RECENT CHANGES IN A FLOOD SERIES

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Abstract

Flood peaks have been measured by the U.S. Geological Survey on the Santa Cruz River at Congress Street since the 1915 water year. In the mid-1970's 30,000 cfs was used for floodplain mapping. Floods of 23,000 and 52,000 cfs occurred in the 1978 and 1984 water years. A channelization scheme through a downtown revitalization project had been built in 1980 for 45,000 cfs capacity with bank protection to the 30,000 level. Re-examination of the 70 year record indicated that larger floods now occur than before World War II, after which urbanization and highway structures impacted 30 miles of floodplain upstream of the gage in the 2,222 square mile watershed. A statistical test proved that the 1960-1984 floods were different from the 1915-1959 series. The recent sub-set was well fitted by the Log Extreme Value distribution, which by the method of moments gave 96,000 cfs for the 100 year flood. It appears that prior to man's drastic impact upon the lower 5% of this semi-arid watershed, floods exceeding 12,000 seldom reached Tucson, possibly because they were stored in vast, flat, pristine floodplains.

Chronological Series of Floods

The October 2, 1983 flood was estimated by the USGS this month, from observed watermarks, as 52,000 cubic feet per second (cfs). Only rough estimates are available for the two previous years because the stream gage was removed, after a national test suggested that the length of record was adequate to estimate future floods. What has transpired since then certainly proved this wrong. Tucson, with its population expected to double in the next 30 years (Fig. 1), should require the Federal Government to reinstate this streamgage now that the notion of an unchanging flood regime has been disproved. The needed cost of obtaining such measurements a quarter mile from the USGS office represents a miniscual diversion of funds from weapons of destruction. Monitoring the natural disasters which lie in store for our community of about a million taxpayers, should of course be followed by funds to check the degredation of this river system and the potential property damages that have accrued from under predicted floods and the Federal Emergency Management Agency's oversight of potential erosion and channel retreat (Laursen, 1984). Many other growing communities could benefit from numerical evaluation of this hazard.

Fig. 2 shows that the 52,000 cfs observed in the 1984 water year at Congress Street in downtown Tucson was more than double the peak observed in 1978. Neither of these events were available when the Federal government prepared the Flood Insurance Maps for this Community. At that earlier time 16,600 and 16,100 cfs were the records in some sixty years of data. It now becomes necessary to re-examine (Reich, 1983) the validity of FEMA's 30,000 cfs estimate of the 100 year flood, in the light of new information.

Altered Occurrence of Large Floods

The earliest flood peak in our official series was 15,000 cfs in December 1914, and remained the record for 47 years. After 1960 annual maximum floods have exceeded this about every six years. The 1950's corresponded to a surge in population growth (Fig. 1) accompanied by major highway works along the floodplain, and increased sand and gravel mining for the construction industry. The 1960's and 1970's saw residential development for 25 miles upstream (south) of Tucson and the progression of downcutting and "natural" channel widening, whose roots lie in and before the 1940's.

Possible causes receive study elsewhere

Visual examination of the chronological flood series (Fig. 2) suggests that before 1955 large flood peaks that may have entered the well vegetated, wide floodplains eight to thirty miles south of Tucson were prevented from exceeding about 11,000 cfs by low conveyance and overbank losses in flood areas of a mile or more wide. Recent changes in some of these topographic features, including the effect of the October 1983 flood are described by Lowe (1984). More detailed historical reference were given by Betancourt (1983). Together they show that "historic" is simply a phase of "ongoing" change when applied to desert rivers. Perhaps there is a moral to be drawn by preditors of 100 year floods. Of course, other possible reasons may have produced the 46 year absence of floods larger than 11,000 cfs before 1961. However, it is interesting to observe (Fig. 3) that annual maximum daily rainfalls observed in Tucson were often larger in those early years. The 45 years between 1915 and 1960 contained twelve with maximum daily rainfall exceeding 2 inches while containing no floods exceeding 12,000 cfs. The more recent 25 years experienced only three daily rainfalls exceeding 2 inches but contained six floods exceeded 12,000 cfs.

The purpose of this paper is not to establish causes for the changed flood regime. Too much remains unknown of the aerial and temporal distributions of storm rainfall of this and previous floods. The intent is simply to present some statistics obtained from analyzing the annual series of flood peaks recorded at Congress Street. It is proved that floods in the most recent twenty-five years are significantly different from those in earlier years. Estimates from earlier, and from the entire history, are contrasted to results with the current period.

