THE STUDY OF MOST PROBABLE MEAN DAILY BANKFULL RUNOFF VOLUMES IN SMALL WATERSHEDS DOMINATED BY CONVECTIVE/FRONTAL CHANNEL FORMING EVENTS AND THE CO-INCIDENT INNER BERM CHANNELS – PART I.

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Abstract

Small watersheds influenced pre-dominantly by rainfall of short-duration (<24 hours), exhibit an inner berm channel that resides below the floodplain. For modelling and calibration; the inner berm and floodplain are two distinct geomorphic stages of hydraulic and hydrologic significance. Bankfull discharge ($Q_{Bankfull}$) and stage represents the incipient floodplain level, the recurrence of $Q_{Bankfull}$ is derived from the annual flood-frequency distribution. Whereas the most probable one-day bankfull runoff volume ($Q_{Daily\ Bankfull}$) and stage coincides with the top of the inner berm sediment deposits (Q_{IB}) and calibrated to a flow duration. Both features can be surveyed and verified using hydraulic & hydrologic analyses and regional bankfull curves (discharge vs. drainage area). Part I presents an empirical procedure to develop ratios of most probable runoff volume to peak ($Q_{Daily\ Bankfull}$ to $Q_{Bankfull}$). Ratios are derived for 34 stream gages stratified by physiographic sections. Thirty three gages have 36 $Q_{Bankfull}$ published in 6 regional curve studies that span the Interior Plains Central Lowland Dissected Till Plains, Appalachian Highlands Piedmont province Piedmont Upland section, and the Atlantic Plain Coastal Plain (western) Embayed section. $Q_{Daily\ Bankfull}$ are derived from published $Q_{Bankfull}$ and calculated ratios, average annual durations are mapped on flow duration curves. Regional $Q_{Daily\ Bankfull}$ curves express Inner Berm growth by power relationships of drainage area. A handful of observations are noted in which published $Q_{Bankfull}$ plots on the $Q_{Daily\ Bankfull}$ regional curve, indicating co-incidence of $Q_{Daily\ Bankfull}$ to a geomorphic surface at Q_{IB}.

INTRODUCTION

A watersheds 'natural bankfull discharge' $Q_{Bankfull}$ is within a range of channel-forming discharges Q_{CF}, where Q_{Peak} is usually in the ~1 to 2-year return interval range ($Q_1 – Q_2$), Leopold, Wolman & Miller (1964). They recognize "*the channel is formed and re-formed during a range of flows lying between the lower limit of competence and an upper limit at which the flow is no longer confined within the channel.*" Wolman & Miller (1960) use 'geomorphic effectiveness' to describe a range of Q_{CF} exceeding threshold forces, that move the most material and perform the most work in modification of surface form. They all agree, $Q_{Effective}$ can often be approximated by $Q_{Bankfull}$, which in many rivers, is ~$Q_{1.5}$. They studied large watersheds whose hydrology was pre-dominantly snowmelt, groundwater or thunderstorm driven. They recognize maximum sediment flux is frequently transported by summer thunderstorms. Ideally, $Q_{Bankfull}$ fills the natural channel to the point of incipient flooding. Discharges above $Q_{Bankfull}$ would spill out onto the adjacent floodplains; suspended sediments and floating debris would transfer away from the channel to act upon the floodplain surfaces. The majority of $Q_{Daily\ Bankfull}$ is contained within the channel to act upon bed and banks dependent on material sizes and critical thresholds attained. $Q_{Daily\ Bankfull}$ is similar to Blench's (1951) dominant discharge *"a steady discharge that would produce the same result as the actual varying discharge."*

Klein (1976) stated one must understand the watershed's hydrologic regime before applying sediment transport equations. He used 'basin peakedness factors" to note hydrologic distinctions in basin characteristics. "Bankfull events" generated in small watersheds by thunderstorms are limited in energy, magnitude, runoff volume and duration; $Q_{Bankfull}$ is usually much larger than $Q_{Daily\ Bankfull}$, such that $Q_{1.5}$ does not produce 24 hours of Q_{CF}. Both Klein and Hewlett & Hibbert (1965) recognize that most of the transportation activity occurs within a short time of the hydrograph peak and recommended to separate 'quick flow' from total flow. Biedenharn & Copeland (2000) propose *for large watersheds* to use a steady mean daily discharge integrated from a flow duration curve with a proper bed-material-load rating curve to determine the flow class interval that moves the largest load fraction. They acknowledge "*mean daily values can under-represent the occurrence of short-duration, high magnitude flow events that occur within the averaging period. On large rivers such as the Mississippi River, the use of the mean daily values is acceptable because the difference between the mean and peak daily discharges is negligible. On smaller streams, flood events may last only a few hours, so that the peak discharge is much greater than the corresponding mean daily discharge."* The inner berm capacity, (Q_{IB}) is shaped over time by various runoff volumes. Melton (1936) recognized the geomorphic significance of the low-flow channel regime: "*those that nearly fill the channel but do not over-top its banks*". Q_{IB} often forms into a non-continuous bench of fine sediments, often vegetated and

alternating banks. Q_{IB} resides at the top of the sediment slope (e.g. point bars), where water slope tends to even out between pools and riffles.

PURPOSE AND SCOPE

In small watersheds where the majority of channel forming events are generated by convective/frontal precipitation (non-snowmelt); the Inner Berm capacity (Q_{IB}) is significant to the sediment regime. Q_{IB} typically convey 99 to 99.4% of all yearly Q_{Daily} at or below the sediment bench stage. In designing stream restoration, bank stabilization, fish passage, and road culvert/bridge crossings, it is important to recognize and match the inner-formation of Q_{IB} to drainage area. Part I outlines a mathematical procedure derived from continuous recording stream gages to estimate the most probable minimum one-day runoff volume ($Q_{Daily\ Bankfull}$), formed by $Q_{Bankfull}$. $Q_{Daily\ Bankfull}$ is the area under a 24-hour bankfull hydrograph; runoff volume and shape sets the duration (T_{CF}) of most effective Q_{CF}. $Q_{Daily\ Bankfull}$ also neatly approximates Q_{IB}. Part II: A study of $Q_{Daily\ Bankfull}$ in the Ninnescah River Watershed, Kansas, compares regionalized $Q_{Daily\ Bankfull}$ curves to surveyed Q_{IB} at fifteen watershed sites, 6 sites include USGS gage stations.

STUDY AREAS

The mathematical procedure is applied on 34 USGS stream gage stations across 4 hydro-physiographic provinces and 7 states. Eight principal authors identified and published 36 $Q_{Bankfull}$ at 33 gage stations: Emmert & Hase (2001) determined $Q_{Bankfull}$ for 8 gages on the Central Lowland Dissected Till Plains (Figure 1). Six gages on the main stem of Soldier Creek (Nemaha & Jackson Counties) allow study of typical growth of Q_{IB} in the downstream direction.

