Do Record Storms Produce Floods of the Same Magnitude?

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The answer is essentially NO, among the main reasons are:

1. antecedent moisture conditions on the land surface and subsurface affect surface runoff,
2. infiltration rates (a function of land cover and subsurface hydrogeology) are independent of climatic inputs, and have a major impact on surface runoff,
3. other topographic conditions (independent of climatic inputs) affecting runoff rates are size, shape, and slope of the drainage area, slope and condition of the main stream channel and tributaries,
4. specification of storm event *duration is required* to compute the average return period for precipitation at a specific point, unlike computation of streamflow recurrence intervals,
5. geographic location of the drainage area with regard to the direction and path of storm movement and *nonuniform* rainfall over the watershed influence the contribution and concentration of areal precipitation to streamflow,
6. the size of the watershed versus the duration of the storm are influencing factors (streams with larger drainage areas require storms of longer duration for a significant increase in streamflow to occur),
7. surface/groundwater interactions influence water storage and transport,
8. regulation of streamflow upstream by control structures alters the flow, and
9. *hydrologic change* - the combined result of climate change (e.g., extreme rainfall) and *land change* (e.g., changes in land-use, land-cover patterns) over time in a nonstationary world.

"In many urbanizing watersheds, annual flood peaks are increasing due to continuous land-use changes. In such situations project designs will need to consider nonstationarity in the probability distribution of flood peaks," Salas and Obeysekera (2014). Flood nonstationarity was demonstrated in the Southeast and Mid-Atlantic Regions of the United States by Barros, *et al.*, 2014.

There are also challenges in obtaining reliable measurements of point rainfall (Sieck, Burges and Steiner, 2007), numerous uncertainties are associated with streamflow records (Kennard, *et al.*, 2010; Hamilton and Moore, 2012), and flood frequency estimation challenges (England, 2011) exist.

The objective in this paper is NOT to indicate particular distributions that can be used for design risk-level exceedance probabilities!

Storm Event and Flood Frequency Methodology

Event *average recurrence intervals* may be computed from Cunnane (1978) as follows:

$$T = \frac{n + 1 - 2\alpha}{m - \alpha}$$

where

T = average recurrence interval (e.g., in years),
n = number of peak values (e.g., number of years),
m = relative ranking of values (largest = 1), and
α = a constant (0 < α ≤ 1).

The *annual exceedance probability* (AEP) may be defined as:

$$p_n = 1 - (1 - p)^n$$

where p is the annual exceedance probability for each year. USGS software such as the **PeakFQ** computer program expresses the AEP as percent in plots of annual peak discharge (ordinate) versus the AEP in percent (abscissa). Version 7.1 of PeakFQ incorporates some of the recommendations documented in **Bulletin 17C** (England, *et al.*, 2017), such as the **Expected Moments Algorithm** (EMA; Cohn, Lane and Baier, 1997).

The General Extreme Value (GEV) probability distribution is given by:

$$F\left(x;\kappa,\alpha,\xi\right)=\exp\left[-\left\{1-\kappa\left(\frac{x-\xi}{\alpha}\right)\right\}^{1/\kappa}\right]$$

$$x(F)=\xi+\alpha\frac{\left\{1-\left(-\log F\right)^{\kappa}\right\}}{\kappa}$$

where

ξ = location parameter, α = scale parameter (> 0), and κ = shape parameter.

L-Moment techniques use linear combinations of order statistics (Hosking, 1990), and these techniques have been applied to both floods and point rainfall (Vivekanandan, 2014; Perica, *et al*., 2013).

The primary advantage of L-Moments is that they are much less influenced by the effects of sampling variability, outliers, and are virtually unbiased for small samples.

L-moments are linear functions of probability-weighted moments PWMs):

$$\beta_r = E\left\{X\left[F_X(x)\right]^r\right\}$$

where β_r is the r^{th} order PWM and $F_X(x)$ is the cumulative distribution function of X. Unbiased sample estimators of the first four PMWs are given by:

$$\beta_0 = \frac{1}{n}\sum_{j=1}^{n} X_j = mean \qquad \beta_1 = \sum_{j=1}^{n-1}\left[\frac{n-j}{n(n-1)}\right]X_{(j)}$$

$$\beta_2 = \sum_{j=1}^{n-2}\left[\frac{(n-j)(n-j-2)}{n(n-1)(n-2)}\right]X_{(j)} \qquad \beta_3 = \sum_{j=1}^{n-3}\left[\frac{(n-j)(n-j-1)(n-j-2)}{n(n-1)(n-2)(n-3)}\right]X_{(j)}$$

where $X_{(j)}$ represents the ranked Annual Maxima Series (AMS), with $X_{(1)}$ the highest value and $X_{(n)}$ the lowest value. The first four L-moments are computed as follows:

$$\lambda_1 = \beta_0 \qquad \lambda_2 = 2\beta_1 - \beta_0 \qquad \lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0$$

The L-moment ratios are calculated as follows:

$$\tau_2 = \frac{\lambda_2}{\lambda_1} \qquad \tau_3 = \frac{\lambda_3}{\lambda_2} \equiv L - skew$$

$$\tau_4 = \frac{\lambda_4}{\lambda_2} \equiv L - kurtosis$$

Computation of the precipitation depth d for a given point nonexceedance probability F is as follows (Asquith, 1998):

$$X_d(F) = \xi + \frac{\alpha}{\kappa}\left\{1 - \left[-\ln(F)\right]^{\kappa}\right\}$$

If a storm depth for a given duration is known, the storm's "point" annual nonexceedance probability can be estimated by:

$$F = \exp - \left\{1 - \frac{\kappa}{\alpha}\left[X_d(F) - \xi\right]\right\}^{1/\kappa}$$

The parameters of the GEV distribution are estimated from L-moments by:

$$Z = \frac{2}{\tau_3} - \frac{ln(2)}{ln(3)} \qquad \kappa \approx 7.8590\,Z + 2.9554\,Z^2$$

$$\alpha = \frac{\lambda_2\,\kappa}{\left(1-2^{-\kappa}\right)\Gamma\left(1+\kappa\right)} \qquad \xi = \lambda_1 + \frac{\alpha}{\kappa}\left\{\Gamma\left(1+\kappa\right)-1\right\}$$

The U.S. Water Resources Council (1967) adopted the Log-Pearson Type III distribution as the standard flood frequency distribution (peak flood discharges) to be used by **all** Federal agencies, such that the probability density function is defined as:

$$f_X\left(x\right) = \frac{1}{\alpha\,x\,\Gamma\left(\beta\right)}\left(\frac{\ln x-\gamma}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{\ln x-\gamma}{\alpha}\right)\right]$$

which states that if the logarithms (*ln* x) of variable x are distributed as a Pearson Type III variate, then the variable x is also distributed as a Log-Pearson Type III variate.

