The Contribution of Small Storms to Annual Runoff Volume Evaluated in a Sample Watershed using the Curve Number Method

Ralph G. Mastromonaco, P.E.
November 2004

As modern storm water regulations emphasize the capture or isolation of early portions of the storm water runoff cycle for treatment and removal of pollutants, it is advantageous to understand the contribution small storms make to the annual runoff budget as capturing runoff for treatment may reduce the total volume of runoff available to streams and wetlands. Determining the magnitude of the impacts of treating storm water depends on gaining an understanding of the annual amount of runoff that would be diverted from the natural system by the treatment device.

For this analysis we developed a continuous runoff model as a composite distribution of storms covering all possible rainfall events from 0.2 inch to about 20 inches per storm for Yorktown, NY. We also developed a means of extracting the contributions of ranges of storm frequencies to the annual runoff volume as well as a means of relating annual runoff to SCS curve number.

Rainfall Record Data

A specific rainfall distribution model is constructed based on 33 years (Oct. 1970- Jan. 2003) of NOAA rainfall data that was tabulated in 15 minute intervals for Yorktown, New York. A frequency distribution of this data was prepared over the entire record as noted in Table 1.

Table 1: Yorktown, NY Distribution of NOAA Rainfall Data 1970-2003

Rainfall (inch)	33 year Exceedance Frequency	Annual Exceedance Frequency	Return Frequency (year)
0	2810	85.15	0.012
0.1	2810	85.15	0.012
0.2	1919	58.15	0.017
0.3	1489	45.12	0.022
0.4	1200	36.36	0.028
0.5	1001	30.33	0.033
0.6	816	24.73	0.040
0.7	678	20.55	0.049
0.8	562	17.03	0.059
0.9	465	14.09	0.071
1	398	12.06	0.083
1.1	335	10.15	0.099
1.2	289	8.76	0.114
1.3	249	7.55	0.133
1.4	212	6.42	0.156
1.5	182	5.52	0.181
1.6	153	4.64	0.216
1.7	125	3.79	0.264
1.8	114	3.45	0.289
1.9	98	2.97	0.337
2	75	2.27	0.440
2.1	63	1.91	0.524
2.2	53	1.61	0.623
2.3	51	1.55	0.647
2.4	43	1.30	0.767
2.5	33	1.00	1.000
2.6	30	0.91	1.100
2.7	28	0.85	1.179
2.8	23	0.70	1.435
2.9	20	0.61	1.650
3	17	0.52	1.941
3.1	15	0.45	2.200

Other available data for individual storms is shown below on the Table 2:

Table 2: Various Sources of Local Storm Frequencies versus 24 hour Rainfall (in).

Frequency (year)	NYC DEP (NWS TP-40)	Westchester Soil and Water Board	Thaler WHCGLHV	**Rainfall Data Used**
2	3.5	2.6	3.00	**3.1**
5	4.5	3.3	-	**3.55**
10	5.0	5	4.80	**4.71**
25	6.0	5.77	6.40	**5.5**
50	7.0	6.3	7.00	**6.5**
100	7.5	7.2	9.00	**7.2**
PMP - 500yr 24 hr	-	-	-	**19.5**

The data for each storm was evaluated from a variety of sources only the data with a “best-fit” continuous progression was used (5). The other rainfall depth for these storms is shown on the chart to indicate the range of values and their source.

Hydrologic Model

There are a few models that relate annual runoff to annual rainfall. These are described as follows:

1. Simple Method (Schueler, 1987), based on impervious area, precipitation and fraction of storm events providing runoff. Model is too general and too imprecise for our function.

2. L-THIA (Long term hydrologic impact assessment) by Harbor, J., Grove, M., Bhaduri, B. and Minner, M., 1998, Long-Term Hydrologic Impact Assessment (L-THIA) GIS. Public Works, 129, p.52-54. No information on he model mechanics are provided by the author.
3. HSPF USGS - Hydrological Simulation Program—Fortran: HSPF simulates for extended periods of time the hydrologic, and associated water quality, processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. HSPF uses continuous rainfall and other meteorological records to compute stream flow hydrographs and pollutographs. Very complex, requiring much data input.

