BALLPARK PMFs

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Abstract

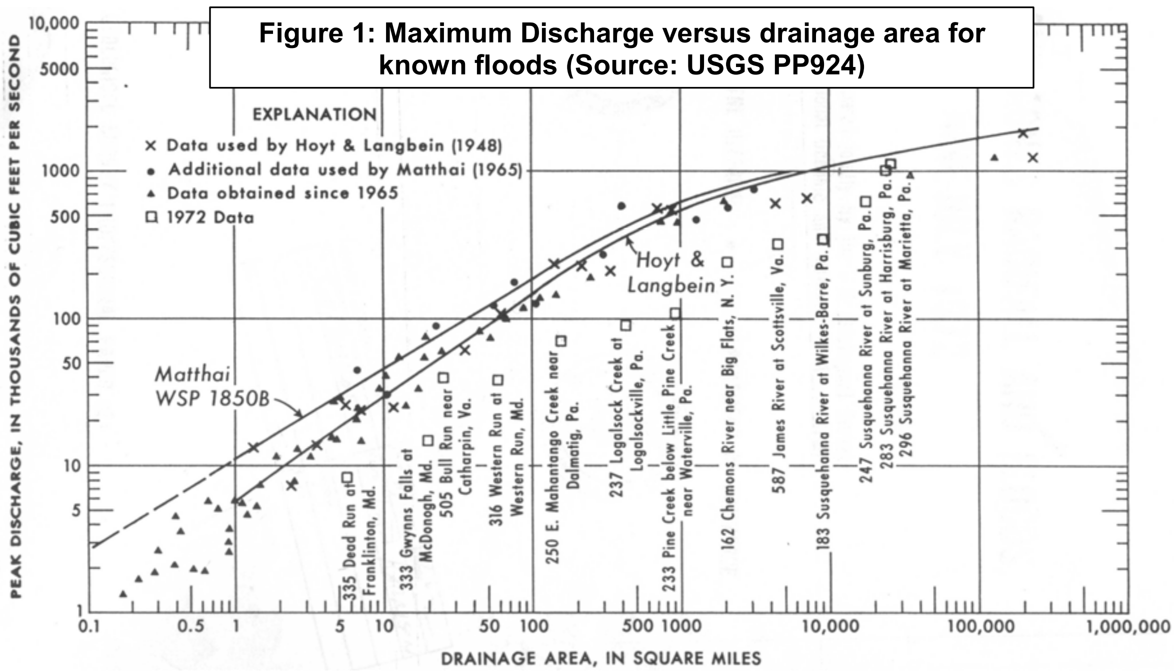
In preliminary studies and proposals, it is often useful to estimate the Probable Maximum Flood (PMF) as a basis for developing a plan of action. Conversely, when any type of engineering analysis is performed, it is useful to have a check to compare against for reasonableness. This paper will provide graphical relationships of approximate PMF discharge versus drainage area for three hydrologically similar regions in the U.S.

Introduction

Of interest to hydrologists is the ability to derive predictive relationships for various frequency floods. The derived relationships are always found to be based primarily on drainage area size. In their National Flood Frequency Program, the USGS, has developed equations for prediction of the 2-yr through 500-yr flood events for each state, many of which are broken into several subregions that incorporate local variations in topography, rainfall, geology, etc.

Of interest to dam engineers and owners is the ability to predict extreme flood events that typically exceed those estimated by the USGS. Figure 1 below is an example of envelope curves developed by Hoyt & Langbein, Matthai, and supplemented by the USGS (1972).

Figure 1: Maximum Discharge versus drainage area for known floods (Source: USGS PP924)



Of note in this figure is the power relationship (linear on log-log plot) of maximum peak discharge versus drainage area up to an area of between 500 and 1000 square miles, at which point the slope of the envelope curve changes significantly. Another interesting flood study was conducted by O'Connor and Costa (USGS, 2003) entitled "Large Floods in the United States: Where They Happen and Why." In that report, they plot the largest annual flows from each of the 22,063 streamflow stations in the U.S. and Puerto Rico (Figure 2). The points above the red line in this figure represent the largest 13 percent of flows relative to drainage area. Similar to Figure 1, Figure 2 indicates a break in slope at a drainage area of approximately 1000 square miles. This decrease in slope may reflect limits in storm size and rainfall rates in the U.S., where there is a marked dropoff in rainfall depth for storms with areas greater than 1,000 mi^2 and durations greater than 6 hours (O'Connor and Costa). The equations for these lines are:

$$Q>1{,}000A^{0.667} \text{ for } A<1{,}000; \text{ and}$$

$$Q>10{,}000A^{0.333} \text{ for } A>1{,}000$$

where Q is peak discharge (cfs) and A is drainage area in square miles (O'Conner & Costa). The stations recording these largest flows are shown in Figure 3. Of note are the concentrations of relatively large flows in certain regions of the U.S. Three of these regions were selected for further study in this paper, namely the central and northern Appalachians, and south central Texas. These three regions approximately correspond to Regions 4, 5 and 10 utilized in studies by Crippen & Bue (1977). Floods in these regions are influenced by subtropical moisture from the Gulf of Mexico and the Atlantic Ocean, and are also closely linked to topography: the Appalachian Mountains of the eastern United States, and the Balcones Escarpment region in south central Texas. These regions were selected given their propensity to produce large unit discharges for any given drainage area, and the resulting greater availability of data.