Implementation of the L-moment method for the Log-Pearson Type III distribution is as follows (Hosking, 1990):

$$F(x;\mu,\sigma,\gamma)=G\left(\frac{\left(x-\mu+\frac{2\sigma}{\gamma}\right)}{\left|\frac{1}{2}\sigma\gamma\right|},\frac{4}{\gamma^2}\right) \quad , \quad \gamma>0$$

$$F(x;\mu,\sigma,\gamma)=1-G\left(-\frac{\left(x-\mu+\frac{2\sigma}{\gamma}\right)}{\left|\frac{1}{2}\sigma\gamma\right|},\frac{4}{\gamma^2}\right) \quad , \quad \gamma<0$$

$x(F)$ not explicitly defined

$$\mathrm{G}(\mathrm{x},\alpha)=\frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t}dt$$ the incomplete gamma integral.

The Extreme-Value Type 1 (EV1) Gumbel (maximum) distribution is defined by:

$$f(x)=\frac{1}{\beta}\exp\left(-\frac{x-\mu}{\beta}\right)\exp\left[-\exp\left(-\frac{x-\mu}{\beta}\right)\right]$$

where

$\mu =$ location parameter $\quad\quad \beta =$ scale parameter

$x =$ extreme (large) value

The L-moment implementation of the EV1 is as follows:

$$F = \exp\left[-\exp\left\{-\frac{x-\xi}{\alpha}\right\}\right] \qquad x(F) = \xi - \alpha \log(-\log F)$$

$$\xi = \beta_0 - \alpha\,\gamma \qquad \gamma = 0.5772 \qquad \alpha = \frac{2\beta_1 - \beta_0}{\log 2}$$

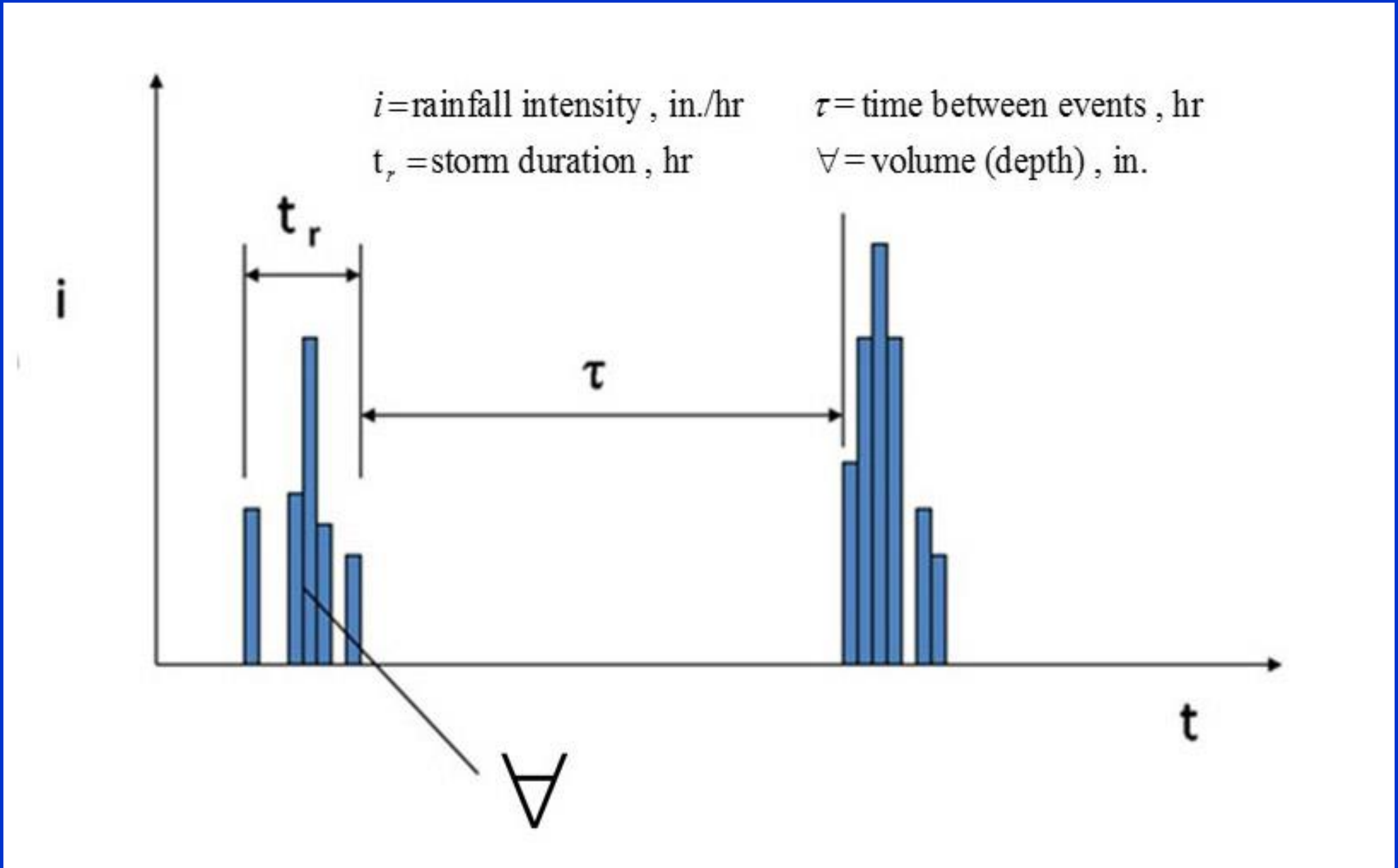
$$y = \frac{x-\xi}{\alpha} \quad \text{(reduced variate)} \qquad \mathrm{y}_T = -\ln\left[-\ln\left(1-\frac{1}{T}\right)\right]$$

The T-year event precipitation Q_T (or event flow) is then:

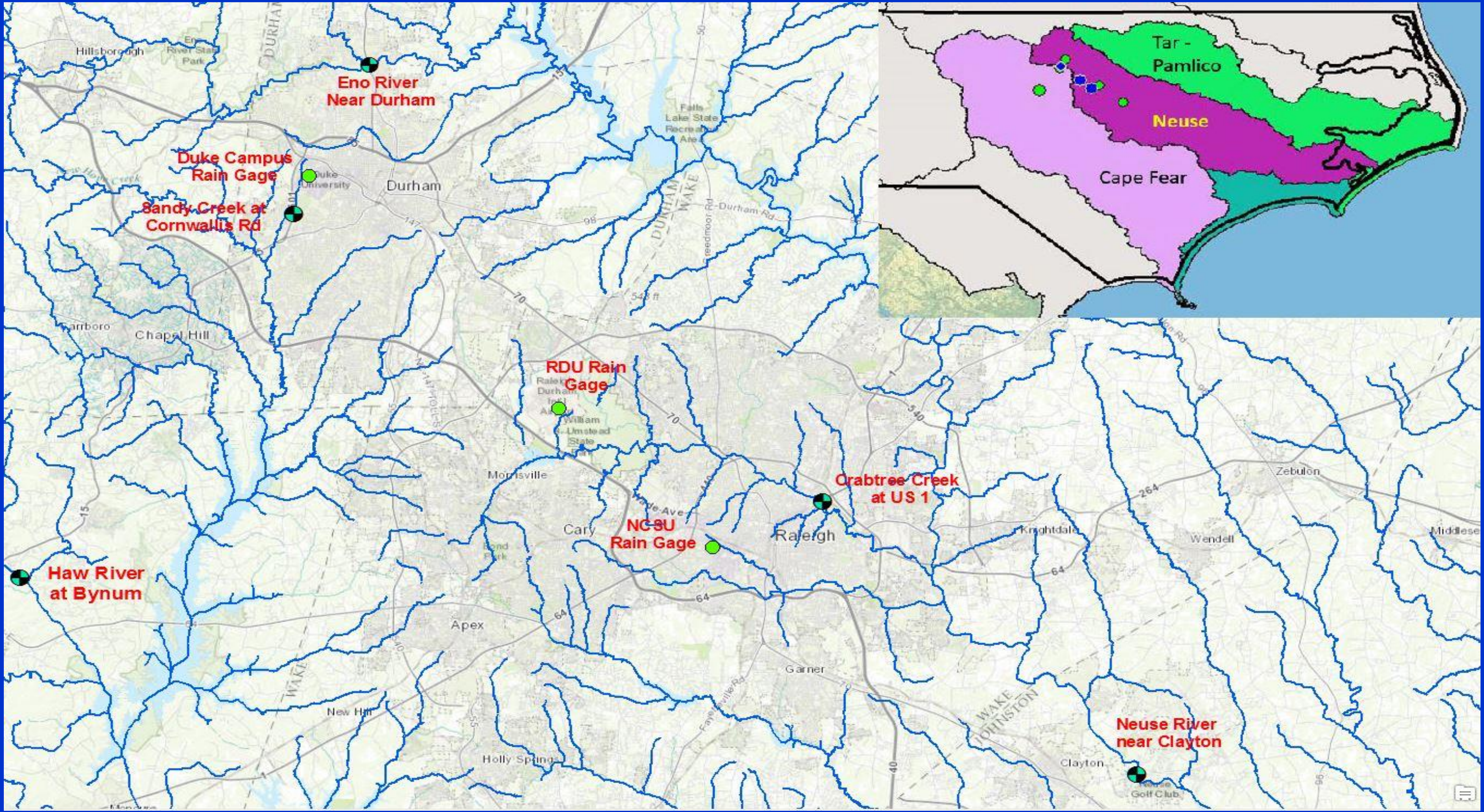
$$Q_T = \xi + \alpha\left[-\ln\left[-\ln\left(1-\frac{1}{T}\right)\right]\right]$$

where T is the return period (recurrence interval) in years.

Definition of Storm Event Variables (For Historical Long-Term Average Storm Event Analysis)



ArcGIS Map of Rainfall and Streamflow Stations in the Raleigh-Durham area



Latitude, Longitude and Elevation of Raleigh-Durham Area Stations

Gaging Station	Lat.	Long. (W)	Elev. (feet)
Rainfall:			
RDU Airport	35° 52' 00"	78° 47' 00"	416
NCSU Raleigh	35° 47' 40"	78° 41' 56"	400
Duke West Campus	36° 00' 20"	78° 56' 48"	378
Streamflow:			
Sandy Creek	35° 59' 00"	78° 57' 25"	266
Eno River, Durham	36° 04' 20"	78° 54' 28"	270
Haw River, Bynum	35° 45' 55"	79° 08' 09"	283
Crabtree Creek	35° 48' 40"	78° 36' 39"	182
Neuse River, Clayton	35° 38' 50"	78° 24' 19"	128

The *storm event average recurrence intervals* (ARIs) for the top 25 events, in terms of volume (depth), for the Raleigh-Durham International (RDU) Airport were computed and are presented in the next slide. The storm event of September 4, 1999 constitutes a record for total volume (depth, **7.45 inches**): it generated a flow of **1390 cfs** at the Eno River near Durham USGS station the next day.

Average Recurrence Intervals (ARI) for RDU International Airport, NC

Storm of 9/4/1999
Depth = 7.45 in.

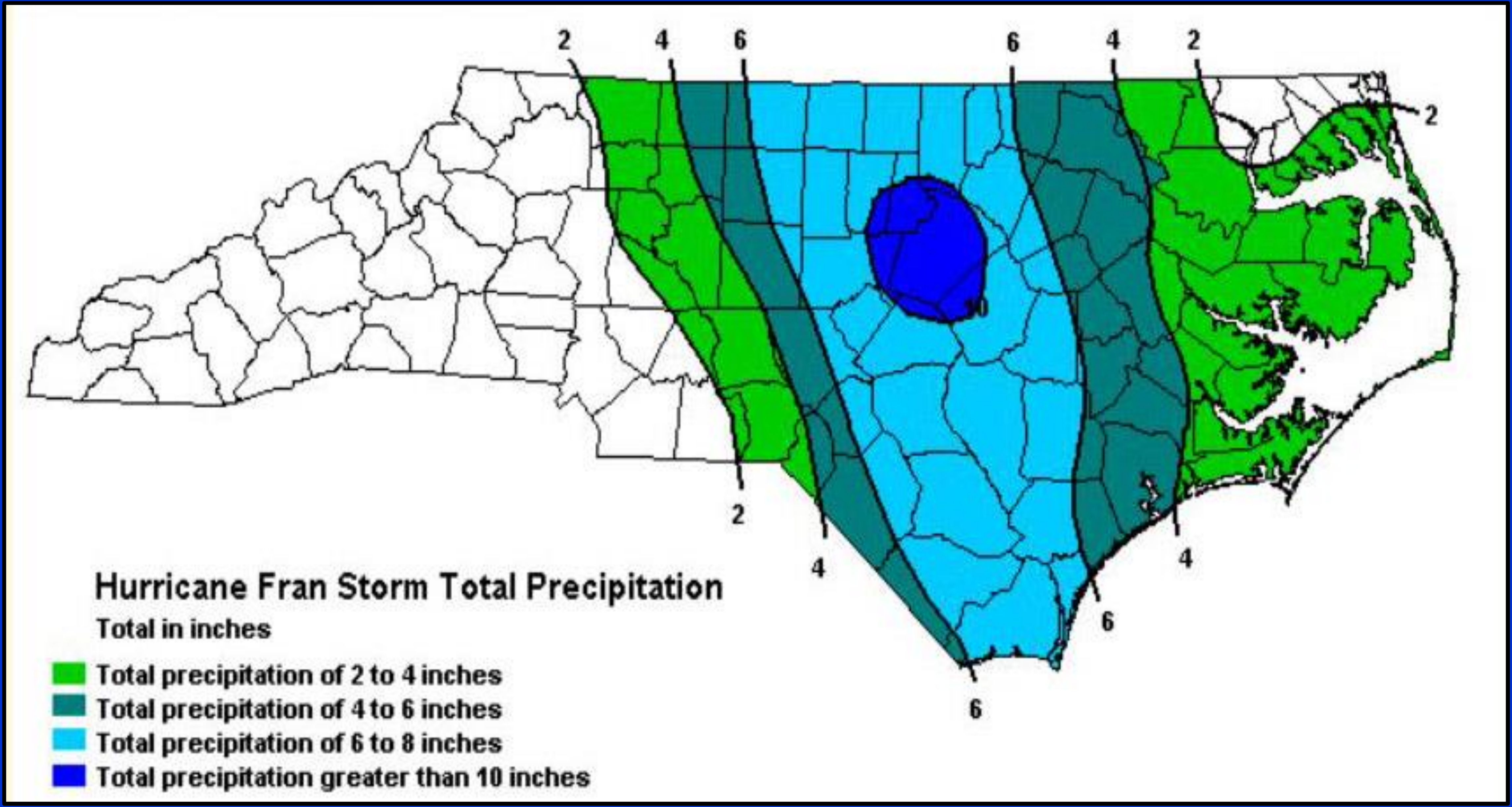
ARI (years)	Rank	Depth (in.)	Date	Time of Day	Event Hours
70.44	1	7.45	09/04/1999	14:00	44.00
36.26	2	6.44	09/14/1999	23:00	35.00
22.18	3	5.79	10/10/2002	19:00	27.00
19.63	4	5.64	06/14/2006	3:00	13.00
17.91	5	5.53	06/06/2013	12:00	29.00
16.03	6	5.4	08/16/1955	18:00	34.00
13.32	7	5.19	09/05/2008	15:00	21.00
10.28	8	4.91	11/05/1963	17:00	37.00
9.80	9	4.86	04/25/1978	6:00	54.00
9.70	10	4.85	10/04/1995	8:00	27.00
6.50	11	4.45	11/10/2009	10:00	67.00
6.23	12	4.41	03/17/1998	16:00	43.00
6.17	13	4.4	05/11/1957	11:00	18.00
5.60	14	4.31	08/06/2011	4:00	7.00
5.25	15	4.25	07/23/1997	23:00	13.00
4.87	16	4.18	08/20/1986	6:00	11.00
4.46	17	4.1	10/14/1954	24:00	16.00
4.27	18	4.06	09/04/2006	20:00	7.00
3.99	19	4	11/20/1985	13:00	55.00
3.64	20	3.92	10/13/1994	13:00	32.00
3.40	21	3.86	03/17/1983	2:00	39.00
3.25	22	3.82	11/09/1962	6:00	21.00
2.93	23	3.73	11/12/1975	19:00	10.00
2.93	24	3.73	08/12/1992	16:00	10.00
2.80	25	3.69	08/26/2008	14:00	36.00