Flood Frequency Analysis

Government's purpose in analyzing past data is to provide management information valid for a few generations. Thus flood data upon which flood frequency predictions are based should represent current conditions, which hopefully shall persist for some foreseeable time through the enforcement of prudent regulations and physical controls. If a substantial continuous part of a gaged stream record contained significantly different floods from a long recent period, the earlier irrelevant years should be eliminated before analysis. Thus if an adequate recent period of record is found to produce significantly larger floods we would be well advised to use it rather that the entire record. Otherwise, mixing present era floods with those from earlier less flood-prone years would be akin to sampling a barrel of cherries and plums in order to determine the size of extremely large plums. Hydrologists are accustomed to applying double-mass analysis to examine more stable data, like total annual rainfall series, for discontinuities. Since flood series exhibit more random variabilty and are relatively short, a test for their stationarity is more complex and often overlooked. However, no flood frequency prediction should be made until a test of this long-term homogeneity has been satisfied.

The Kruskal-Wallis test

The author was fortunate to have the assistance of Todd Rasmussen, a graduate student of Hydrology at the University of Arizona, to perform a computerized version of this pre-test. This statistical test was developed in 1952 to check the null hypothesis that two or more populatons are identical against the alternative that some tend to furnish greater observed values over other populations (W.J. Conover, 1971). This application to Congress Street floods considered the latest twenty-five peak discharges as one population. It was chosen to be as long as possible, while incorporating the hydrologic consequences that accrued from the surge of human activity which struck the 30 miles of valley upstream of Tucson in the 1950's. The other population against which it was tested comprised the Congress Street flood peaks measured from 1915 through 1959. It is not possible to determine in advance a single year at which a dichotomy occurred. This Kruskal-Wallis test showed that the recent flood population is different from the earlier one at the 7.2% level. One is therefore about 93% sure that this test outcome could not have resulted from random arrangement of floods in an unchanging river regime.

A graphical test.

A pictorial analog of the above statistical test is presented in Fig. 4. The recent and earlier series were plotted (C. Cunnane, 1978) separately on the same piece of Log Extreme Value paper (B.M. Reich, 1976). The two plots of observed points are widely separated. With a view to eliminating personal judgment or bias, the straight lines were fitted through each series by the method of moments. An estimate of the 100 year peak (Q 100) is 96,400 cfs for the recent series. The small spread of all but the smallest, and thus least important, flood of the 1960-1984 series is a most desirable property. This suggests (B.M. Reich & K.G. Renard, 1981) that the Log Extreme Value (LEV) distribution is appropriate to the population of recent floods. This linearity is not exhibited by the earlier record plotted in Fig. 4. The longer, older series of x's in Fig. 4 form dog legs that may result from a sequence of watershed changes occurring within that 45 year period. It is not like the last 25 years of floods which appear to have stabilized into an orderly series, after major disturbances of the 1950's. The method of moments estimate of Q 100 = 35,600 for the older series should not be used, because its plotted points lack linearity.

Flood statistics of progressive thirds of data.

Dividing the series of flood peaks into virtually equal segments allowed the calculation of averages, and coefficients of skewness and variation of the logarithms of the floods. These are displayed in Table 1.

TABLE 1 Statistics of Various Segments of Congress Street's Flood Peak Series

Segment of Record	Geometric Mean cfs.	Coefficient of Skewness of Logs of Floods	L.P. III 100 year Prediction	Log E.V. 100 year Prediction
1915/1937	4,337	0.093	22,000	42,000
1938/1961	5,466	-0.056	20,000	37,000
1962/1984	6,504	0.264	50,000	98,000
1960/1983	6,224	-0.269	28,000	66,400
1960/1984	6,776	0.288	54,000	96,000
above less 1965 low.	7,286	0.677	59,000	83,000

The geometric mean.

This statistic is a relatively stable measure of the average flood size for each segment of the record. Stability is illustrated by the fact that adding October 1983's 52,000 cfs to the previous 24 year's floods only raised the geometric mean from 6,224 to 6,776 cfs. A large single value within a sub-series is thus unlikely to affect the geometric mean as substantially as will the same total increase in annual floods spread throughout many years. Table 1 shows that the first and second thirds of this series had geometric means of 4,337 and 5,466 cfs relative to about six and half thousand in the last quarter century. Even without the October 1983 event the geometric mean of Congress Street flood peaks has been continually increasing.