Figure 2 : Largest annual flow from each of 22,063 streamflow stations in U.S. and Puerto Rico (Source USGS Circular 1245)

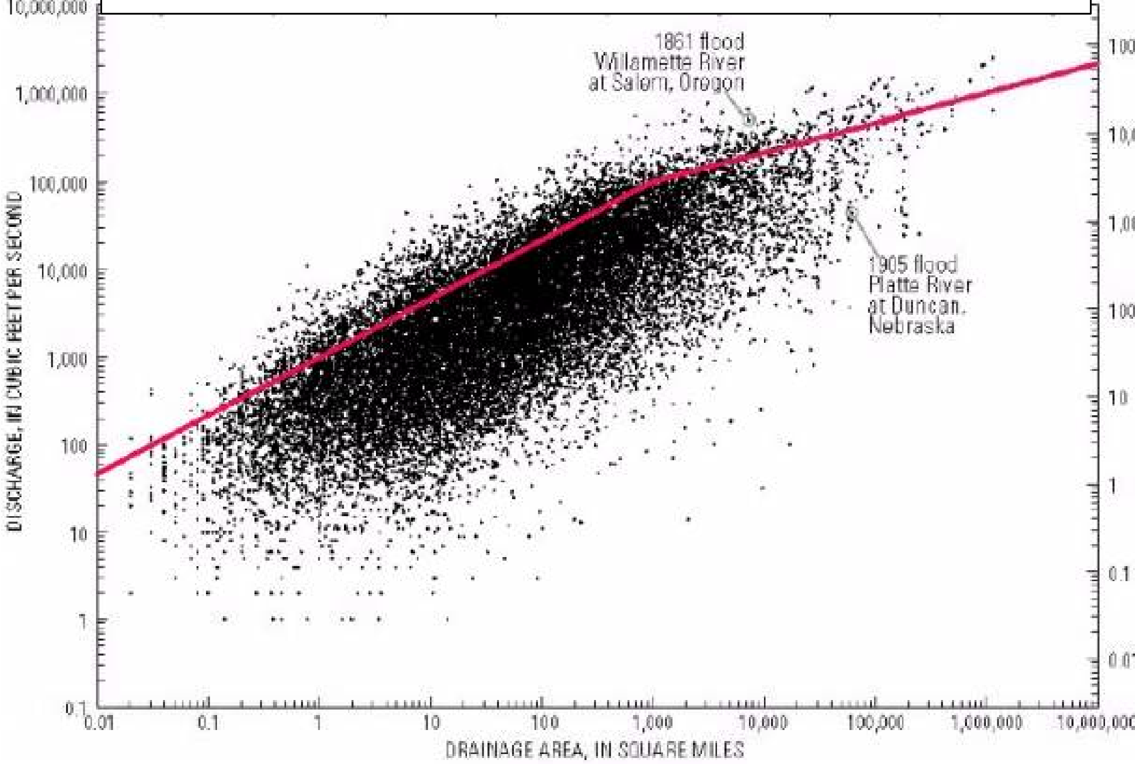
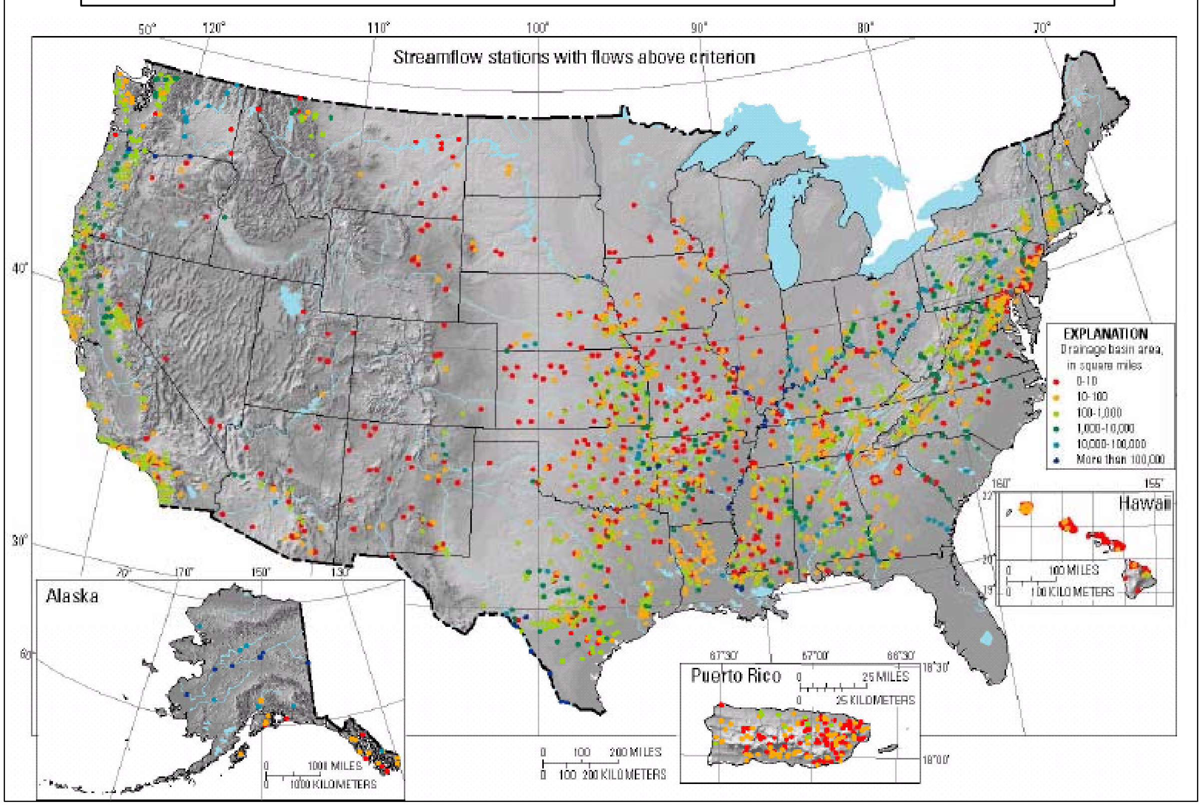