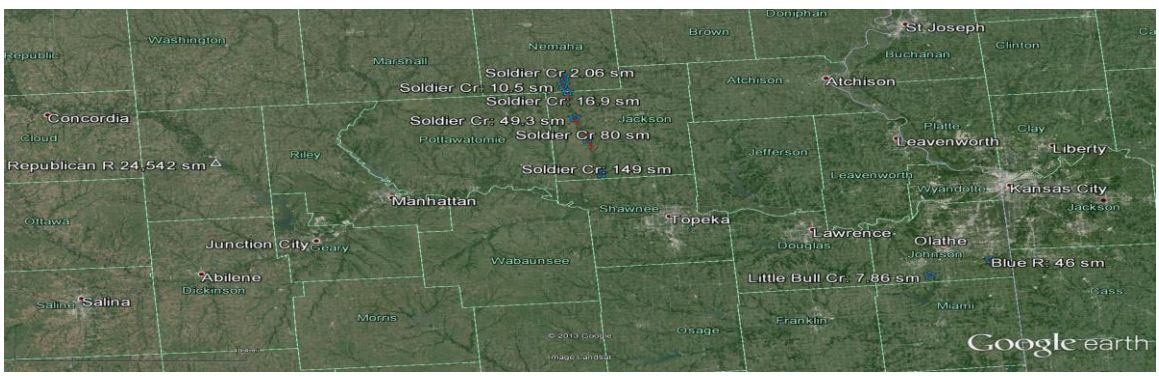

Figure 1 Eight gage locations on the Central Lowland Dissected Till Plains of Kansas

Leopold et al. (1964), White (2001), Cinotto (2003), McCandless et al. (2002), Harman et al. (1999) determined $Q_{Bankfull}$ for 20 gages on the Piedmont Upland section (Figure 2) across Pennsylvania, Maryland, and North Carolina.

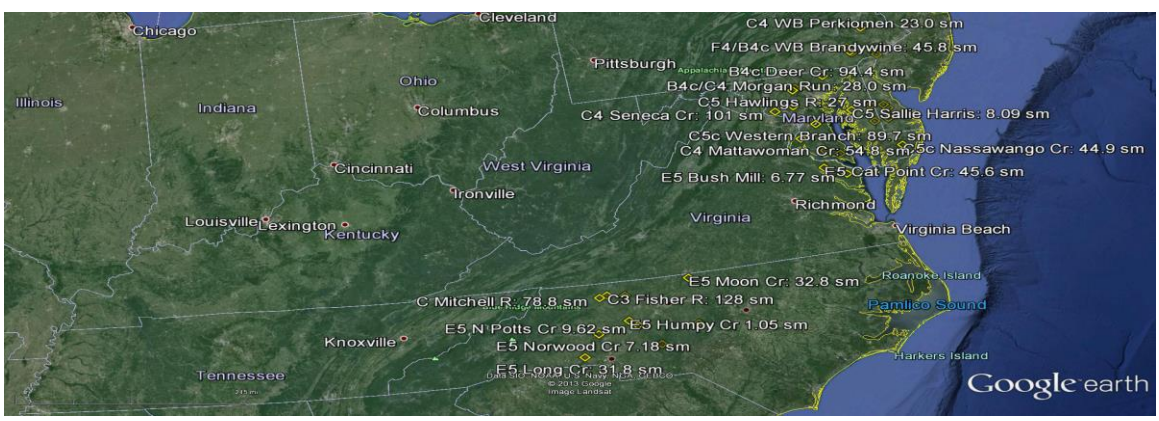

Figure 2 Twenty gage locations on the Piedmont Upland section (PA, MD & NC)

McCandless (2003) and Krstolic et al. (2007) determined $Q_{Bankfull}$ for 5 gages on the Atlantic Coastal Plain, western embayed section (Figure 3) spanning Delaware, Maryland and Virginia.

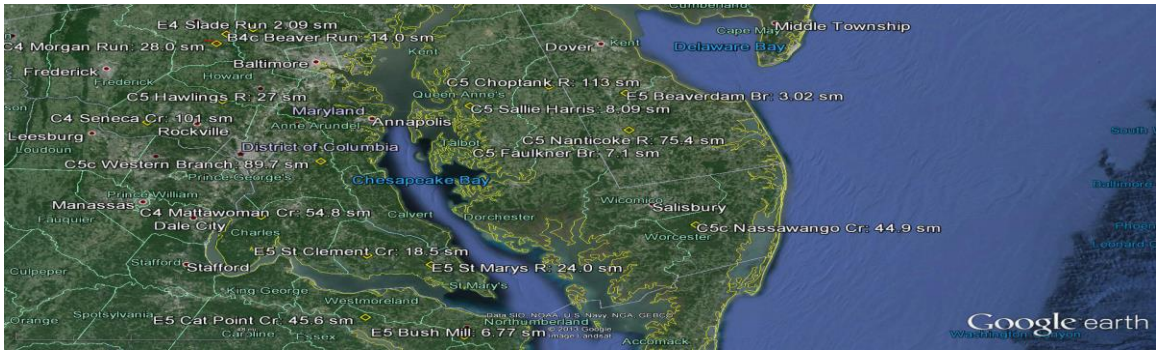

Figure 3 Gages located on the Atlantic Coastal Plain embayed section (DE, MD & VA)

METHODS

Determination of $Q_{Bankfull}$ Return Interval (RI)

The Log Pearson Type III distribution (LPIII) and the 1st order least squares curve-fit of the Weibull distribution are averaged to determine the recurrence intervals of $Q_{Bankfull}$. Outliers (annual Q_{Peak} too high or low) identified in the LPIII process were also removed from the Weibull plotting positions. Figure 4 shows the two flood frequency distributions for Seneca Creek at Dawsonville, Maryland USGS 01645000.

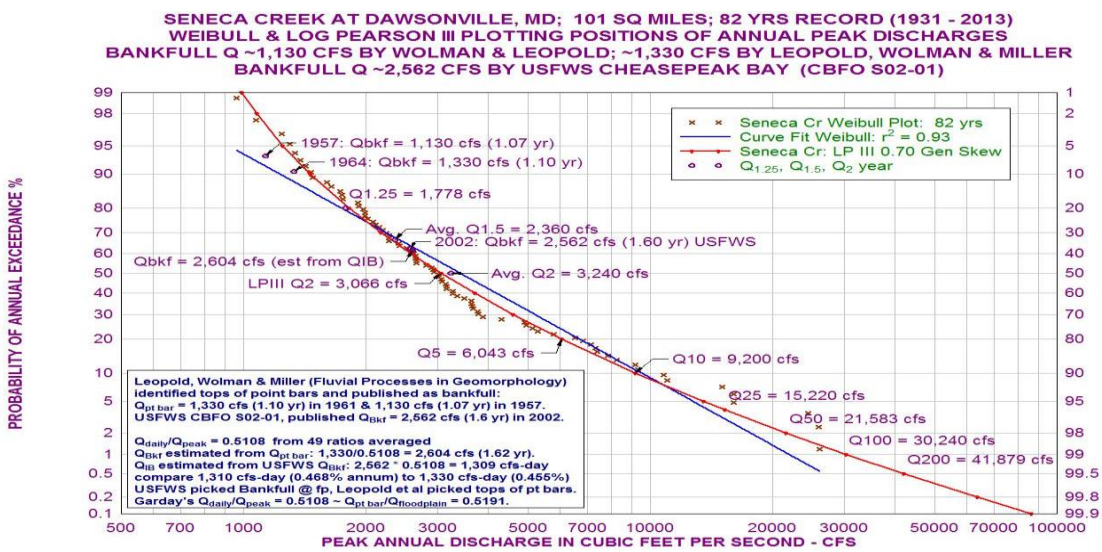

Figure 4 Log Pearson Type III and Weibull Distributions for Seneca Creek, Maryland