Coefficient of skewness of the logs of floods (CSL)

This measures the asymetry of the data about the geometric mean. If floods are Log Normally distributed, this statistic should be zero, and they may plot with a linear trend on that type of paper. Positive values generally indicate flood series which curve upwards for large floods on Log Normal paper. CSL is the statistic used to release the Log Pearson Type III curves from linearity, as suggested by the Water Resources Council. Unfortunately, this statistic varies greatly with sampling in time and space (B.M. Reich, 1977), as can be seen in Table 1. CSL would be 1.139 for floods which plotted in a perfect straight line on Log Extreme Value (LEV) paper. The considerable impact upon the CSL of one outlier which is substantially off a generally linear LEV array is illustrated in Fig. 5. Most of the deviation of the logs from the otherwise linear trend is due to the very smallest flood, of no interest to designers. Never-the-less, it reduced CSL from the theoretically desirable value of 1.139 to 0.288. Elimination of this anomoulously small 1965 flood raises CSL to 0.677, which is acceptabley close to the theoretical ideal of 1.139; which suggests an LEV model. It can also be noticed in Table 1 that inclusion of the 1984 water year caused a change of more than five tenths in this statistic, before elimination of the small oulier.

LP III Q 100.

Although not a classical parameter for mathematical statisticians, in the same sense as the geometric mean or CSL, the 100 year estimate obtained from applying the Log Pearson Type III method has become all too familiar to engineers and Federal Agencies (B.M. Reich, 1977). It is therefore listed in Table 1 at the right of CSL, upon which it is heavily dependent. Whether LP III Q 100 is an acceptable estimate of the 100 year flood can only be established after studying how the LP III curve fits the plotted data. An example of how this method is controlled by a CSL, determined largely by small outliers, is given in Fig. 5. The curve is positioned across the required prediction range, from 25 - to 100-year return periods, by curvature established by the numerous small floods which are not generally of concern in flood control work. In this case LP III Q 100 is about the size of a event already observed in 25 years. Even this statistic shows in Table 1 that the post-1960 flood potential at Congress Street has more than doubled; even without the inclusion of last year's 52,000 cfs.

LEV Q 100.

Another flood "statistic" which shows that Tucson's flood potential increased about two and a half times in the last 25 years is the 100 year estimate according to Log Extreme Value theory. This corresponds to mathematically fitting a straight line on LEV paper. The dashed line on Fig. 5 presents an example of the goodness of fit through the data, particularly the larger observations. The last column of Table 1 shows about a 12% decrease in LEV Q 100 between the first and second thirds of the record, traceable to the coefficient of variation of the logs of the floods being 0.0814 and 0.0626 for the sub-histories. A 10% decrease in LP III Q 100 was experienced in the same time frame. Such variability is the expected outcome of sampling in time. The subtlety of such measures can be appreciated by comtemplating the visually imperceptable difference in variability between the 1915/1937 and 1938/1961 sub-histories in Fig. 2. The coefficient of variation of the logs increased again to 0.0814 for 1961/1983. Inclusion of 52,000 cfs event in the next water year raised this to 0.0924. These recent coefficient of variation in combination with the increased geometric means and standard deviations of recent years brought LEV Q 100 up to 96,000 cfs and 66,000 cfs, with and without the October 1983 event respectively. These increases above an average LEV Q 100 of about 40,000 cfs for years between 1915 and 1960, are hard to dismiss as random variability caused by sampling at different times in an unchanging river record.

Uncertainty in predicting floods.

Before closing it is essential to talk generally about how wrong the future may prove our predictions to be, even if the flood regime of a river no longer displays persistant changes. What if for instance 1965, with its "flood" of 1,190 cfs which was much smaller than any annual maximum since 1915, had not occurred. Procedures have been developed for testing whether such outliers should be eliminated before flood frequency analysis. They have not been invoked here. However, it is interesting to note that elimination of this low outlier produced a far better LEV curve, with a 100 year prediction of 83,000 cfs.

No flood frequency line can predict a design flood with the certainty by which Newton's laws of physics can determine the speed of a free-falling apple. A rudimentary discussion of confidence bands was given (Reich, 1983) for Congress Street floods. For instance, it was shown that the 1960-1984 period suggests that 5% of future 25 year records may actually produce LEV Q 100's larger than 125,000 cfs. That simple analysis also suggested that 25% of future scenarios, also on an unchanging river, could produce LEV Q 100's smaller than 80,000 cfs.

