo Wash, Tucson	15.3	6.60	19.0	33.1	29.9	86.8	208
Walnut Gulch 63.008	15.5	22.5	64.5	123	30.1	87.4	210
Sabino Creek, Tucson	91.9	37.0	125	276	72.8	211	570
Tanque Verde Creek, Tucson	111	48.9	130	245	79.1	229	626
Rincon Creek	116	35.6	185	539	80.6	233	640
Santa Cruz, Lochiel	213	46.8	137	278	104	300	856
Willow Creek, Point of Pines	264	23.3	63.4	124	113	326	944
Eagle Creek, Double Circle	976	80.0	248	544	177	511	1,610
Santa Cruz River, Nogales	1,380	132	321	599	197	567	1,830
Eagle Creek, above pumping plant	1,588	82.8	409	1,260	205	590	1,920
San Carlos River, Peridot	2,660	223	698	1,580	235	676	2,280
San Pedro River, Charleston	3,157	205	485	899	245	705	2,400
Santa Cruz River, Tucson	5,750	151	389	800	281	805	2,860
San Pedro River, Reddington	7,610	205	604	1,330	297	851	3,080
Gila River, Virden	8,296	143	434	914	302	865	3,140
Santa Cruz River, Cortaro	9,070	260	616	1,160	307	879	3,210
Gila River, Clifton	10,390	177	433	842	315	900	3,320

Note: Multiply m³/s by 35.31 to obtain cfs. Multiply km² by 0.3861 to obtain sq mi.

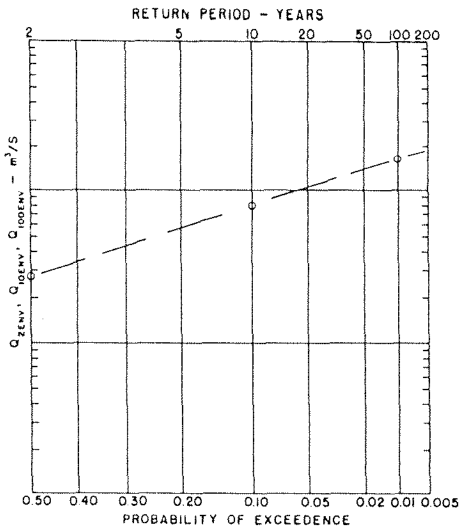

FIG. 3. Flood Frequency Interpolation Diagram for Specific Size Drainage areas

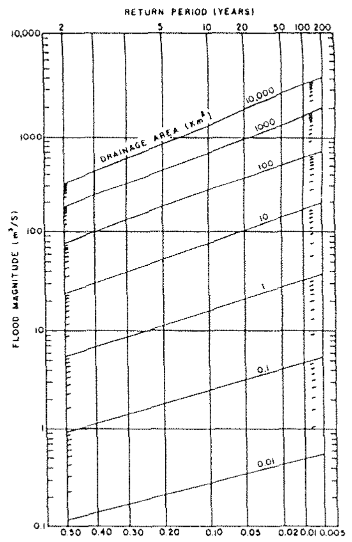

FIG. 4. Flood Frequency Interpolation Diagram for Varying Size Drainage areas

flood frequency distribution is conservative. It seems to the writers that it is desirable to be conservative when floods are estimated on ungaged watersheds.

Eqs. 6–8 and Figs. 3 and 4 are also useful with gaged watersheds. When flood frequency estimates from streamflow records are very low in relation to the envelope values, there is reason for caution in using the streamflow data alone. The Santa Cruz River, at Tucson, is one example of where a long record of streamflow was unreliable for estimating the flood potential of the watershed. Similarly, when estimates of floods made from a streamflow record are significantly higher than the envelope values, some additional investigation would be warranted.

CONCLUSION

The information of flood frequencies, which is summarized in Eqs. 6–8 and in Figs. 3 and 4 provides a simple means of obtaining a conservative estimate of the distribution of flood frequencies on ungaged watersheds with drainage areas ranging from 0.01 to 10,000 km² in southeastern Arizona. The procedure outlined in this paper also provides design envelope values against which flood frequencies derived from streamflow data can be compared to identify when estimates are significantly higher or lower than the generalized values from other watersheds in the region. The procedure has potential for use as a regional flood frequency technique in other areas.

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