To predict the contributions of ranges of storm frequencies we developed a mathematical model of all rainfall, from the lowest rainfall to the greatest precipitation possible. The model relies upon fairly representing all rainfall over time as a series of individual one-day storms, each having a relative probability of occurrence and a discrete rainfall amount. This hydrologic model is authenticated and correlated to the historic record in terms of (1) annual rainfall, (2) the number of storms per year and (3) annual runoff.

Annual Rainfall - The 33 year Yorktown data record indicates annual rainfall of 41.34 inches, however, we expect the rainfall to range from 43.15 (Table 3 Northeast United States) to 43.9 inches per year based on the recent range from 1996 to 2003 and as reported by weather sites.

Table 3: Northeast US Annual Rainfall – 33-Year and Annual Rainfall Amount (inches)

Year	Rainfall
2003	50.68
2002	43.50
2001	34.04
2000	44.48
1999	42.47
1998	42.85
1997	39.37
1996	53.79
1995	39.01
1994	44.15
1993	43.16
1992	40.83
1991	38.67
1990	49.63
1989	44.67
1988	36.86
1987	39.81
1986	43.07

Year	Rainfall
1985	38.79
1984	44.24
1983	50.25
1982	38.33
1981	41.70
1980	36.30
1979	47.94
1978	39.73
1977	47.85
1976	44.67
1975	47.35
1974	42.12
1973	47.22
1972	50.91
1971	40.14
1970	39.99
Average	43.15

Similarly, the annual rainfall for Albany, NY is 38.37 inches and NYC is 49.88 inches. Yorktown is between the two NOAA stations, and the average of NYC and Albany rainfall is 44.12 inches per year, providing further indication of the annual rainfall amount.

Number of Storms per Year

From the NOAA (Table 1) data we know that there are 85 storms per year when storms that register at least 0.1 inch are counted. Thaler reports 96 to 122 storms per year of greater than 0.01 inches in the area of our study - Yorktown, NY, from the year 1930.

Annual Runoff

The USGS stream data indicates an average runoff in the locality of about 22.28 inches, as noted in Table 4. Annual runoff should range between 19 and 26 inches or about 50% of annual rainfall based on USGS records.

Table 4: USGS Records of Annual Runoff Near Yorktown, NY

Location	Record Period	Annual Runoff (in)
Hunter Brook South of Yorktown, NY	1996-2003	21.59
Kisco River Below Mount Kisco, NY	1996-2003	22.62
Angle Fly Brook at Whitehall Corners, NY	1996-2003	19.67
Muscoot River at Baldwin Place, NY	1996-2003	23.48
Stone Hill River South of Katonah, NY	1999-2003	18.82
Cross River Near Cross River, NY	1996-2003	22.27
Horse Pound Brook near Lake Carmel, NY	1996-2003	24.28
East Branch Croton River near Putnam Lake, NY	1996-2003	25.49
Average Runoff (in)	-	22.28