Figure 3 : Location of stations above line in Figure 2 (Source USGS Circular 1245)



The incidence of high magnitude flooding is greater in the Balcones Escarpment area than in any other region of the United States. Principal among these factors are 1) the intensity of sporadic rainstorms, especially those related to tropical storms and hurricanes; and 2) the rapidity of runoff from the steep bedrock slopes that characterize much of the region (Caran and Baker, 1986).

In the Appalachian regions, factors influencing the magnitude of flooding are 1) the typical range of the southern limit of the jet stream in the summer months, where fronts occasionally stall for an extended time, 2) proximity to the Atlantic Ocean, and 3) topographic relief.

Historic Data and Previous Studies

Data from the previously referenced O'Connor and Costa study (highest 10% flows) was obtained, as well as extreme peak flow measurements at ungaged locations by other agencies (listed in Bureau of Reclamation's paper entitled *Comparison of Estimated Maximum Flood Peaks with Historic Floods* (Bullard, 1986). Given the relatively small number of gaging stations compared to the total number of watersheds in the U.S., it is typical that the highest unit discharge occurring on a particular stream will occur at some location other than at the gage.

Crippen & Bue developed envelope curves for 17 different hydrologic regions of the conterminous United States (Figure 4). Although topographic and geologic characteristics within a given region can vary significantly, these region boundaries provide a convenient means of comparing floods in generalized regions. For comparison, the three hydrologic regions studied in this paper are presented together in Figure 5. This figure presents the USGS' highest 10% flows (nationally) that fall into each of the three regions, plus other observed extreme events from Bullard's paper. This data was plotted together with the Crippen & Bue envelope curves.