Approximation of Most Probable Duration (T_{CF}) for Q > $Q_{Daily\ Bankfull}$

For small watersheds, the bankfull event is modelled as a one-day hydrograph, the area under the hydrograph is $24*Q_{Daily\ Bankfull}$. Assumed hydrograph shape is trapezoidal below $Q_{Daily\ Bankfull}$, and triangular above with $Q_{Bankfull}$ at the apex. The trapezoidal base is 24-hour; it may start and end with or without base flow. The duration (T_{CF}) for which Q exceeds $Q_{Daily\ Bankfull}$ must equal the upper trapezoidal time base at $Q_{Daily\ Bankfull}$. Figure 5 shows the bankfull hydrograph based on these requirements for a gage on Soldier Creek in Kansas. Note the cross-shaded areas below $Q_{Daily\ Bankfull}$ must equal the cross-shaded area above $Q_{Daily\ Bankfull}$.

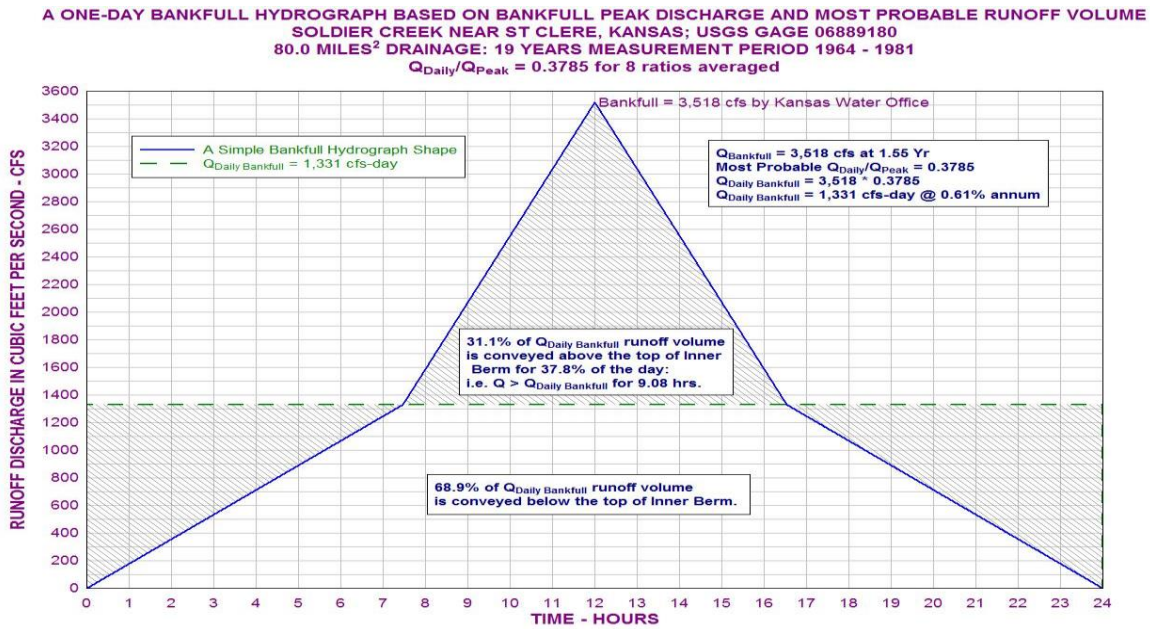

Figure 5 Assumed 1-day bankfull hydrograph shape based on peak and most probable runoff volume.

The duration (hours) of T_{CF}, represents strongest flow (Q exceeds $Q_{Daily\ Bankfull}$) in a minimal bankfull event, it can be solved by setting the sum of the trapezoidal and the triangular areas equal to the runoff volume in cfs-hours.

$$\tfrac{1}{2} * (24 + T_{CF}) * Q_{Daily\ Bankfull} + \tfrac{1}{2} * T_{CF} * (Q_{Bankfull} - Q_{Daily\ Bankfull}) = 24 * Q_{Daily\ Bankfull} \quad (1)$$

$$T_{CF} = 24 * Q_{Daily\ Bankfull}/Q_{Bankfull} \text{ (hours) for which } Q > Q_{Daily\ Bankfull} \quad (2)$$

Computation of the Most Probable $Q_{Daily\ Bankfull}/Q_{Bankfull}$ Ratio

It is further assumed the long-term most probable $Q_{Daily\ Bankfull}/Q_{Bankfull}$ hydrologic ratio can be approximated using sufficient gage data: the average of Q_{Daily}/Q_{Peak} ratios for which Q_{Peak} is in the channel-forming range (Q_{CF}). Q_{CF} in all this work is generally between $Q_{1.25}$ and the mean annual flood (Q_{MA}). In calculating the return intervals of Q_{MA}, high outliers were removed from the flood averages. The return interval of Q_{MA} generally varies from 2.3 to 3.1 years it is somewhat sensitive to number of years of record relative to the magnitudes of floods in the period of record. Q_{MA} being a flood discharge is plotted on the LPIII curve and is not averaged with the Weibull distribution.

$Q_{Daily\ Bankfull}$ is computed as the product of $Q_{Bankfull}$ and the most probable Q_{Daily}/Q_{Peak} ratio.

$$Q_{Daily\ Bankfull} = Q_{Bankfull} * Q_{Daily}/Q_{Peak} \quad (3)$$

Computation is demonstrated using USGS gage 01645000 Seneca Creek at Dawsonville, MD. Seneca Creek $Q_{Bankfull}$ is documented by Leopold et al. (1964) and McCandless et al. (2002). For 82 years of annual maximums, 49 Q_{Peak} qualify as 1-day channel-forming events, 49 Q_{Daily}/Q_{Peak} ratios are averaged: 40 ratios involve Q_{Peak} between ~$Q_{1.25}$ and ~Q_2 and 9 ratios between ~Q_2 and ~Q_{MA}. Single event Q_{Daily}/Q_{Peak} ratios range from 0.12 to 0.75, but cumulatively, the running average or most probable Q_{Daily}/Q_{Peak} ratio converges to 0.51 and remains unchanged (to 2 decimal places) for the largest 15 Q_{Peak} at or below Q_{MA}.

Table 1 lists annual maximum discharges Q_{Peak} (column 3) in ascending order, the *largest* Q_{Daily} of the three days surrounding Q_{Peak} (1-day prior, on, or 1-day after) is chosen, (column 2) and single event Q_{Daily}/Q_{Peak} ratios (column 6). The most probable Q_{Daily}/Q_{Peak} ratio (0.5109) is the mean of all ratios (last value in column 7).