Figure 1: All Storm Frequency versus Rainfall depth

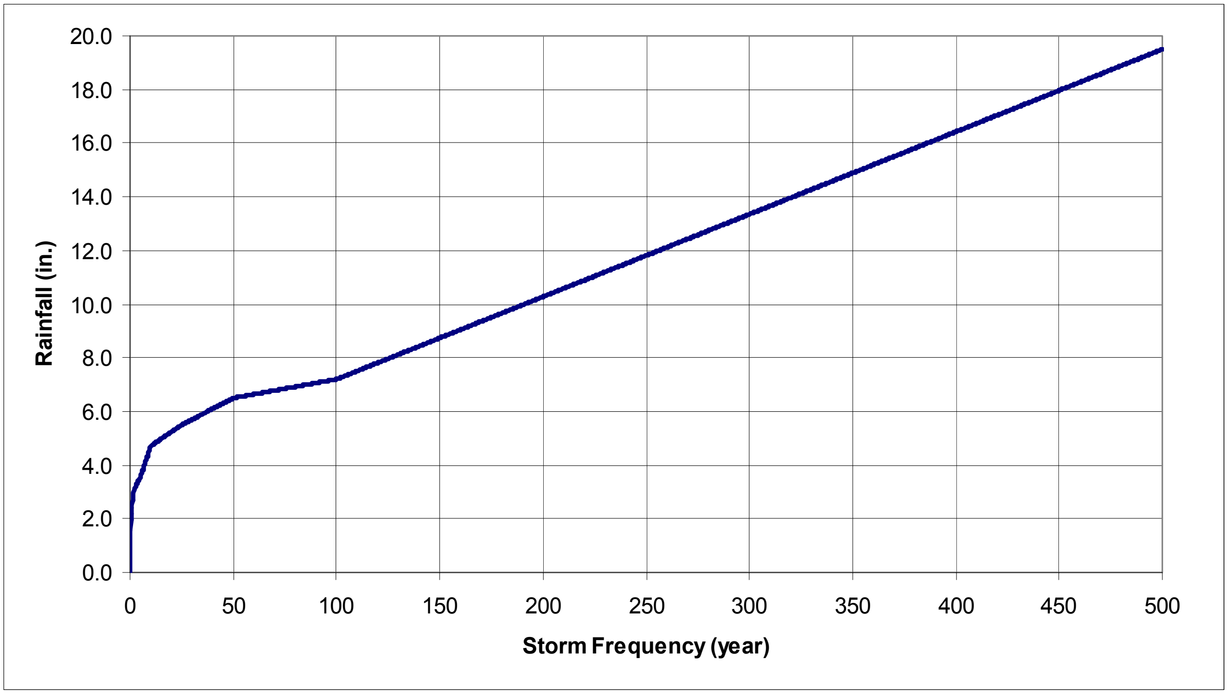
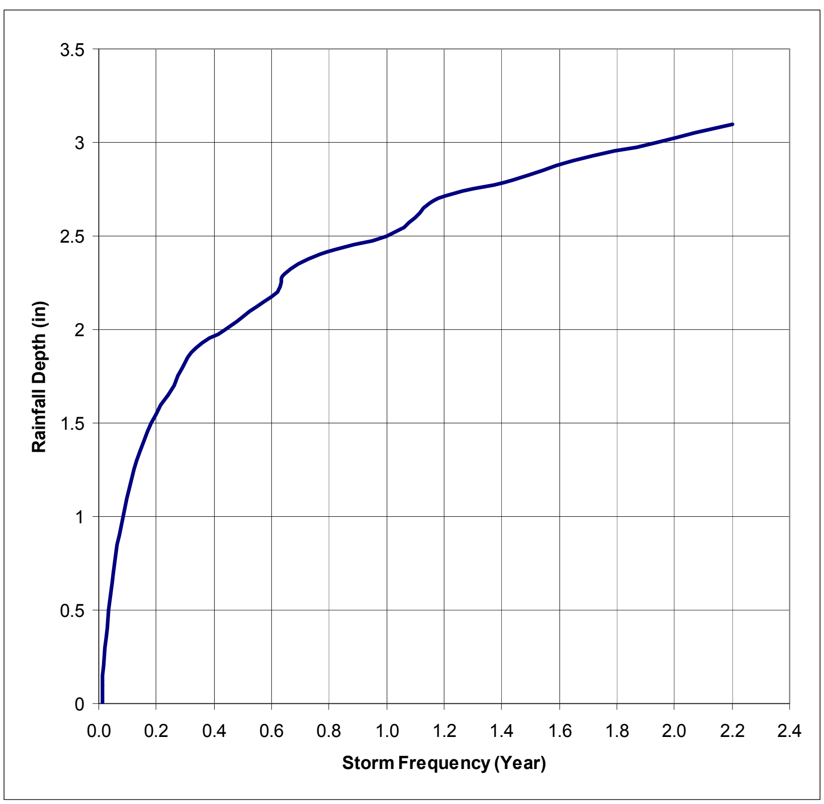


Figure 2: Small Storm Frequency versus Rainfall Depth (NOAA 970-2003) Yorktown, NY



The importance of this particular, full range model is that we can now account for the contribution of large, rarely occurring storms in the annual runoff. Large storms contribute huge volumes to the natural system though they occur less frequently than small storms. For this model we use the probability that any storm frequency can occur in any one year. For example, the 100 year storm in Yorktown of 7.5 inches per day contributes over 4 inches of runoff while the 1 year storm contributes only about ½ inch of runoff.