Figure 4 : Crippen & Bue's Hydrologic Regions

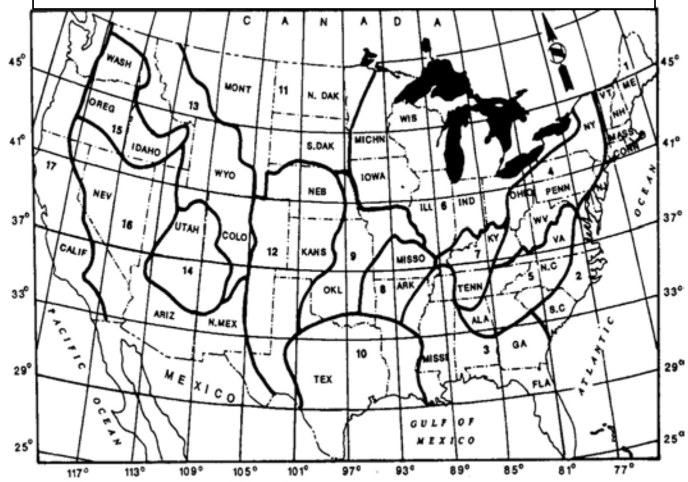
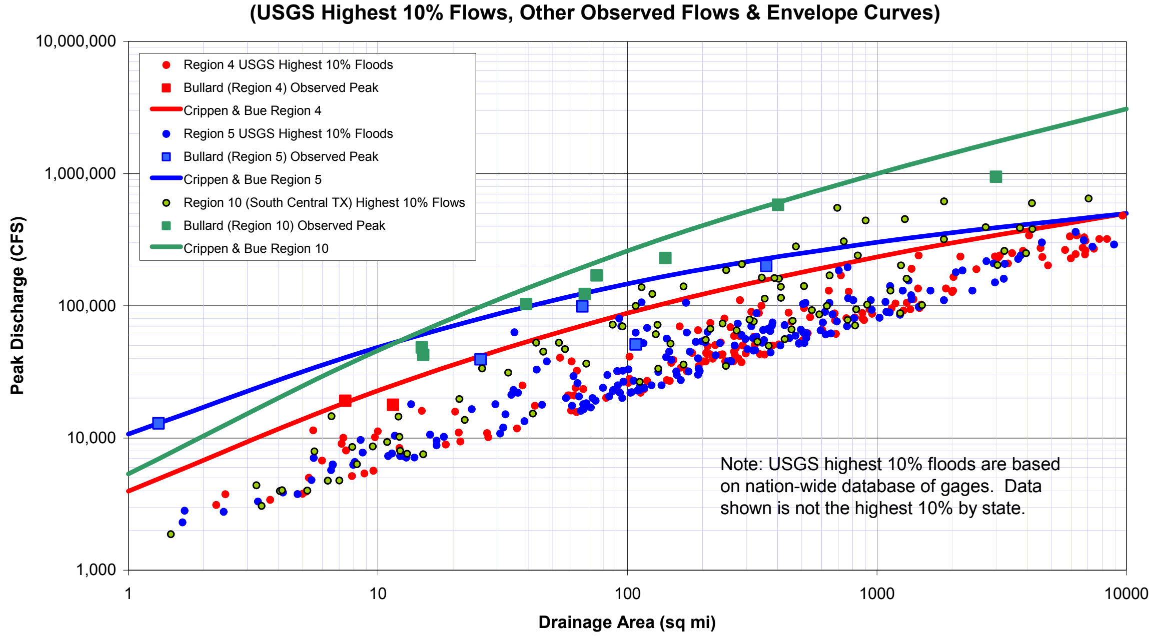


Figure 5: Peak Discharge vs Drainage Area
(USGS Highest 10% Flows, Other Observed Flows & Envelope Curves)