Point Precipitation Frequency Estimates for RDU International Airport (NOAA, 2017)

PRECIPITATION FREQUENCY ESTIMATES										
by duration for ARI (years):	1	2	5	10	25	50	100	200	500	1000
5-min:	0.4	0.46	0.53	0.59	0.65	0.69	0.73	0.76	0.8	0.82
10-min:	0.63	0.74	0.85	0.94	1.03	1.1	1.16	1.21	1.26	1.29
15-min:	0.79	0.93	1.08	1.19	1.31	1.39	1.47	1.52	1.58	1.62
30-min:	1.08	1.28	1.53	1.73	1.94	2.1	2.24	2.37	2.52	2.63
60-min:	1.35	1.61	1.96	2.25	2.58	2.84	3.09	3.32	3.62	3.84
2-hr:	1.56	1.87	2.3	2.65	3.09	3.44	3.77	4.11	4.53	4.86
3-hr:	1.65	1.98	2.45	2.84	3.35	3.76	4.17	4.58	5.13	5.58
6-hr:	2	2.4	2.96	3.44	4.07	4.59	5.11	5.64	6.36	6.95
12-hr:	2.37	2.84	3.52	4.12	4.9	5.57	6.24	6.94	7.9	8.72
24-hr:	2.83	3.42	4.28	4.95	5.86	6.57	7.3	8.05	9.06	9.85
2-day:	3.26	3.92	4.87	5.6	6.58	7.34	8.12	8.91	9.97	10.79
3-day:	3.45	4.14	5.11	5.87	6.89	7.7	8.51	9.34	10.46	11.33
4-day:	3.64	4.36	5.36	6.15	7.21	8.05	8.91	9.78	10.96	11.87
7-day:	4.22	5.03	6.11	6.96	8.12	9.04	9.98	10.93	12.22	13.22
10-day:	4.8	5.7	6.85	7.74	8.95	9.9	10.85	11.82	13.12	14.12
20-day:	6.41	7.56	8.93	10.01	11.48	12.65	13.81	15	16.61	17.85
30-day:	7.95	9.35	10.86	12.04	13.59	14.77	15.95	17.13	18.69	19.88
45-day:	10.15	11.88	13.59	14.92	16.65	17.96	19.25	20.52	22.18	23.44
60-day:	12.19	14.21	16.03	17.44	19.25	20.62	21.93	23.2	24.83	26.04

Through application of **NOAA Atlas 14, Volume 2, Version 3 online** (NOAA, 2017), the storm event of 9/4/1999 would rank **near a 50-yr event** (7.34 inches) **for a 48-hr duration**. An estimate applying the Generalized Extreme Value Distribution (GEV) fitted using L-moments (Hosking, 1990) yielded **6.91 inches** for a **50-yr return period**.

Areawide Precipitation Totals from Hurricane Fran : 9/6/1996



Hurricane Fran precipitation at RDU was not ranked within the top 100 point rainfall events. Record flooding at downstream streamflow gauging stations was caused by extensive areawide precipitation contribution.

A Type I Extreme value (EV1) frequency analysis using L-moments ranks a **50-yr flood** as having a flow of **20,232 cfs** at the Neuse River near Clayton station, and a Pearson Type III **50-yr flood** value of **19,588 cfs was calculated (**observed peak of **19,700 cfs).**

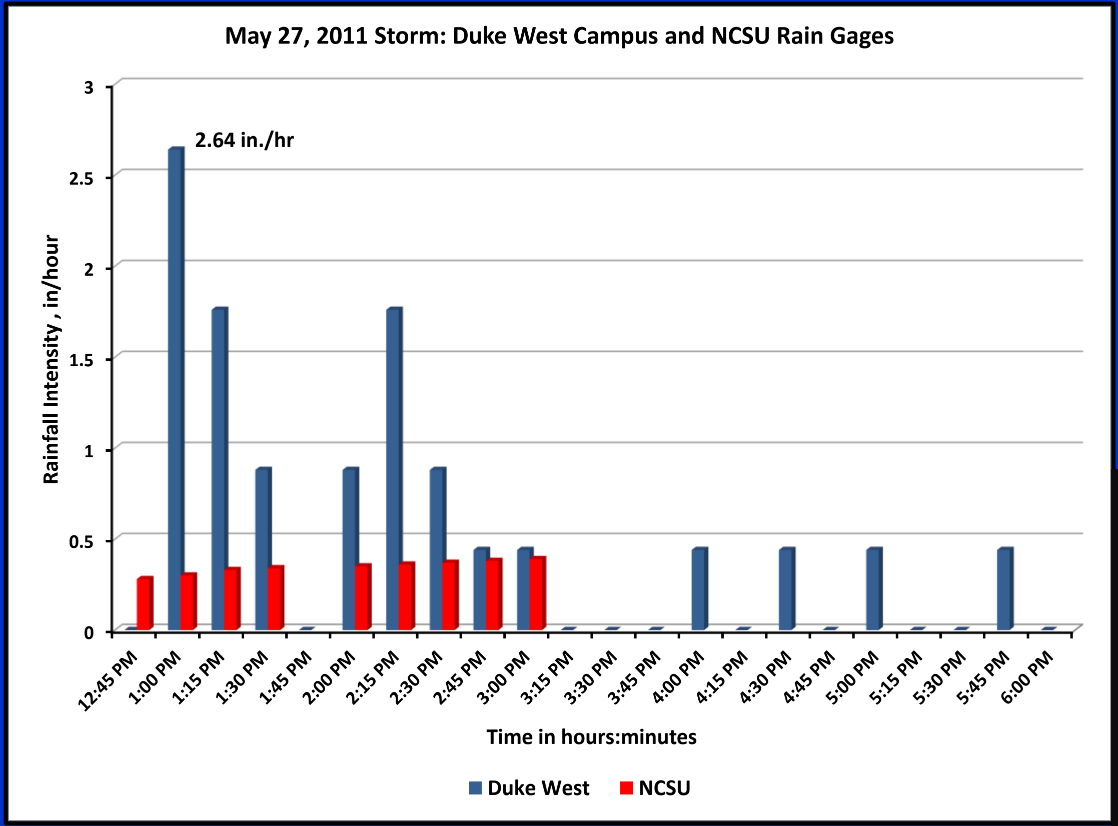
Storm of 5/27/2011 tied record highest intensity: 2.64 in./hour