Table 1 Computations of Seneca Creek's most probable Q_{Daily}/Q_{Peak} Ratio

Date of annual peak	Q_{Daily} (cfs-day)	Q_{Peak} (cfs)	Probability Weibull Plot	Gage Ht. feet	Single Event Q_{Daily}/Q_{Peak} Ratio	Running Average: Q_{Daily}/Q_{Peak}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1/14/1968		1640	86.75	6.37		
7/1/1931	483	1730	85.54	6.08	0.2792	0.2792
4/20/1940	931	1740	84.34	6.41	0.5351	0.4071
3/27/1992	963	1750	83.13	6.55	0.5503	0.4548
3/22/2000	1330	1910	81.93	6.79	0.6963	0.5152
3/12/1962	1450	1920	80.72	6.83	0.7552	0.5632
8/8/1959	700	1970	79.52	6.9	0.3553	0.5286
8/20/1947	242	1990	78.31	6.75	0.1216	0.4704
6/30/1948	722	1990	77.11	6.78	0.3628	0.4570
1/3/1936	1370	2020	75.90	6.88	0.6782	0.4816
8/6/1995	936	2080	74.70	7.03	0.4500	0.4784
8/1/1945	1220	2110	73.49	6.9	0.5782	0.4875
1/30/1939	1400	2150	72.29	6.93	0.6512	0.5011
7/10/1970	980	2200	71.08	7.18	0.4455	0.4968
7/16/1949	729	2240	69.88	7.03	0.3254	0.4846
4/2/1990	1040	2270	68.67	7.24	0.4581	0.4828
10/23/1937	1630	2280	67.47	7.08	0.7149	0.4973
3/23/1950	1310	2280	66.27	7.12	0.5746	0.5019
9/17/1934	1080	2410	65.06	7.3	0.4481	0.4989
12/4/1950	1420	2420	63.86	7.26	0.5868	0.5035
1/9/1964	1290	2520	62.65	7.51	0.5119	0.5039
8/27/1937	1210	2610	61.45	7.45	0.4636	0.5020
8/13/1955	1950	2620	60.24	7.6	0.7443	0.5130
8/26/1965	717	2640	59.04	7.62	0.2716	0.5025
5/26/2009	1200	2650	57.83	7.65	0.4528	0.5005
11/9/1943	1360	2660	56.63	7.52	0.5113	0.5009
8/27/1967	1710	2660	55.42	7.64	0.6429	0.5064
9/1/1952	2080	2810	54.22	7.77	0.7402	0.5150
10/13/2011	908	2890	53.01	8.3	0.3142	0.5078
12/26/2009	2040	2930	51.81	7.98	0.6962	0.5143
6/2/1946	1880	2940	50.60	7.73	0.6395	0.5185
3/29/1984	2190	3010	49.40	7.92	0.7276	0.5253
9/14/1973	1280	3020	48.19	7.94	0.4238	0.5221
9/16/1999	1500	3060	46.99	7.95	0.4902	0.5211
6/10/1961	1060	3070	45.78	7.98	0.3453	0.5159
8/12/2001	887	3140	44.58	8.01	0.2825	0.5093
12/26/1973	1330	3160	43.37	7.95	0.4209	0.5068
6/13/1982	1460	3160	42.17	8.02	0.4620	0.5056
4/10/1983	2060	3260	40.96	8.09	0.6319	0.5089
9/14/1966	1580	3270	39.76	8.12	0.4832	0.5083
4/16/1993	1520	3350	38.55	8.15	0.4537	0.5069
9/4/1969	1840	3490	37.35	8.26	0.5272	0.5074
10/16/1942	1900	3620	36.14	8.31	0.5249	0.5078
2/12/1985	1980	3620	34.94	8.33	0.5470	0.5087
12/21/1957	1400	3640	33.73	8.35	0.3846	0.5059
5/12/2008	2560	3660	32.53	8.74	0.6995	0.5102
7/8/2005	1990	3750	31.33	8.83	0.5307	0.5107
10/9/1976	1780	3770	30.12	8.42	0.4721	0.5098
10/19/1996	2920	3880	28.92	8.49	0.7526	0.5149
5/27/2002	1360	4310	27.71	9.26	0.3155	0.5109

Durations of $Q_{Daily\ Bankfull}$ Annual Exceedance

Each gage is/was a continuous recording gage, (CRG) which produce Q_{Daily} for the respective period of record. Flow duration curves (FDC) were assembled using EXCEL spreadsheets that sorts and counts Q_{Daily} records by water year. Q_{Daily} from all water years are combined into 39 flow class intervals determined by the flow values closest to 100%, 99.99, 95, 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 40, 35, 30, 25, 20, 15, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, and 0.05% annual exceedances. One percent annual exceedance (1% annum) is 3.6525 days/year or ~87.66 hours/year. The USGS rounds Q_{Daily} to the nearest integer above 10 cfs-day and to the nearest 10 cfs-day above 1,000 cfs-day. As percent annums are often developed from irrational fractions, it is not always possible to derive an integral flow on the specified exceedance class interval. For Seneca Creek, Q_{Daily} of 29 cfs-day is at 90.5% annum which is the closest integral flow to the desired 90.0% interval.

Leopold, Wolman & Miller (1964) identified bankfull durations of 0.40-0.60% annum common for the Maryland/Pennsylvania Piedmont Upland section (hydrologic records up to 1963). Nixon (1959), who studied rivers in the United Kingdom, concluded bankfull stage is co-incident with flows equaled or exceeded 0.6% annum on the FDC. Figure 6 shows three FDC's with similarities in shape but variations in annual duration of $Q_{Daily\ Bankfull}$. Seneca Creek at Dawsonville is plotted with Hawlings River near Sandy Spring, MD, both Upland section streams with similar $Q_{Daily\ Bankfull}$ durations. Whereas the $Q_{Daily\ Bankfull}$ duration of Beaverdam Branch at Houston, DE on the Coastal Plain (western) embayed section, downslope to the Piedmont Upland section, is ~twice as long.