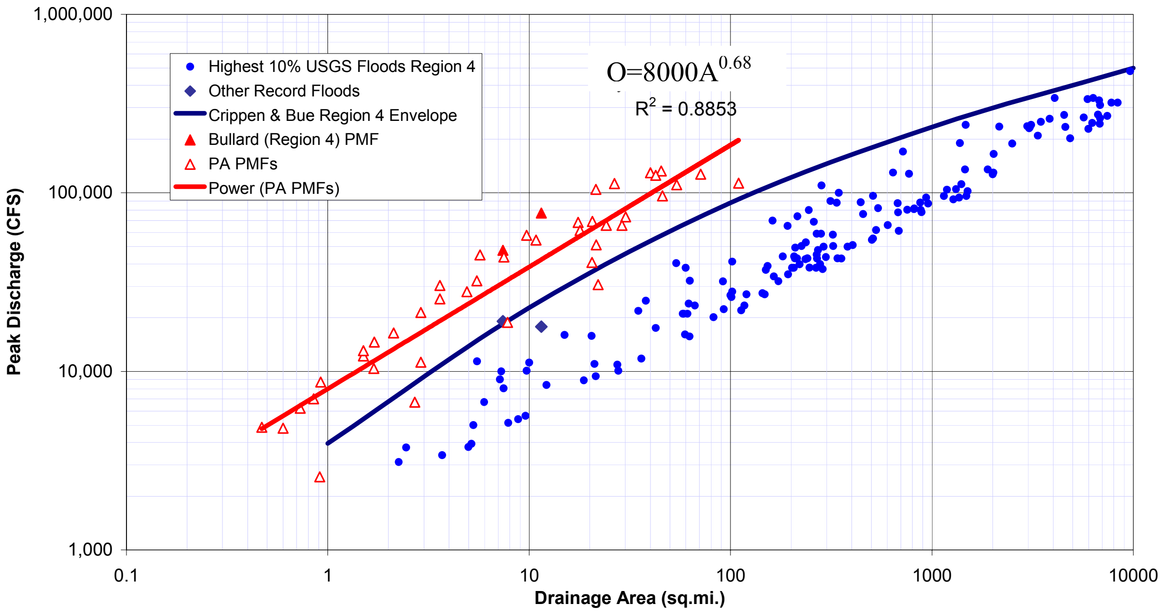


As can be observed from the figure, the envelope curves provide a relatively good depiction of the maximum observed events within each region. Also of note in the figure, Region 5 exceeds the other two regions (and in fact all other hydrologic regions) at the low end of the scale. This is due to an extreme observed event of 12,900 cfs for a drainage area of 1.32 square miles at Big Creek near Waynesville, NC (1940). That flood is also the control point at the low end for Matthai's curve in Figure 1.

Comparison of Historic Data to Estimated PMFs

Observed floods and envelope curves were next compared to probable maximum floods (PMFs) estimated using HMR51 for each of the study regions. PMFs were obtained from a variety of sources, including published data (Bullard, BUREC), state agencies, and analyses performed by the authors. Bullard's study included both historical and estimated PMF flows for 61 drainage areas varying from 0.3 to over 3000 square miles. As noted earlier, both the Bullard and the Crippen & Bue data included estimates at ungaged locations where extremely high peak discharges were observed. Graphs of each of the regions are presented in Figures 6 through 8.

Figure 6: Northern Appalachian (Crippen & Bue Region 4)
Observed Flows and Computed PMFs (HMR 51)



To represent Region 4, estimates of the PMF for 41 drainage areas throughout Pennsylvania ranging from 0.5 to 200 square miles were obtained from studies performed by the authors and from data provided by the Pennsylvania Department of Environmental Protection, Division of Dam Safety. The PMF estimates were developed using HMR 51 and 52. The NRCS dimensionless unit hydrograph was used for all basins, except for the two largest basins, where calibrated unit hydrographs were derived from storms approximating 500-yr events.

In each of the plots, the best-fit PMF slope is approximately tangent to (or parallel to the tangent) of the Crippen & Bue envelope curve for each range of data. However, the equation of the best fit line was found to be highly dependent on the range of PMF values. For Region 4, the sample PMFs ranged from about 0.5 to 100 square miles, while the Region 5 sample PMFs ranged from 1 to 500 square miles, and those in Region 10 ranged from about 15 to 3000 square miles. In Region 4, there was significant variation of PMF values for any given drainage area. This may be due simply to the larger data set in Region 4. Also, several of the basins were located in the northern glaciated region of the state where kettle lakes and swamps exist, which would result in PMFs that vary significantly from those in the southern part of the state.

Figure 7: Central Appalachian (Crippen & Bue Region 5)
Observed Flows and Computed PMFs (HMR 51)