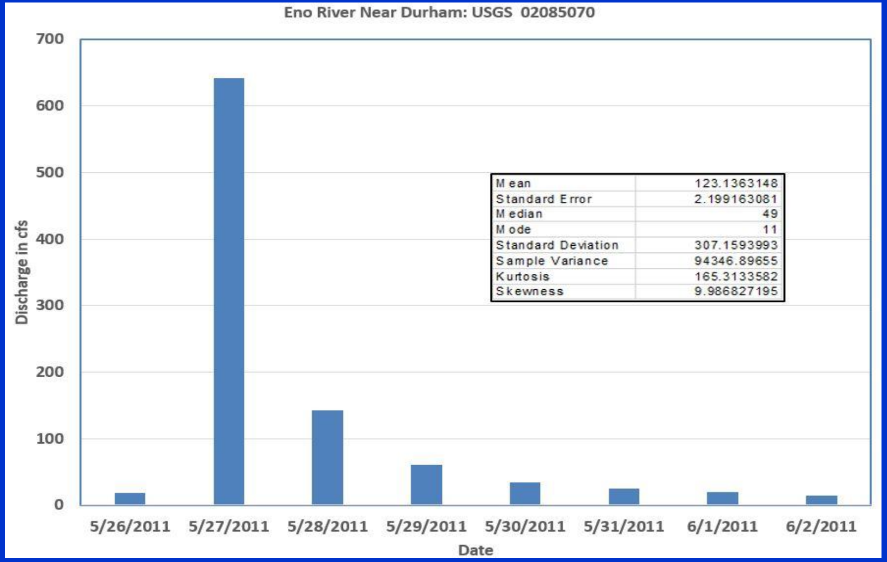
Average Recurrence Intervals for Storms and Floods Generated Subsequently

Rainfall/Stream Station	Storm Event - Duration	ARI, yrs. [in.]	Flood	Distribution, ARI (yrs.) [cfs]
RDU Airport	9/4/1999 - 48 hrs.	**50 [7.45]**		
Eno River (Durham)			9/5/1999	**LPIII, <2 [1390]**
Crabtree Creek			9/4/1999	**LPIII, 2 [3500]**
RDU Airport	9/6/1996 - 24 hrs.	**No rank**[1] **[8.8]**		
Eno River (Durham)			9/6/1996	**LPIII, 50 [14700]**
Eno River (Durham)			9/6/1996	**EV1, 100**
Eno River (Durham)			9/6/1996	**PeakFQ, 100**
Haw River (Bynum)			9/6/1996	**LPIII, 100 [76700]**
Haw River (Bynum)			9/6/1996	**EV1, 150**
Haw River (Bynum)			9/6/1996	**PeakFQ, 100**
Crabtree Creek			9/6/1996	**LPIII, 50 [12700]**
Neuse River (Clayton)			9/7/1996	**EV1, 50 [19700]**
Neuse River (Clayton)			9/7/1996	**LPIII, 50**
Duke West Campus	5/27/2011 - 6 hrs.	**< 5 [2.97]**		
Eno River (Durham)			5/27/2011	**LPIII, <<2 [642]**

[1] Note: Storm event is **not ranked within the top 100 point rainfall events**. Large flooding caused by **concentration** of extensive areal precipitation upstream of streamflow gage location.

A Log Pearson Type III frequency analysis using L-moments ranks a **50-yr flood** as having a flow of **14,200 cfs** at the Eno River (observed peak was 14,700 cfs).





Mean	123.1363148
Standard Error	2.199163081
Median	49
Mode	11
Standard Deviation	307.1593993
Sample Variance	94346.89655
Kurtosis	165.3133582
Skewness	9.986827195

Daily streamflow jumped **from 19 cfs the previous day to 642 cfs on May 27, 2011** at the Eno River near Durham gauging station (USGS 02085070).

Local urban flooding was **much more severe** than that generated from Hurricane Fran.