This model recognizes the contribution of the 100 year storm in any year by averaging the runoff from that storm over 100 years and applying probable portions of the runoff in one year. Similarly, the model also accounts for the 98, 96, 95 … etc. storms and their runoff. We refer here to the larger storm's contribution in one year as "probable" rainfall and "probable" runoff. The composite nature of the extended rainfall model is outlined below:

1. Small Storms

For the smaller storms, below the 2 year frequency, we use actual data developed from the record data of 33 years. This data is derived from the information in Table 1.

2. Medium Storms

An examination of the 33 year data shows that the larger storms up to 100 years should not be represented since the record base is only 33 years. Accordingly, we use other rainfall and frequency data for the storms greater than 2 year frequency, interpolating between each rainfall depth in inches per storm, up to 7.2 inches per storm for the 100 year event.

3. Probable Maximum Precipitation

To augment the record even further, we use the probable maximum rainfall of 19.5 inches that we represent here as a 500 year storm. The National Oceanic and Atmospheric Service publish probable maximum precipitation maps in its Hydrologic Meteorology Report No 51. Figure 30 of that report indicates that the all-season PMP for the 24 hour storm over 1000 square miles is 19.5 inches.

The SCS rainfall to runoff formula applies only to individual storms. It is adapted to our model as we have segmented the entire rainfall regime into individual rainfalls. The initial abstraction is computed by the formula based on the runoff curve number. An initial, trial curve number of 70 is chosen as it represents a mix of woods, open space, and light developments in the local watershed. In this model, the trial curve number of 70 produces an annual runoff that is very close to the USGS averages. Ultimately, the curve number model must be calibrated to the total annual runoff by stream flow records.

To determine the volume of runoff for any single storm we use the SCS volume formula found in NRCS (SCS) publication TR-55, defined as follows:

Table 4: Computation of Runoff

Watershed Curve Number CN	70
Q=(P-Ia)2/((P-Ia)+S)	
S=(1000/CN)-10	4.29
Ia=0.2S	0.86

Where:
Q = Runoff (in.)
P = Rainfall (in.)
S = Potential maximum retention after runoff begins (in.)
Ia = initial Abstraction (in.)

Watershed Data

The land use and soil types in the area of Yorktown provide runoff curve numbers of about 70 due to the variety of land uses in the locale. Since we are not seeking peak flows, the curve number will only be used to determine runoff depth per storm.

The SCS formula for runoff depth is also used to determine the Initial abstraction (Ia) that is defined as the rainfall value at which runoff begins. In other words, for rainfall less than the initial abstraction, there is no runoff.

Probable Rainfall

Since, for example, the 100 year storm has a 1% probability of occurring in any one year, we computed the runoff from a single 100 year storm and averaged the runoff each year as a contribution. Continuing in this manner we performed the same computation for all possible storms, in 0.2 year increments, adding the runoff contribution from each storm to the probable annual runoff.

Probable Runoff

The spreadsheet in Table 6 indicates the format and formulas used to determine the theoretical contribution of all storms to a single year's annual runoff. The possibility that a storm contributes runoff flow in any one year is the probable runoff.

The working of the rainfall model and the column formulas are described as follows in Table 5.