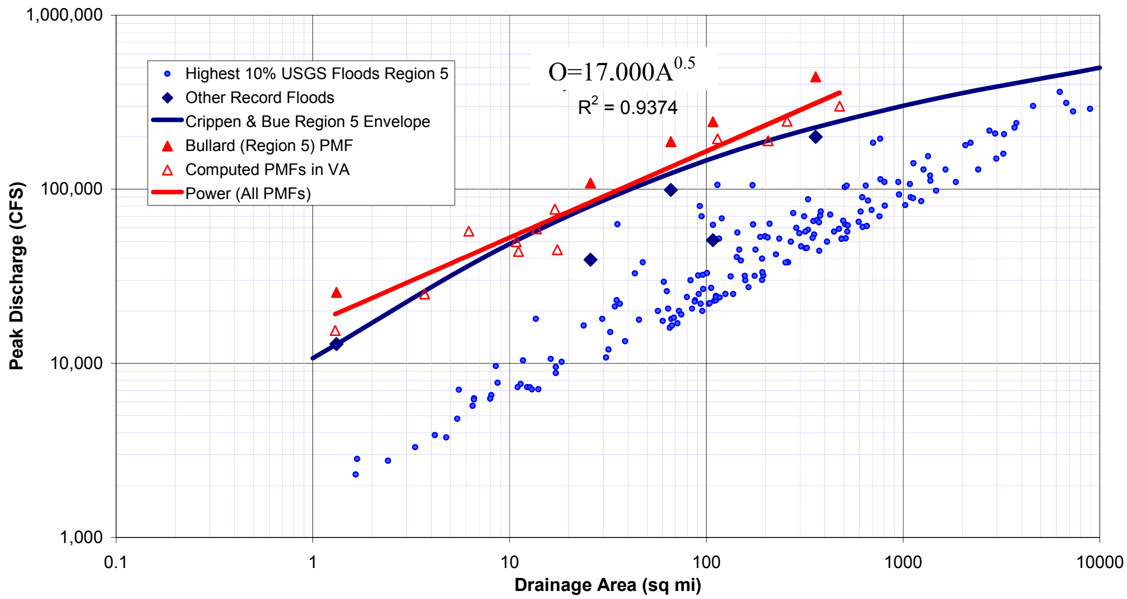
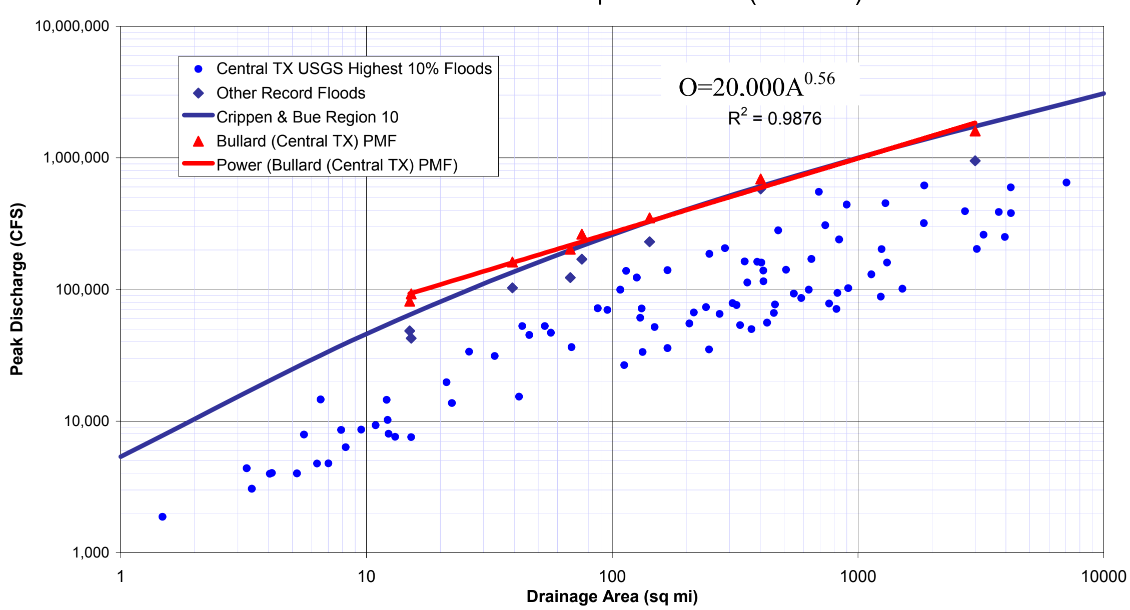


Figure 8: South Central Texas (Crippen & Bue Region 10, West)
Observed Flows and Computed PMFs (HMR 51)



Also of note is how close the best-fit PMF line is to the envelope curves in Regions 5 and 10, while the best-fit PMF line lies significantly higher than the envelope curve in Region 4. Part of the reason for this is the previously mentioned extreme flood at the low end of Region 5, which far exceeds other observed floods in the region. Extreme floods are more frequent in the Central Appalachians than the Northern Appalachians; however, one of the world record storm events for short durations occurred in Smethport, PA, in 1942 when 30.8 inches of rain fell in 4.5 hours. To the authors' knowledge, no post-flood estimate of flow was performed for this flood, but if an estimate were to exist, it would likely have significantly affected the Region 4 envelope curve.

For the larger basins in Regions 4 and 5, calibrated unit hydrographs (from storms approaching 500-yr flood events) tended to yield lower PMF peak flows relative to those developed using the NRCS unit hydrograph for similar basin size. This tends to support the limitation of the NRCS dimensionless unit hydrographs to smaller basins. The FERC Guidelines allow use of the NRCS unit hydrograph for subbasins up to 20 square miles, and total basin areas of no more than 100 square miles.

Other Predictive Methods

Besides using drainage area alone in attempting to estimate a PMF, other basin characteristics were used in a regression analysis. The following regression equations were developed from the Pennsylvania data referenced earlier. This data was used to correlate peak flow with drainage area and other watershed properties including average basin slope, channel slope, and drainage area length to width ratio.

(1) $Q = 8{,}148A^{0.69}$ (R^2=0.88)

(2) $Q = 20{,}555A^{0.5}{S_c}^{0.09}$ (R^2=0.83)

(3) $Q = 17{,}510A^{0.5}{S_b}^{0.12}$ (R^2=0.83)

(4) $Q = 20{,}055A^{0.5}{S_c}^{0.06}r^{-0.08}$ (R^2=0.83)

Where:
- Q: Estimated PMF flow (cfs)
- A: Drainage Area (sq. mi.)
- S_c: Channel Slope (ft/ft)
- S_b: Average Basin Slope (ft/ft)
- r: Watershed L/W

While other factors have minor influence, the best predictor of PMF peak flow for the evaluated basins was found to be drainage area. Because the PMF is not associated with any specific return period, correlation of the PMF with a specific frequency flood (say the 100 or 500-yr flood) would likely vary from region to region.