Heavy rains flood Durham businesses

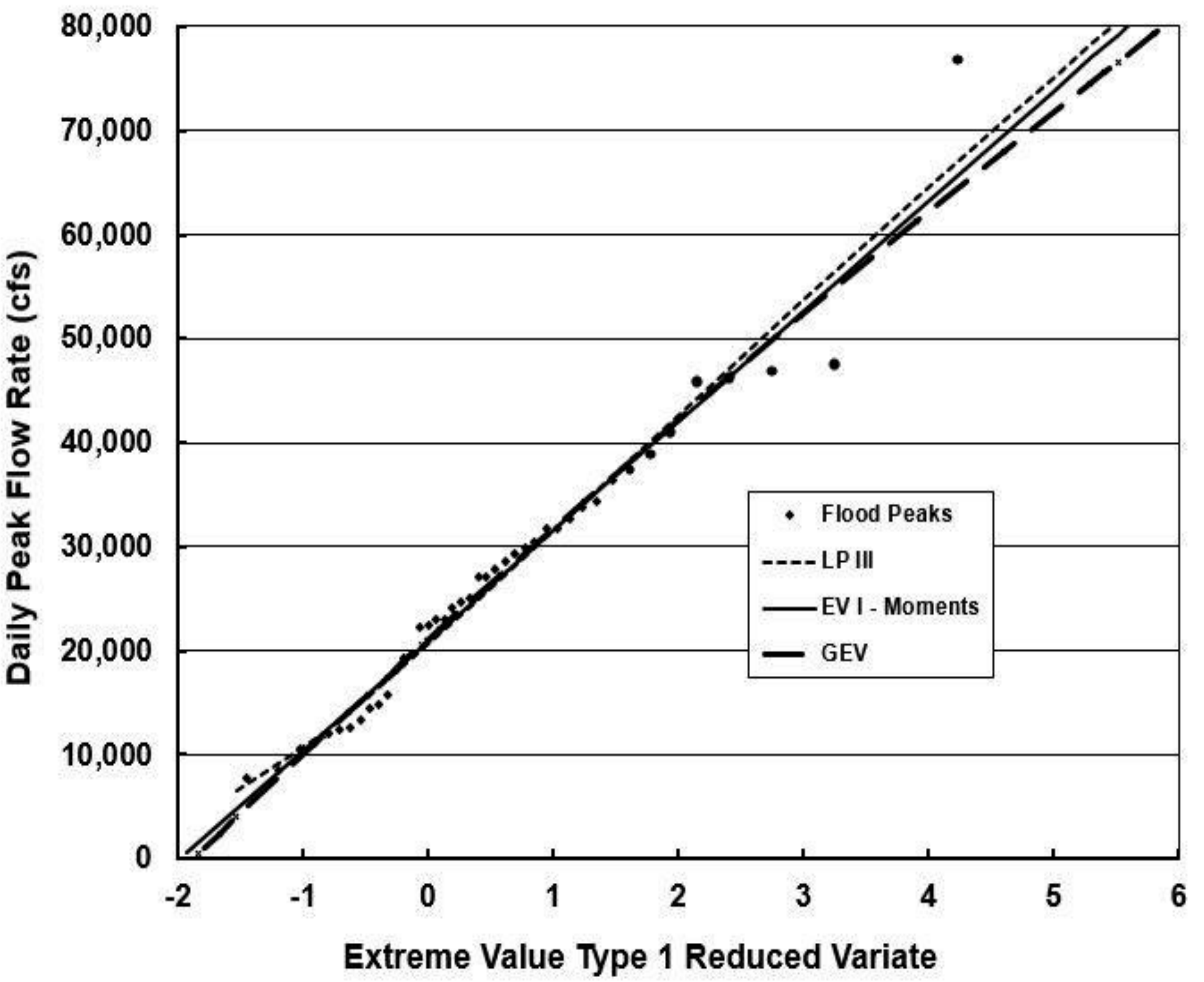
Source:
WRAL-TV Raleigh, NC

Heavy rains caused flooding in Durham on May 27, 2011.

A plot of daily peak flow rates for the Haw River at Bynum versus the EV1 reduced variate:

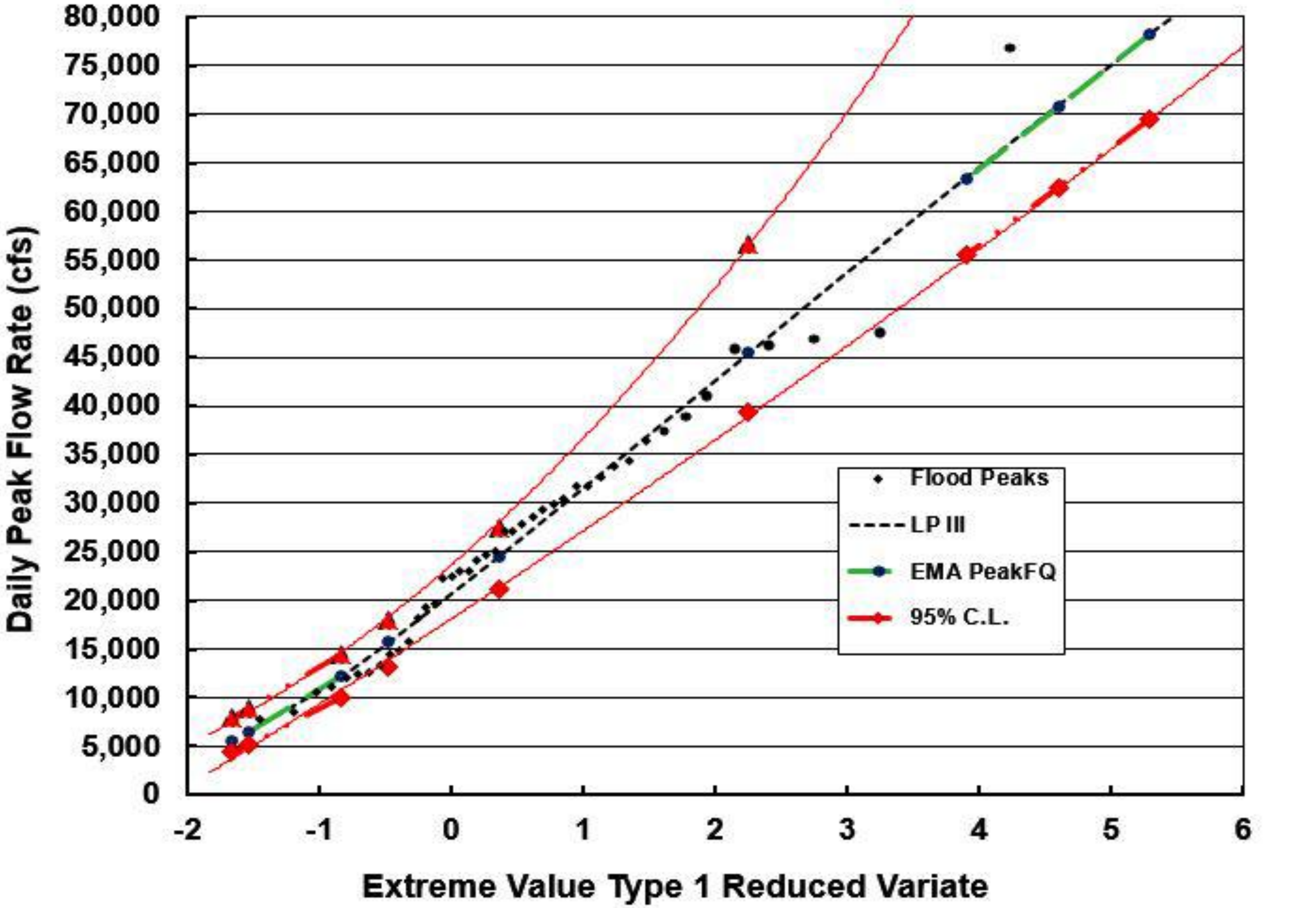
$$y = \frac{x - \xi}{\alpha}$$

shows good results for the distribution choices.



Flood Frequency - Annual Maximum Peak Flow Rates, Haw River At Bynum, NC, USGS Sta 02096960, 1974-2016.

Results of applying PeakFQ using the EMA option for the Haw River at Bynum, NC.: daily peak flow rates are plotted versus the EV1 reduced variate, including the 95 % confidence limits.



Flood Frequency - Annual Maximum Peak Flow Rates, Haw River At Bynum, NC, USGS Sta 02096960, 1974-2016.

Rain gauges and a streamflow station for the Lower Pecos River, near Shumla, TX.