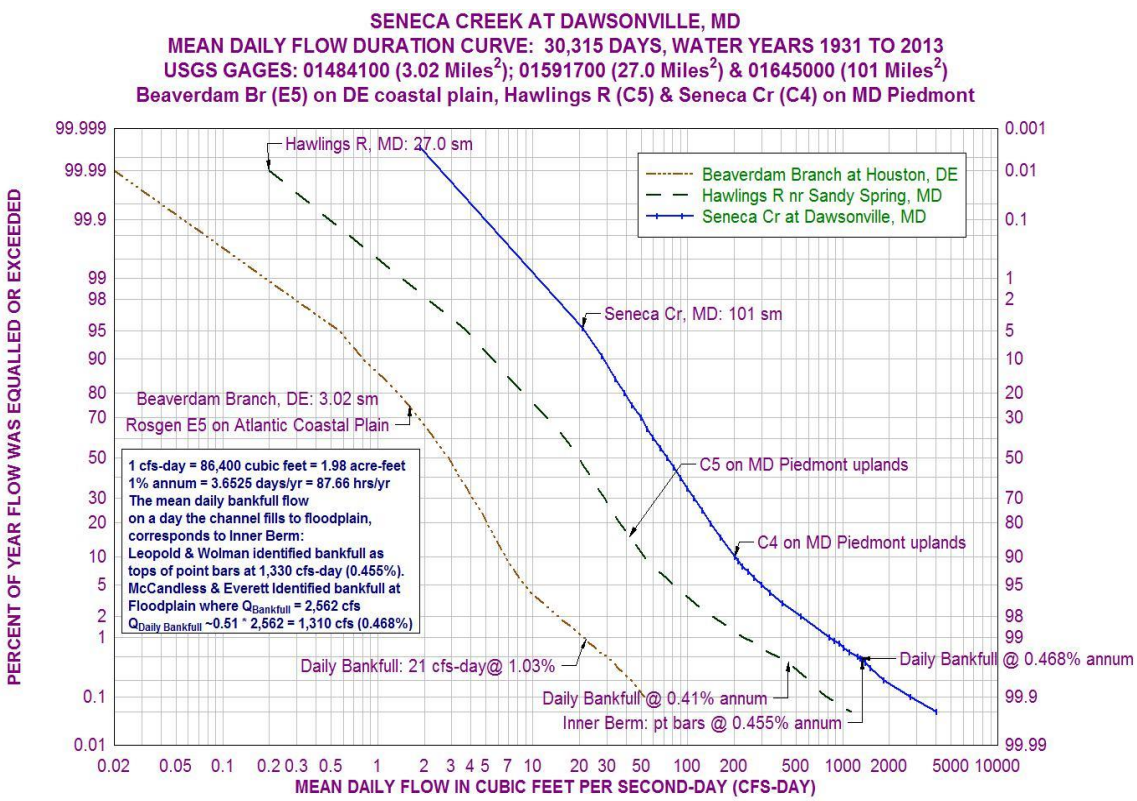

Figure 6 Flow Duration Curves of 3 Rosgen stream types in MD & DE across 2 physiographic regions

RESULTS

The gages (and results) are stratified by physiographic province according to Fenneman (1946). Results are presented in Tables (summarizing published $Q_{Bankfull}$, calculated Q_{Daily}/Q_{Peak} ratios, most probable $Q_{Daily\ Bankfull}$ and associated % annum durations), Figures (plots of Regional $Q_{Daily\ Bankfull}$ vs. DA & $Q_{Bankfull}$ vs. DA Curves), & Equations (first-order curve fits of Regional Curves using the DPLOT plotting program). The two derived power equations are substituted into equation 2 to express most probable duration T_{CF} that flow is above $Q_{Daily\ Bankfull}$.

Interior Plains Central Lowland Dissected Till Plains

Table 2 Summary of $Q_{Daily\ Bankfull}$ and percent annum for the Dissected Till Plains section

Gage #	Drainage Area (miles^2)	$Q_{Bankfull}$ (cfs)	Return interval of $Q_{Bankfull}$ (years)	Most probable Q_{Daily}/Q_{Peak} Ratio	$Q_{Daily\ Bankfull}$ (cfs-day) 1-day runoff volume	% annum: $Q_{Daily\ Bankfull}$ on FDC	Reference source for $Q_{Bankfull}$ (cfs) only
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
06889100	2.06	**191**	1.25	0.21	40.5	0.77	**KWO**
06914990	7.86	**659**	1.14	0.24	160	1.00	**KWO**
06889120	10.5	**688**	1.23	0.26	179	0.91	**KWO**
06889140	16.9	**823**	1.11	0.29	239	0.95	**KWO**
06893080	46.0	**1,736**	1.13	0.33	573	1.10	**KWO**
06889160	49.3	**2,600**	1.18	0.32	831	0.75	**KWO**
06889180	80	**3,518**	1.55	0.38	1,330	0.61	**KWO**
06889200	149	**3,279**	1.46	0.71	2,320	0.60	**KWO**
Kansas Regional Averages			**1.30**			**0.76**	

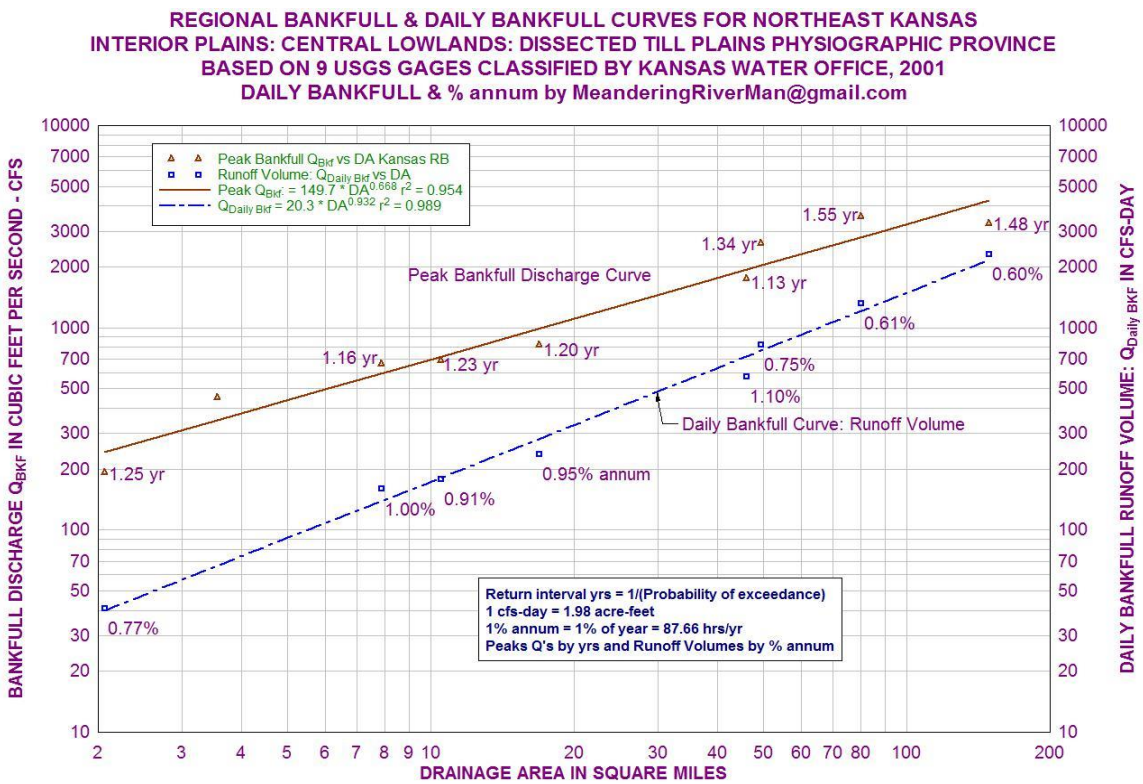

Figure 7 Regional $Q_{Bankfull}$ and $Q_{Daily\ Bankfull}$ Curves for Northeast Kansas

Equations 4, 5 & 6 apply to small watersheds in northeast KS for drainage areas 2.06 miles^2 to 149 miles^2.

$$Q_{Bankfull} = 149.7 * DA^{0.668} \quad \text{(cfs)} \quad r^2 = 0.954 \tag{4}$$

$$Q_{Daily\ Bankfull} = 20.31 * DA^{0.932} \quad \text{(cfs-day)} \quad r^2 = 0.989 \tag{5}$$

$$T_{CF} = 3.256 * DA^{0.264} \quad \text{(hours)} \tag{6}$$

Appalachian Highlands Piedmont province Piedmont Upland section

Generally, the North Carolina watersheds have ~25.3% less annual runoff, ~25% less channel-forming time, but ~22.5% more inner berm capacity than in similar watersheds of Maryland and Pennsylvania. The 20 gage set was stratified further by runoff criteria resulting in two sets of regional curves & power equations. Equations 7, 8 & 9 apply to small watersheds in NC Piedmont uplands for drainage areas 1.05 miles^2 to 128 miles^2.