Table 5: Description of Column Formulas for Table 6

Column Number	Description
1	The list of storm frequencies from 0 to 500 years in 0.2 year increments
2	The probable number of storm represented by 1/Column (1) – Row 1 for the range 0 to 0.2 is taken from the 33 year NOAA tables
3	The rainfall per storm event is interpolated from the rainfall probabilities for the 2, 5, 10, 25, 50, 100 and 500 year storms. Rainfall per Event in the 0 to 2 year range is taken from the NOAA data
4	The annual rainfall depth is the number of storm events times the rainfall (4)=(2) x (3)
5	The interval Annual Rainfall Depth accounts for the fact that we have used 0.2 years as an interval thus we must multiply the annual rainfall depth by 0.2 to obtain the rainfall in the specific range (4) x 0.2 = (5)
6	Runoff per Storm is computed by the SCS Volume formula, relying upon P, Ia, S, and CN
7	Runoff per Storm Event is repeated and is only used if the user sets a minimum
8	Annual Runoff Depth per Storm is the runoff per storm event times the number of storms (2) x (7) = (8)
9	Interval Probable Runoff Depth accounts for the 0.2 year interval (8) x 0.2 = (9)
10	Cumulative Runoff is the cumulative sum of the runoff in column (9) from smaller storms up to the indicated storm.
11	Fraction of annual runoff is the runoff in column (10) as a fraction of the annual runoff.

The entire 2500 lines of the spreadsheet as the return frequency increases from 0 to 500 years by the 0.2 year step, are not shown to save space. The entire excel spreadsheet is available on www.hec-1.com our hydrology website.

Derivation of the Model's Numerical Progression

1. Runoff per storm = SCS runoff formula at a given rainfall depth and a given curve number

2. Probable number of storms = 1 / Return Frequency

3. Probable annual runoff depth per storm = Probable number of storms of a return year x runoff per storm

4. Annual Runoff = $\sum_{n = 0 \text{ years}}^{500 \text{ years}}$ Probable annual runoff depth per storm x ΔReturn Frequency

Table 6: Sample Model Computation, Partial Sheet, CN=70

Return Frequency (1)	Probable Number of Storms (2)	Rainfall per Event (3)	Annual Rainfall Depth (4)	Interval Annual Rainfall Depth (5)	Runoff per Storm Event (6)	Runoff per Storm Event (adjusted) (7)	Annual Runoff Depth per Storm (8)	Interval Probable Runoff Depth (9)	Cumulative Runoff (10)	Fraction of Annual Runoff (11)
0	85.000	**0.00**	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000
0.2	5.000	**1.55**	7.75	1.55	0.096	0.096	0.482	0.096	0.096	0.004
0.4	2.500	**1.95**	4.88	0.98	0.222	0.222	0.555	0.111	0.207	0.010
0.6	1.667	**2.2**	3.67	0.73	0.320	0.320	0.534	0.107	0.314	0.015
0.8	1.250	**2.4**	3.00	0.60	0.408	0.408	0.511	0.102	0.416	0.019
1	**1.000**	**2.5**	**2.50**	**0.50**	**0.455**	**0.455**	**0.455**	**0.091**	**0.507**	**0.024**
1.2	0.833	**2.7**	2.25	0.45	0.554	0.554	0.462	0.092	0.600	0.028
1.4	0.714	**2.8**	2.00	0.40	0.606	0.606	0.433	0.087	0.686	0.032
1.6	0.625	**2.9**	1.81	0.36	0.659	0.659	0.412	0.082	0.769	0.036
1.8	0.556	**2.95**	1.64	0.33	0.687	0.687	0.381	0.076	0.845	0.039
2	**0.500**	**3.1**	**1.55**	**0.31**	**0.771**	**0.771**	**0.385**	**0.077**	**0.922**	**0.043**
2.2	0.455	3.130	1.42	0.28	0.788	0.788	0.358	0.072	0.994	0.046
2.4	0.417	3.160	1.32	0.26	0.805	0.805	0.335	0.067	1.061	0.049
2.6	0.385	3.190	1.23	0.25	0.822	0.822	0.316	0.063	1.124	0.052
2.8	0.357	3.220	1.15	0.23	0.840	0.840	0.300	0.060	1.184	0.055
3	0.333	3.250	1.08	0.22	0.857	0.857	0.286	0.057	1.241	0.058
3.2	0.313	3.280	1.03	0.21	0.875	0.875	0.273	0.055	1.296	0.060
3.4	0.294	3.310	0.97	0.19	0.893	0.893	0.263	0.053	1.348	0.063
3.6	0.278	3.340	0.93	0.19	0.911	0.911	0.253	0.051	1.399	0.065
3.8	0.263	3.370	0.89	0.18	0.929	0.929	0.244	0.049	1.448	0.067
4	0.250	3.400	0.85	0.17	0.947	0.947	0.237	0.047	1.495	0.069
4.2	0.238	3.430	0.82	0.16	0.965	0.965	0.230	0.046	1.541	0.071
4.4	0.227	3.460	0.79	0.16	0.983	0.983	0.224	0.045	1.586	0.074
4.6	0.217	3.490	0.76	0.15	1.002	1.002	0.218	0.044	1.629	0.076
4.8	0.208	3.520	0.73	0.15	1.020	1.020	0.213	0.043	1.672	0.078
5	**0.200**	**3.550**	**0.71**	**0.14**	**1.039**	**1.039**	**0.208**	**0.042**	**1.714**	**0.079**
					Continuation from 5 to 500 years not shown					
500	**0.002**	**19.500**	**0.04**	**0.01**	15.158	15.158	0.030	0.006	21.568	1.000
TOTALS	**127.00**			**44.29**				**21.568**		