Comparison of Hypothetical PMF Estimates to the National Flood Frequency Program

While the frequency of the PMF is difficult to estimate, it is clearly a significantly larger event than the 500-year flood. The USGS National Flood Frequency (NFF) program provides regression equations for return period floods for various regions within each state. Pennsylvania is broken into two regions. For Region A, which comprises all but the northwest quarter of the state (Region B), the NFF equation for the 500-year flood is as follows:

$$Q_{500} = 1{,}696DA^{0.6994}(1+0.01F)^{-1.2666}(1+.01U)^{0.0208}(1+.01C)^{-.9877}(1+.01CA)^{-.3834}$$

Where: Q_{500}: Estimated 500-year flow (cfs)
DA: Drainage area (sq. mi.)
F: Percentage forested area
U: Percentage urban development
C: Percentage carbonate area
CA: Percentage controlled (by lakes, etc.) area

This equation was used to compute the 500-year storm for various drainage areas. Other variables were randomly generated and an average peak flow computed from 50 iterations. This value was compared to the peak computed PMF flow using Equation (1) provided in the previous section of this paper. Results were as follows:

Drainage Area (sq. mi.)	PMF Flow (cfs)	500-year Flow (cfs)	Q_{500}/Q_{PMF}
10	39,910	8,400	0.21
100	195,400	42,000	0.21
1,000	957,300	210,000	0.22

The results indicate that the regression equation developed for estimating the approximate PMF has a similar slope to that of the above USGS NFF regression equation (based on actual stream flow data), and that a PMF for the evaluated data in Region 4 may be roughly five times the estimated 500-year flood.

For the basins in Virginia, of the five watersheds within the Blue Ridge NFF Region, the ratio of Q_{500}/Q_{PMF} ranged from 0.13 to 0.24 for basin areas ranging from 11 to 476 square miles, respectively. In general, the ratio increased with increase in basin area.

While the data here supports some correlation between the NFF 500-year estimates and the PMF, care should be taken when applying this relationship across regions, since precipitation estimates between these two events may not correlate consistently in different regions. This is evident when comparing the rainfall frequency atlases (i.e., NOAA Atlas 14, vol 2, Ver. 2) to HMR51 estimates of the PMP. The following estimates for the 24 hour 500-year rainfall and the PMP for three locations in Virginia exemplify the differences in derivation of these two documents:

Location	24-hr rainfall		Ratio 500-yr/PMP
	500-year	PMP	
Richmond	11.4"	38”	0.30
Culpepper	12.2"	36”	0.34
Monterey	7.5”	36”	0.21

It is also noteworthy that the NFF Program breaks Virginia into 8 hydrologic regions, while Pennsylvania is broken only into 2 regions. Additional investigations can be performed to assess whether the USGS 500-yr regression equations can be used to predict the PMF in hydrologically similar regions.

It must be emphasized that all of the PMFs included in this paper utilize HMR 51 for precipitation data. Other studies, such as HMR 56 in the Tennessee Valley (which is in Crippen and Bue’s Region 5), have much higher PMP estimates as compared to

HMR 51. Thus the generalized relationships herein are only valid when referencing HMR 51. The HMR51 report notes that more detailed studies may be required to incorporate orographic effects within the stippled region of the eastern U.S. (i.e., Appalachian Mountain region). However, there are currently no efforts underway to update HMR 51, and most states within the stippled region still refer to HMR 51 for PMP estimates when computing the PMF.

Summary Graph

A summary graph (Figure 9) was developed from a combination of the regression equations and data from the previous studies referenced herein. The equations of the lines were varied slightly from those developed earlier. The reason for this is that the slope of the line was found to be highly dependent on the range of evaluated drainage

Figure 9: Approximate PMF vs Drainage Area for Evaluated Regions
(Base graph source: USGS PP924)