These two problems will hopefully attract academic investigation employing avant-garde statistical theory.

Conclusions

The author draws the following conclusions. They do not necessarily represent official views of the City of Tucson.

1. The Kruskal - Wallis test on annual maximum flood peaks at Tucson shows that the series prior to 1960 is significantly different to those in the most recent 25 years.

2. Flood statistics, like the geometric mean, the coefficient of skewness of their logs, LP III Q 100, and LEV Q 100 were computed for three equal sequential segments starting in 1915. All pointed to increased floods in the latest 25 years.

3. The rational course is to discard data from the 45 early year's that was collected on a physical system that others have found to have been hydraulically very different from today's. Estimation of design floods must use the most recent 25 years as a model for the future.

4. The Log Pearson Type III when tried on this recent subset curves downwards to fit the twelve smaller floods. Rather than to emulate the substantially linear trend of the nineteen larger observations, it curves 13,000 cfs below the latest flood. As a result it predicts Q 100 as 53,500 cfs compared to 52,000 cfs which was the maximum observed in these 25 recent years.

5. Method of moments fitting of the Log Extreme Value distribution describes the nine larger floods while giving minor weight to the sixteen small items which are non-linear and of no consequence for predicting rare floods. LEV estimates Q 100 as 96,000 cfs and passes through the largest observation of 52,000 cfs, to which it assigns a 40 year return period.

6. If the 1,190 cfs 1965 "flood", which is the smallest observed in 70 years, is removed from the latest 25 years as being an outlier then the coefficient of skewness of the logs becomes 0.677. This suggest Log Extreme Value to be most appropriate of the generally used flood freuency models. A good linear trend through the 19 larger floods then yields 83,000 cfs as a 100 year prediction.

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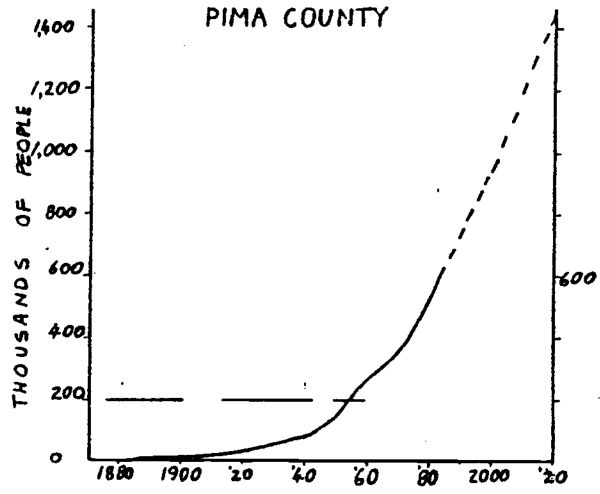

Fig. 1 Population Growth Around Tucson.