Table 3 Summary of $Q_{Daily\ Bankfull}$ and percent annum for the Piedmont Upland section.

Gage #	Drainage Area (miles^2)	$Q_{Bankfull}$ (cfs)	Return interval of $Q_{Bankfull}$ (years)	Most probable Q_{Daily}/Q_{Peak} Ratio	$Q_{Daily\ Bankfull}$ (cfs-day) 1-day runoff volume	% annum: $Q_{Daily\ Bankfull}$ on FDC	Reference source for $Q_{Bankfull}$ (cfs) only
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
02117030	1.05	**83**	1.78	0.21	17.6	0.46	**NCSU**
0214253830	7.18	**254**	1.23	0.35	88.7	0.77	**NCSU**
02121180	9.62	**507**	1.74	0.31	159	0.55	**NCSU**
02101800	15.5	**655**	1.37	0.44	291	0.61	**NCSU**
02144000	31.8	**1,041**	1.57	0.52	546	0.38	**NCSU**
02075160	32.8	**709**	1.68	0.62	441	0.26	**NCSU**
02114450	42.8	**2,236**	1.54	0.31	700	0.43	**NCSU**
02112360	78.8	**2,681**	1.58	0.40	1,080	0.31	**NCSU**
02113000	128	**3,687**	1.33	0.46	1,680	0.46	**NCSU**
NC Regional Averages			**1.54**	**-**		**0.47**	
01583000	2.09	**115**	1.45	0.16	18	0.60	**CBFO-S02-01**
01586210	14.0	**559**	1.44	0.24	137	0.50	**WRIR 03-4014**
01586210	14.0	**628**	1.60	0.24	154	0.42	**CBFO S02-01**
01475850	15.8	**601**	1.13	0.31	188	1.00	**WRIR 03-4014**
01480300	18.7	824	1.33	0.40	**333**	**0.60**	**WRIR 03-4014**
01472199	23.0	**1,000**	1.26	0.45	454	0.51	**WRIR 01-4146**
01586610	28.0	**970**	1.52	0.34	331	0.37	**WRIR 03-4014**
01586610	28.0	**1,024**	1.59	0.34	349	0.33	**CBFO S02-01**
01480500	45.8	**1,097**	1.24	0.55	602	0.65	**WRIR 03-4014**
01480617	55.0	**1,643**	1.33	0.42	686	0.78	**WRIR 03-4014**
01477000	61.1	**1,772**	1.22	0.41	733	0.82	**WRIR 03-4014**
01580000	94.4	**2,614**	1.31	0.35	905	0.60	**CBFO S02-01**
01645000	101	**2,562**	1.60	0.51	1,310	0.48	**CBFO S02-01**
01645000	101	**1,330**	1.08	0.51	679	1.37	**Leopold, Wolman & Miller**
MD/PA Regional Averages			**1.39**			**0.59**	
NC/MD/PA Regional Averages			**1.46**			**0.54**	
Maryland Piedmont upland gages							
North Carolina Piedmont upland gages							
Pennsylvania Piedmont upland gages							

$$Q_{Bankfull} = 68.87 * DA^{0.813} \quad \text{(cfs)} \quad r^2 = 0.948 \quad (7)$$

$$Q_{Daily\ Bankfull} = 16.98 * DA^{0.964} \quad \text{(cfs-day)} \quad r^2 = 0.990 \quad (8)$$

$$T_{CF} = 5.917 * DA^{0.151} \quad \text{(hours)} \quad (9)$$

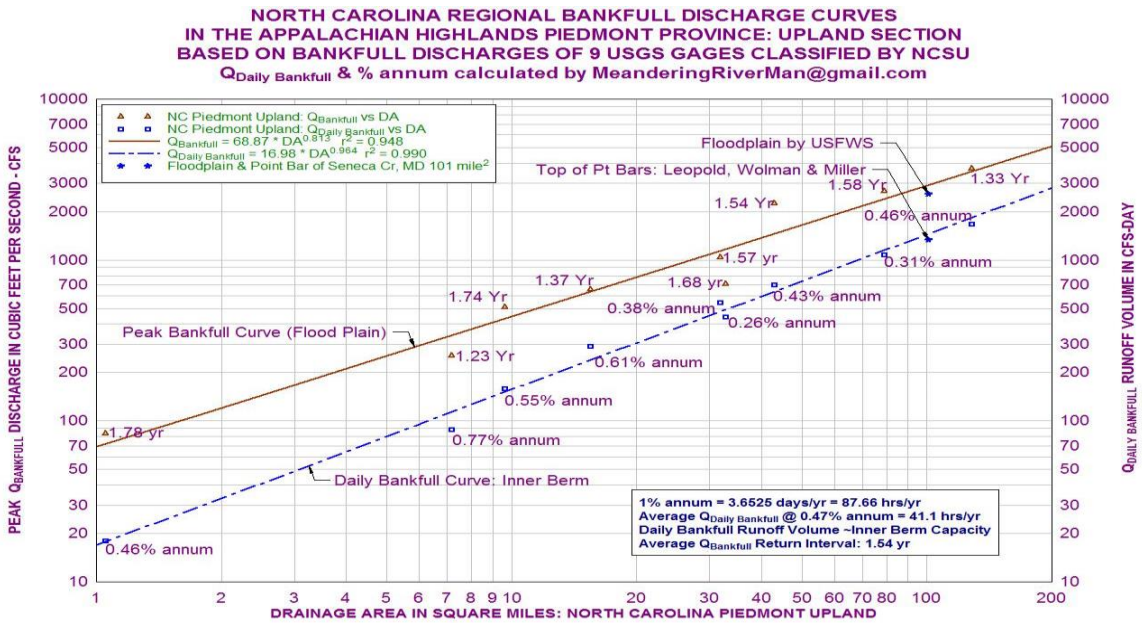

Figure 8: Regional $Q_{Bankfull}$ and $Q_{Daily\ Bankfull}$ Curves of Piedmont Upland section in North Carolina