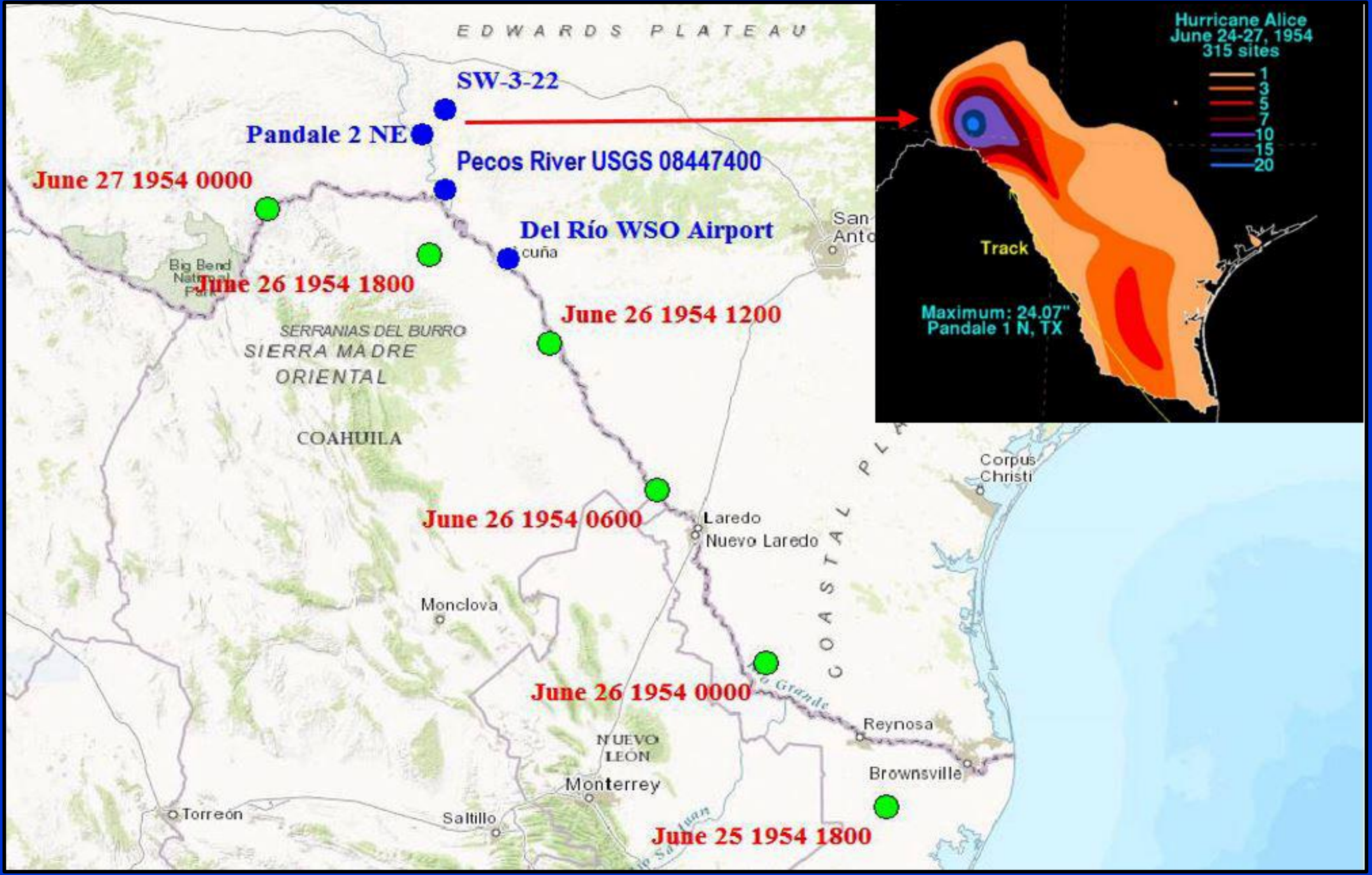
Gaging Station	Lat.	Long. (W)	Elev. (feet)	Record Length
Rainfall:				
SW-3-22*	30° 22' 00"	101° 23' 00"	2244	6/23-28/1954
Pandale 2 NE	30° 12' 00"	101° 33' 00"	1646	1909-1994
Del Río WSO Airport	29° 22' 00"	100° 55' 00"	1168	1906-1994
Streamflow:				
USGS 08447400	29° 50' 00"	101° 23' 00"	1159	1900-1966
*Note: USACE SW Division				

The path of Hurricane Alice from June 25-26, 1954 is illustrated in the next slide: it resulted in significant areal precipitation just upstream of the Pecos River near the Shumla gauging station (USGS 08447400), dropping a point maximum amount of 15.5-16.02 inches in 24 hours at Pandale, Texas (27.1 inches in 48 hours, Weather Bureau, 1954), and 29.2 inches in 24 hours at SW-3-22.

Hurricane Path, Rain Gauges and Pecos River Streamflow station near Shumla, Texas

Less concentration and contribution of areal precipitation upstream of the Pecos River USGS streamflow gauging station …

The computation of point precipitation depth at the Pandale 2 NE station and at SW-3-22 are presented in the next slide. Asquith (1998) and Asquith and Roussel (2004) determined that the GEV distribution was the best fit for storm durations from 1 to 7 days for Texas.



No NOAA Atlas 14 Point Precipitation Frequency Estimates for Texas!

Point Precipitation Depth at Pandale Using GEV and L-Moments

GEV	L-Moments		26-Jun-54		
Duration: 1-day			Recorded		
Station:	Lat.	Long.	24-hr Rainfall		
Pandale 2 NE	30° 12' 00"	100° 55' 00"	16.02		
Xi	Alpha	K	T (years)	F	X_d (in.)
2.5	1	-0.219	100	0.990	10.44
			200	0.995	12.50
			250	0.996	13.23
			300	0.997	13.85
			400	0.998	14.89
			500	0.998	15.74
			540	0.998	16.04