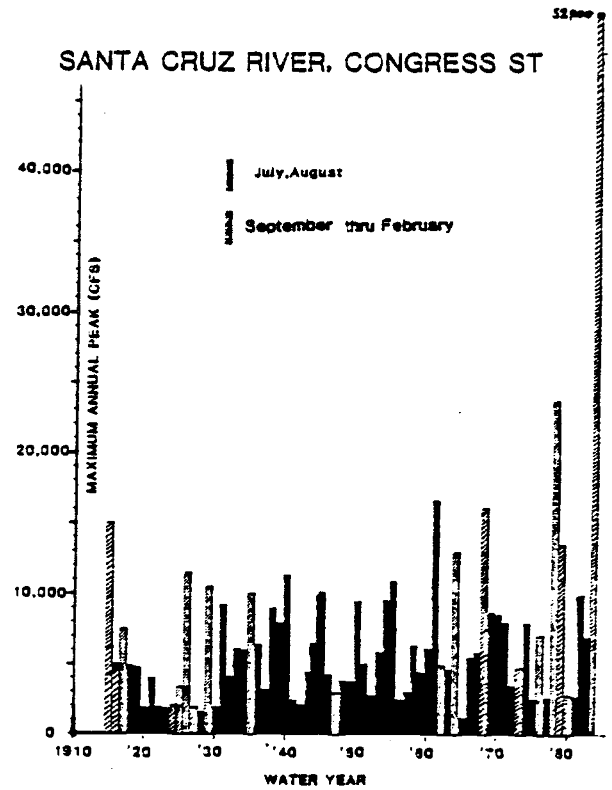

Fig. 2 Chronological Series of Floods

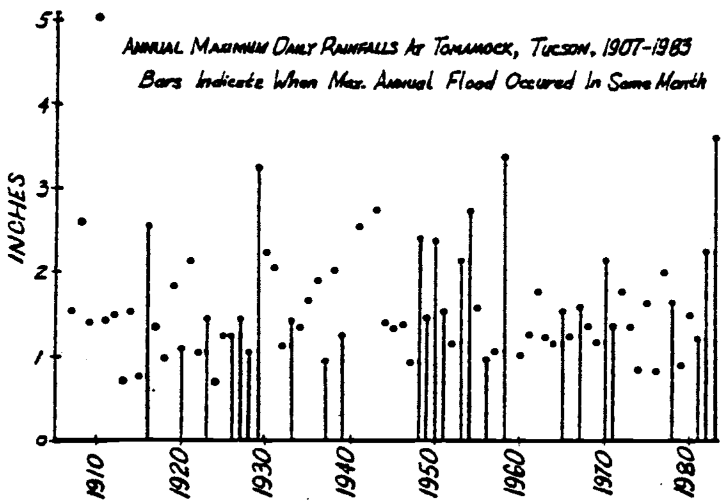

Fig. 3 Max-Annual Daily Rains, Tucson

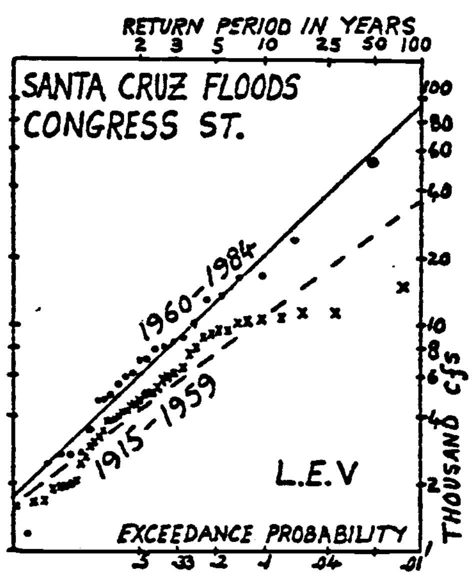

Fig. 4 Graphical Analog of Kruskal-Wallis Test shows Flood Change

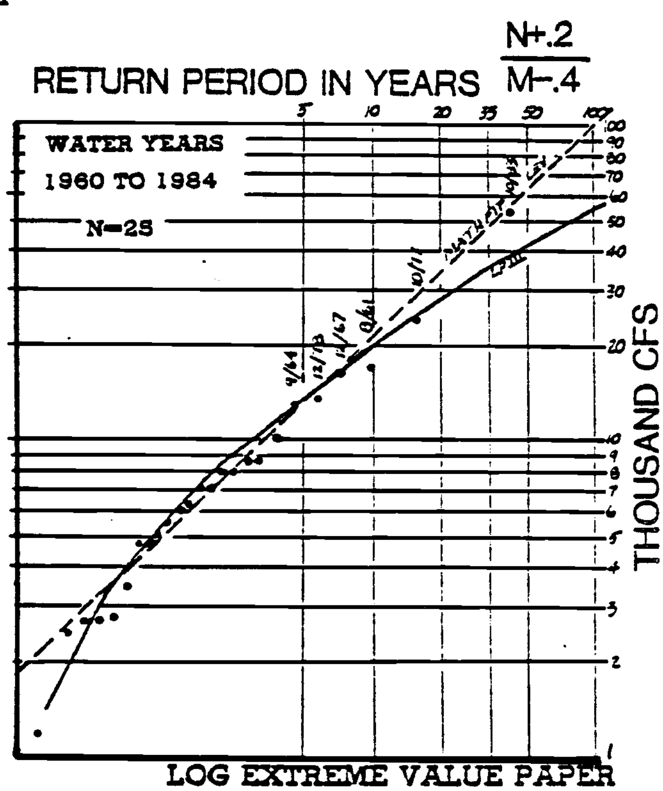

Fig. 5 Data Fitted with LPIII and LEV.