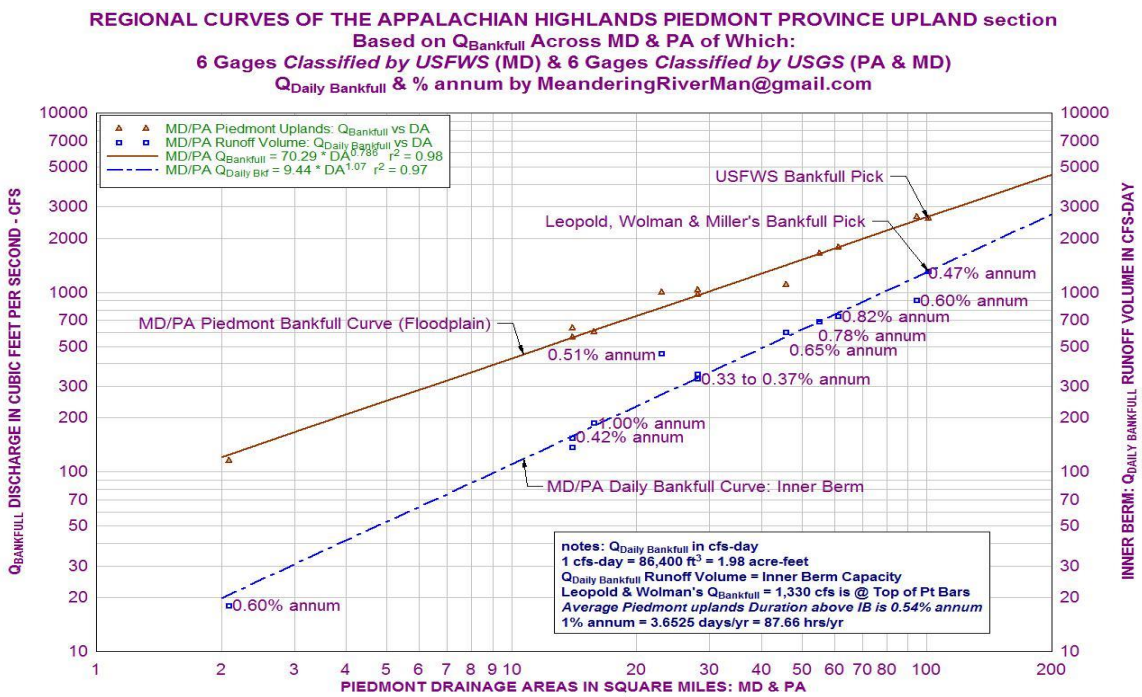

Figure 9 Regional $Q_{Bankfull}$ and $Q_{Daily\ Bankfull}$ Curves of Piedmont Upland section in MD & PA

Equations 10 - 12 apply for small watersheds in MD & PA Piedmont uplands for drainage areas 2.09 to 101 miles^2.

$$Q_{Bankfull} = 70.29 * DA^{0.786} \quad \text{(cfs)} \quad r^2 = 0.983 \tag{10}$$

$$Q_{Daily\ Bankfull} = 9.44 * DA^{1.07} \quad \text{(cfs-day)} \quad r^2 = 0.971 \tag{11}$$

$$T_{CF} = 3.223 * DA^{0.284} \quad \text{(hours)} \tag{12}$$

Atlantic Plain Coastal Plain (western) Embayed section

Table 4 Summary of $Q_{Daily\ Bankfull}$ and % annum for the Atlantic Coastal Plain (western) embayed section

Gage #	Drainage Area (miles^2)	$Q_{Bankfull}$ (cfs)	Return interval of $Q_{Bankfull}$ (years)	Most probable Q_{Daily}/Q_{Peak} Ratio	$Q_{Daily\ Bankfull}$ (cfs-day) 1-day runoff volume	% annum: $Q_{Daily\ Bankfull}$ on FDC	Reference source for $Q_{Bankfull}$ (cfs) only
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
01484100	3.02	**35**	**1.29**	0.59	21	1.03	**CBFO S03-02**
01661800	6.77	99	1.33	0.50	**50**	**1.01**	**SIR 2007-5162**
01661050	18.5	**273**	**1.23**	0.58	160	1.00	**CBFO S03-02**
01661500	24.0	**465**	**1.23**	0.54	252	0.91	**CBFO S03-02**
01658000	54.8	696	1.30	0.78	**540**	**1.05**	**CBFO S03-02**
Atlantic Coastal Plain Regional Averages			**1.28**	**-**		**1.00**	
FDC: Flow Duration Curve; 1 cfs-day = 1.98 acre-feet; 1% annum = 86.77 hrs./yr.							
Atlantic Coastal Plain Embayed section western gages							

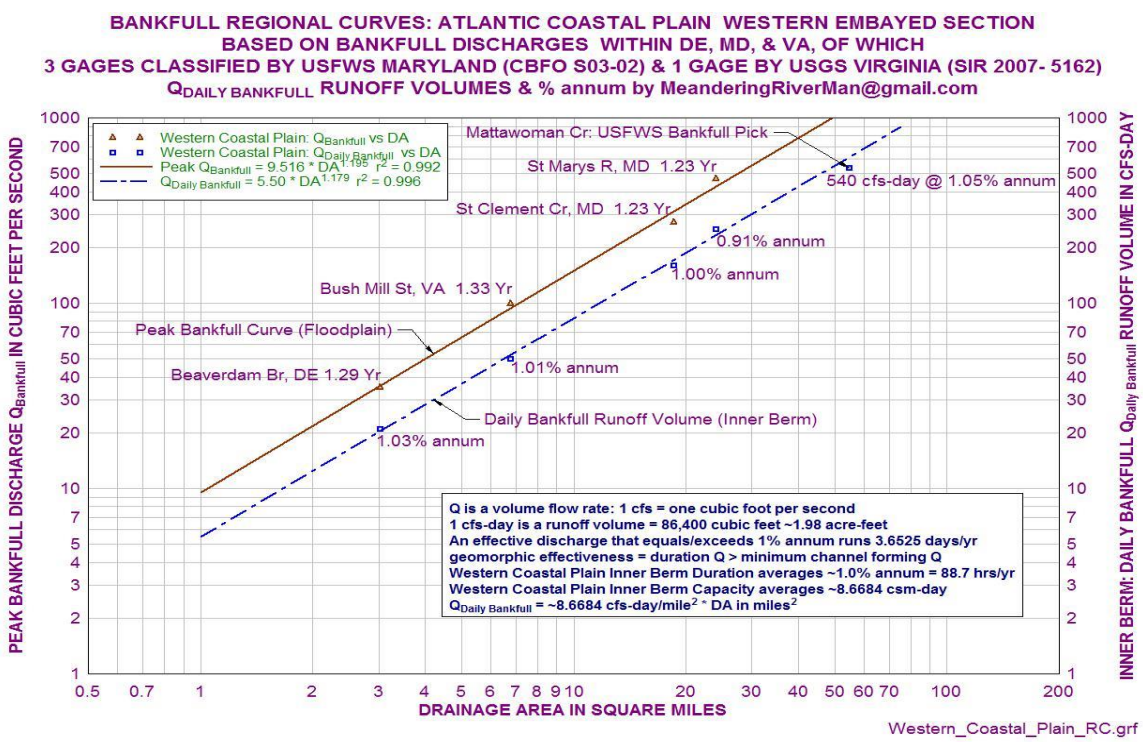

Figure 10 Regional $Q_{Bankfull}$ and $Q_{Daily\ Bankfull}$ Curves along the western Coastal Plain Embayed section