The probable runoff is shown as computed directly from the rainfall using the SCS formula. The probable runoff is based on the number of storms expected per year and represents the possibility of large storms contributing runoff in any one year.

Over the range of storms we plotted the relationship, cumulatively, up to the 500 year storm.

Figure 3: Full Range (0 to 500 years) of the Annual Runoff versus Cumulative Storm Frequency (CN=70)

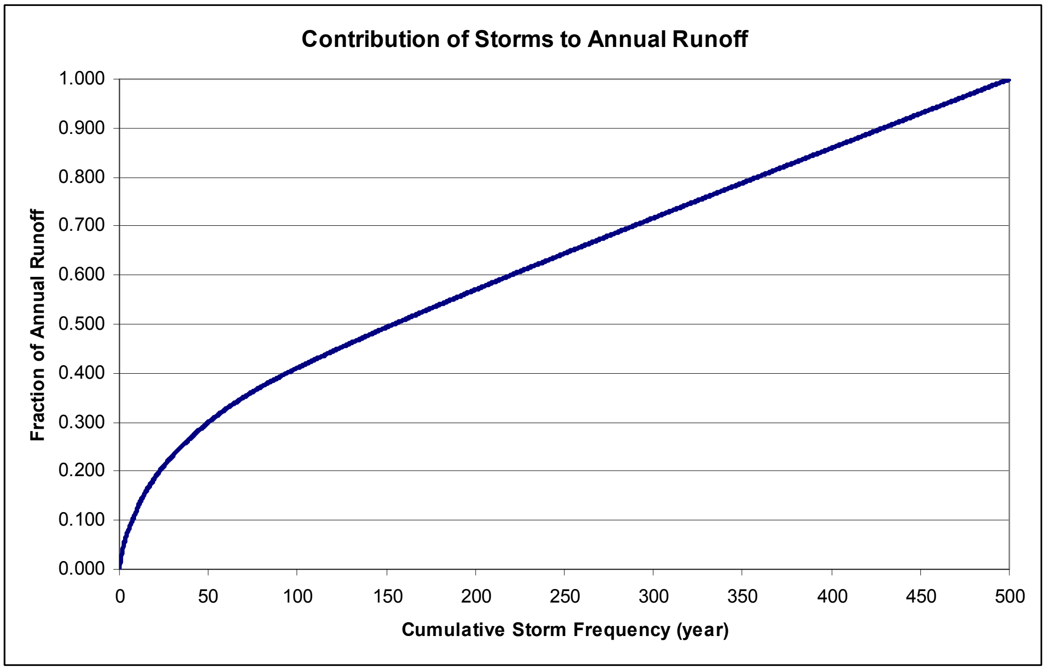
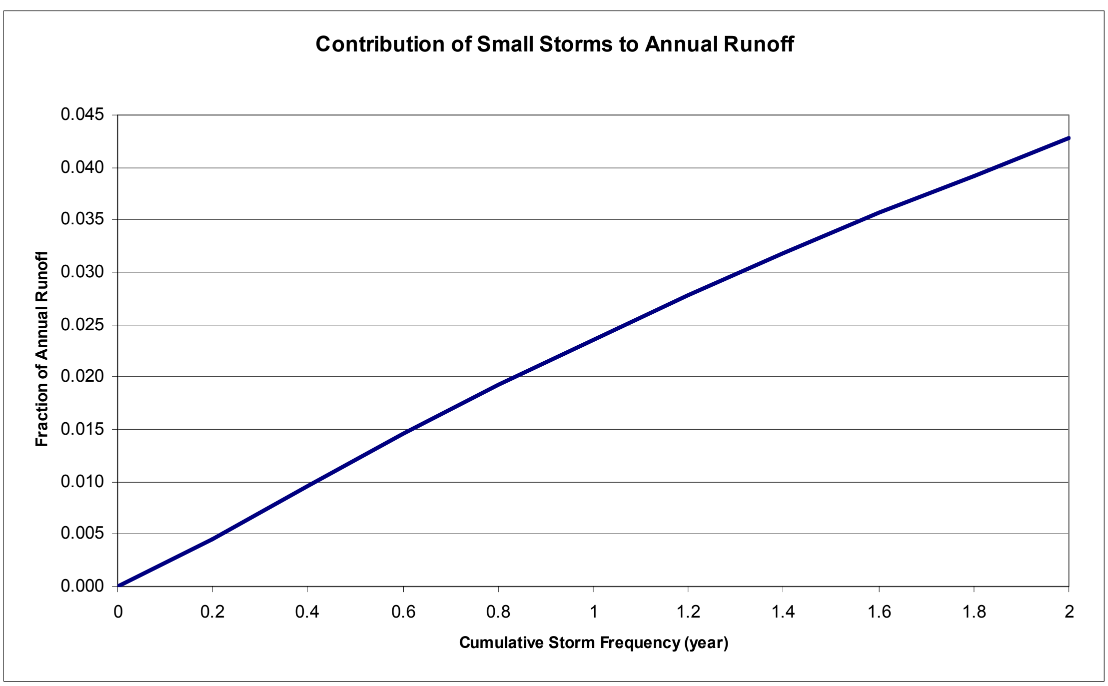