Point Precipitation Depth at SW-3-22 Using GEV and L-Moments

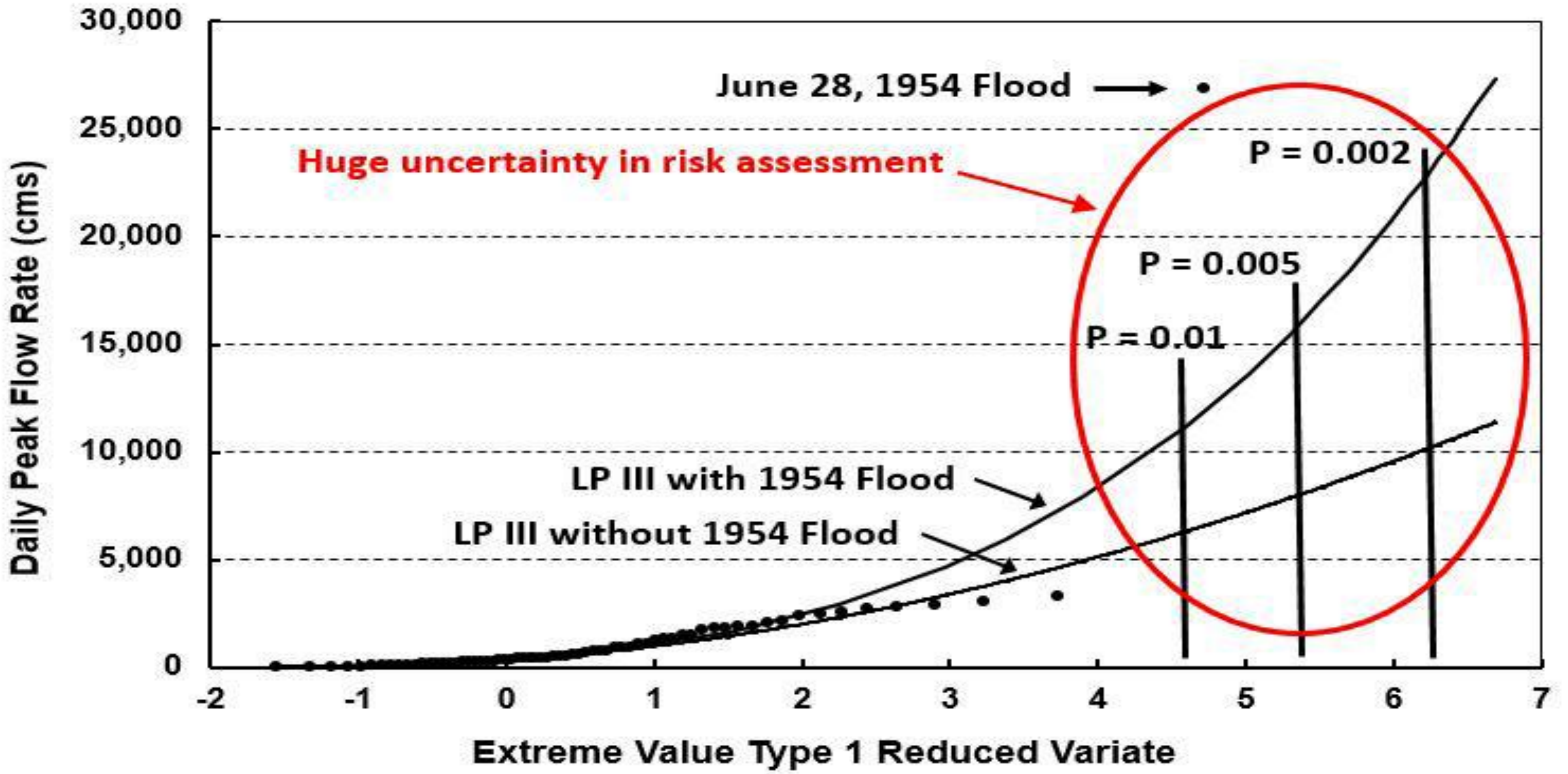
GEV	L-Moments		27-Jun-54		
Duration: 1-day			Reported		
Station:	Lat.	Long.	24-hr Rainfall		
SW-3-22	30° 22' 00"	-101° 23' 00"	29.2		
Xi	Alpha	K	T (years)	F	X_d (in.)
2.5	1	-0.219	100	0.990	10.44
			200	0.995	12.50
			250	0.996	13.23
			300	0.997	13.85
			400	0.998	14.89
			500	0.998	15.74
			1000	0.999	18.66
			2000	1.000	22.06
			3000	1.000	24.30

Sources:

Asquith, William H., 1998, “Depth-Duration Frequency of Precipitation for Texas,” U.S.G.S. Water-Resources Investigations Report 98-4044, Austin, Texas.

Asquith, W. H. and M. C. Roussel, 2004, “Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas,” U.S. Geological Survey Scientific Investigations Report 2004–5041, Denver, Colorado.

Uncertainty in Risk Assessment (modified after Burges, 2016)



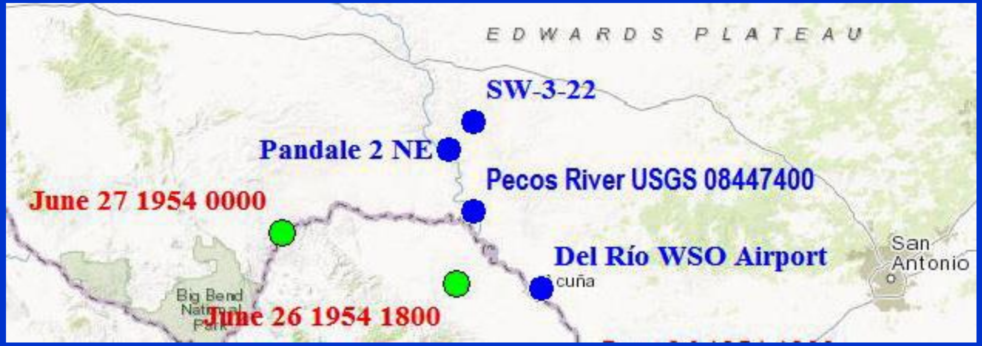
Flood Frequency - Annual Maximum Peak Flow Rates, Pecos River Near Shumla, TX, USGS Gauge 08447400, 1900-1966.

Rainfall/Stream (NC)	Storm Event - Duration	ARI, yrs. [in.]	Flood	Distribution, ARI, yrs. [cfs]
RDU Airport	9/4/1999 - 48 hrs.	**50 [7.45]**		
Eno River (Durham)			9/4/1999	**LPIII, <2 [1,390]**
Crabtree Creek			9/4/1999	**LPIII, 2 [3,500]**
RDU Airport	9/6/1996 - 24 hrs.	**No rank [8.8]**		
Eno River (Durham)			9/6/1996	**EV1, 100 [14,700]**
Eno River (Durham)			9/6/1996	**PeakFQ, 100**
Eno River (Durham)			9/6/1996	**LPIII, 50**
Haw River (Bynum)			9/6/1996	**LPIII, 100 [76,700]**
Haw River (Bynum)			9/6/1996	**EV1, 150**
Haw River (Bynum)			9/6/1996	**PeakFQ, 100**
Crabtree Creek			9/6/1996	**LPIII, 50 [12,700]**
Neuse River (Clayton)			9/7/1996	**LPIII, 50 [19,700]**
Neuse River (Clayton)			9/7/1996	**EV1, 50**
Duke West Campus	5/27/2011 – 6 hrs.	**< 5 [2.97]**		
Eno River (Durham)			5/27/2011	**LPIII, <<2 [642]**
Rainfall/Stream (Texas)	**Storm Event - Duration**	**ARI, yrs. [in.]**	**Flood**	**Distribution, ARI, yrs. [cfs]**
Pandale 2 NE	06/26/1954 24 hrs.	**540 [16.02]**		
SW-3-22	06/27/1954 24 hrs.	**3000 [29.2]**		
USGS 08447400			06/26-27/1954	**LPIII, 800 [948,000]**
			06/26-27/1954	**PeakFQ, 500**

Summary of Average Recurrence Intervals (years) for Storms [in.] and their Floods [cfs] produced downstream. Distributions used are noted.

The Expected Moments Algorithm (EMA) was applied to the LPIII distribution to compute the Annual Exceedance Probability (AEP) in PeakFQ .

Bulletin 17C (England, *et al.*, 2017)



Summary and Conclusions

Although many experienced hydrologists have suspected that record extreme storm events do not necessarily generate extreme floods of the same magnitude, this fact has been quantitatively demonstrated in this paper for several events at multiple locations. All the statistical computations using L-moments were confirmed with independent codes (.e.g., Excel built-in functions, FORTRAN codes, etc.). The USGS streamflow gauging stations used in the analysis were chosen by downstream proximity to the rain gauge stations, with results presented for riverine segments unaltered by flow regulation. The floods generated by Hurricanes Fran (North Carolina) and Alice (Texas) were influenced by concentrated areal precipitation, particularly for Hurricane Fran. In the case of Hurricane Alice near Pandale, Texas (and Station SW-3-22 further northeast), the storm event point precipitations were extreme, but it appears that there was much less concentration and contribution of areal precipitation upstream of the Pecos River USGS streamflow gauging station near Shumla, Texas than for Hurricane Fran upstream of the Raleigh-Durham area streamflow gauging stations.

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