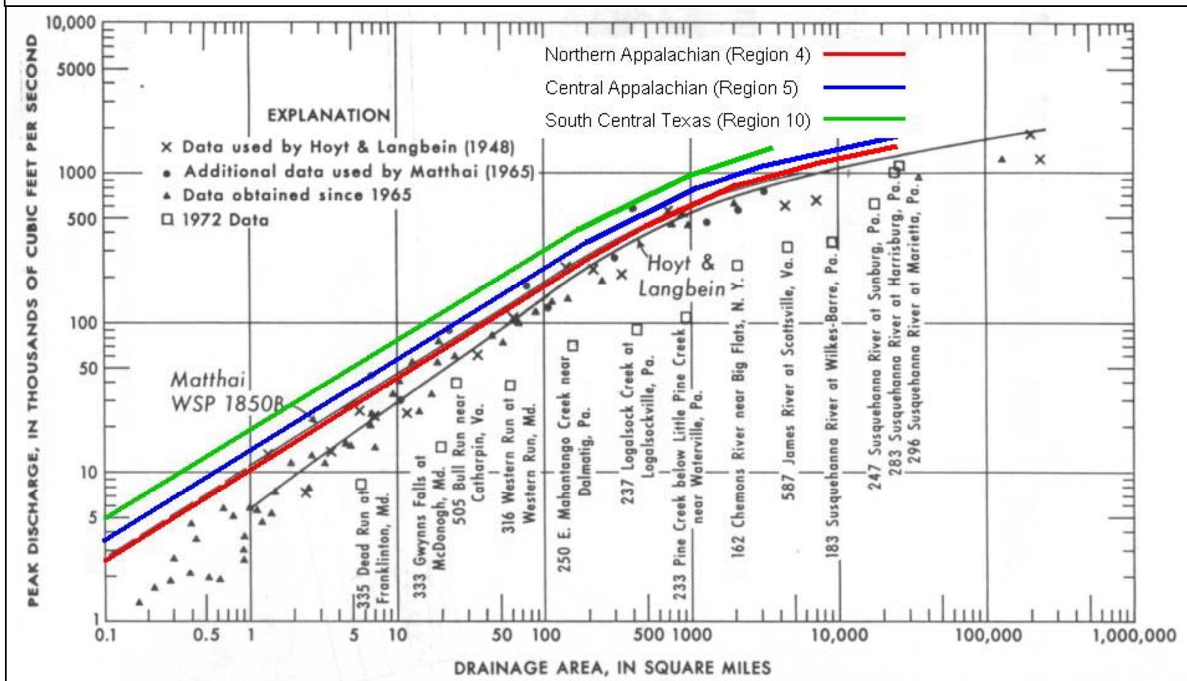


FIGURE 35.—Maximum discharge versus drainage area for known floods.

areas. Also, the NFF equation exponents for drainage areas tend to decrease with increase in flood magnitude. An exponent of 0.6 was selected to represent the three evaluated regions, which appears to be a reasonable extrapolation from the other coefficients in the NFF equations in Virginia and Pennsylvania. Also, a coefficient of 0.6 approximately parallels the envelope curve of Matthai in the figure. Finally, the rationale for transitioning the slope of the curve at a drainage area of about 1000 square miles was adopted from the findings of the USGS maximum flood flows (Figure 2) and other envelope curves. Note that the upper end of the Region 4 curve is slightly above the data points for the Susquehanna River at Harrisburg and Marietta (1972). Hurricane

Agnes equated to an approximate 0.8 PMP for a drainage area of 50,000 square miles for an area centered approximately over these basins. Increasing that flow by about 20 percent provided an estimate for the Region 4 upper point. The Region 5 curve was increased above that for Region 4 by the approximate difference in PMP between the regions. The data for Region 10 was not extended beyond a drainage area of about 3000 square miles since there was insufficient data to form a basis. The approximate equations of the various lines between 0.1 and 1000 square miles were as follows:

Region 4: $Q_{PMF} = 10{,}000A^{0.6}$
Region 5: $Q_{PMF} = 14{,}000A^{0.6}$
Region 10: $Q_{PMF} = 20{,}000A^{0.6}$

Conclusions

Approximate regional curves were developed for three hydrologic regions within the United States. Significant variation in the data indicates the approximate nature of these curves, which should only be used in preliminary estimates, or possibly checking the reasonableness of a computed PMF. Because basin shape, geology, slopes, land cover, etc., all have an influence on a computed PMF, the curves should be used with engineering judgment. These factors should be considered when estimating whether a particular basin's PMF would fall above or below the approximate curves provided above.

Other investigations indicate that the PMF may be correlated to the USGS NFF equations for extreme floods such as the 100 or 500-year floods. Our evaluations in Pennsylvania indicated that the PMF may be roughly approximated by applying a factor of 5 to the 500-year flood. Such correlations would likely vary according to regions much smaller than evaluated here. For example, the 100-year rainfall in Virginia varies significantly across the state (as is evident in the rainfall frequency atlases). The correlation of a 100 or 500-yr flood to a PMP (which in HMR 51 does *not* vary significantly across the state) would require a significant variation in the correlation of the two according to region. This is further evidence for the difficulty in providing generalized curves for such broad regions, and poses the opportunity for research into correlations between the NFF equations and the PMF for specific regions.

References

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