Equations 13 - 15 apply to small watersheds in DE, MD and VA coastal plain drainage areas 3.02 to 54.8 miles^2.

$$Q_{Bankfull} = 9.516 * DA^{1.195} \quad \text{(cfs)} \quad r^2 = 0.992 \qquad (13)$$

$$Q_{Daily\ Bankfull} = 5.497 * DA^{1.179} \quad \text{(cfs-day)} \quad r^2 = 0.996 \qquad (14)$$

$$T_{CF} = 13.864 * DA^{-0.016} \quad \text{(hours)} \qquad (15)$$

DISCUSSION

The intention in developing $Q_{Bankfull}$ power equations and Regional Curves is not to supersede the work of the original authors, but to demonstrate the r^2 coefficients of the $Q_{Daily\ Bankfull}$ curves are generally better than for $Q_{Bankfull}$.

Co-Incidence of Regional $Q_{Daily\ Bankfull}$ Curves and Inner Berm (Q_{IB})

Seneca Creek: Leopold, Wolman & Miller (1964) published $Q_{Bankfull}$ at 1,330 cfs (1.1 year RI) at tops of point bars, 1,330 cfs-day corresponds to 0.46% annum flow duration. In 2002, McCandless and Everett, published $Q_{Bankfull}$ at 2,562 cfs (1.6 year RI). Using McCandless and Everett bankfull pick and Q_{Daily}/Q_{Peak} = 0.51, (derived from Table 1). Predicted $Q_{Daily\ Bankfull}$ = 2,562 cfs * 0.51 = 1,310 cfs-day at 0.47% annum on FDC, (Figure 6), a 1.6% difference.

$$Q_{Point\ Bar}/Q_{Floodplain} = 1{,}330/2{,}562 = 0.5191 \quad (16)$$

$$Q_{Daily\ Bankfull}/Q_{Bankfull} \sim Q_{Daily}/Q_{Peak} = 0.5109 \quad (17)$$

$$Q_{Daily}/Q_{Peak} \sim Q_{Daily\ Bankfull}/Q_{Bankfull} \sim Q_{Inner\ Berm}/Q_{Floodplain} \quad (18)$$

In Table 4 and Figure 10, $Q_{Bankfull}$ for Bush Mill Stream (01661800) and for Mattawoman Creek (01658000) are plotted to demonstrate that the USGS and USFWS identified geomorphic surfaces at 50 cfs (1.06 year) & 540 cfs (1.18 year) respectively, both plot close to the calculated Q_{IB} curve. On respective FDC's; 50 cfs-day plots at 1.01% annum, 540 cfs-day plots at 1.05% annum, both strongly agree with other $Q_{Daily\ Bankfull}$ durations of gages in the Atlantic Coastal Plain western embayed section.

Table 2, Figures 7 & 11 demonstrate changes in the Q_{Daily}/Q_{Peak} ratios (& $Q_{Daily\ Bankfull}$) of six gages on the main stem of Soldier Creek, (same valley type) are consistent in the *downstream direction.* As drainage area increases the inner berm stage (top of sediment bars) approaches bankfull (floodplain) stage. Simultaneously $Q_{Daily\ Bankfull}$ approaches $Q_{Bankfull}$ and the surrogate Q_{Daily}/Q_{Peak} ratio approaches unity. The two curves are asymptotic, but intersection of two linear curves would define "large watersheds", where Biedenharn & Copeland's (2000) assumptions hold true. Figure 11 is courtesy of Paul D. Miller, P.E. C.F.M., with GBA in Lenexa, KS. Mr. Miller surveyed & analyzed $Q_{Bankfull}$ for gages (red triangles) around the Kansas City area, then super-imposed his set with equations 4 (Central Kansas (Garday) and 5 (Q_{IB} (Garday)). His independent analyses, demonstrates *physical geomorphic features coincident with predicted $Q_{Daily\ Bankfull}$.*

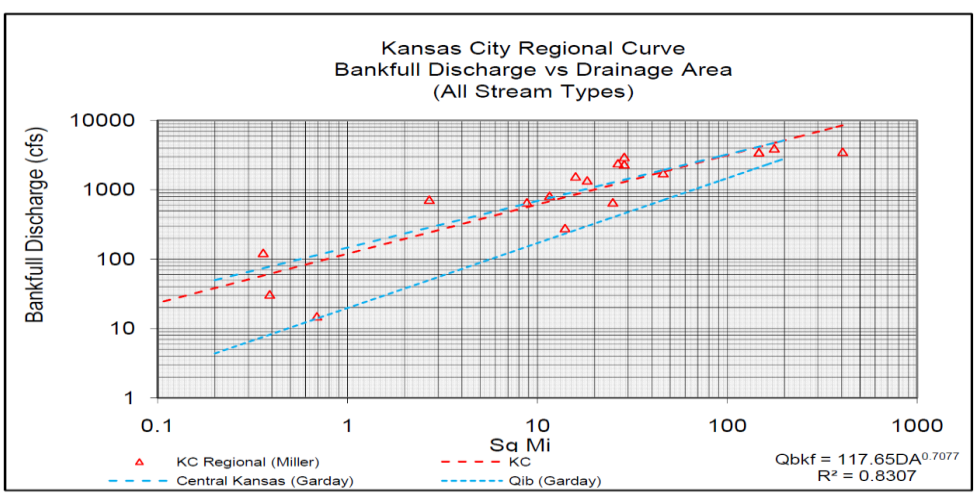

Figure 11 Kansas City Regional Bankfull Discharge Curves, Courtesy Paul D. Miller.

Most Probable Q_{Daily}/Q_{Peak} Ratios

Other methods to determine most probable Q_{Daily}/Q_{Peak} were evaluated: 15-minute instantaneous discharges were analyzed to use the largest 24-hour runoff volume under Q_{CF}. Surveys and analyses of 5 riffle cross-sections on the Sinsinawa River near Menominee; Illinois gage 05414820 at 39.6 miles^2 in the Wisconsin Driftless section: The Q_{Daily}/Q_{Peak} (**0.2243**) from averaging twenty (15-minute interval) storm hydrographs (1989-2004; $Q_{1.27} < Q_{Peak} < Q_{3.11}$) compared to Q_{Daily}/Q_{Peak} (**0.2338**) from averaging twenty three annual maximums (1967-2012; $Q_{1.25} < Q_{Peak} < Q_{2.99}$). Results of geomorphic surveys: $Q_{Bankfull}$ = 1,534 cfs and Q_{IB} = 364 cfs-day at 0.45% annum on FDC. Estimated $Q_{Daily\ Bankfull}$ = 359 cfs-day at 0.46% annum on FDC, actual $Q_{Inner\ Berm}/Q_{Bankfull}$ ~**0.2373**.

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