Figure 4: Small Range (0 to 2 years) of the Annual Runoff versus Cumulative Storm Frequency (CN=70)



Discussion

Model Calibration

The total annual runoff is the summation of the probable runoff for each storm. Based on our estimate of the watershed curve number of 70, the model's computations indicate an annual runoff of 21.6 inches (Table 6). This is very close to the average annual runoff in the locale of 22.28 inches and tends to validate the model in terms of runoff.

Further, the annual rainfall summed in the model at 44.29 inches (Table 5) which is very close to the 33 year Yorktown data record of 41.34 inches and closer to the to 43.9 inches per year based on recent data from 1996 to 2003. The closeness of the rainfall data further validates our model.

We know that there are 85 storms per year when storms that register at least 0.1 inch are counted. Thaler reports 96 to 122 storms per year greater than 0.01 inches in the area surrounding Yorktown, NY from the year 1930. The number of storms predicted by our model is 127. This result calibrates favorably with the actual count since we are counting all storms and one would expect a slightly higher count. The closeness between the number of storms predicted to the recorded number of storms also validates the model.

The model also indicates, presumptively, that 100% of the runoff is provided by storms up to the 500 year storm event.

Interpretation of Results

The plotted results show that about 40% of annual runoff is provided by all storms up to the 100 year event (Figure 3). Further, only 4.3% of the annual runoff is contributed by storms up to the 2 year storm event, while storms up to the 2 year storm contribute only about 4.3% (0.043) of the total annual runoff, storms up to the 5 year storm contribute 7.9% (0.079) of the annual runoff.

Accordingly, modern stormwater treatment systems that divert all runoff up to the 2 year storm are removing only about 4.3% of the annual runoff from downstream watercourses in typical watersheds. In general, this is not a significant quantity. In fact, this is less than the year-to-year variation in annual runoff.

The model was run also to determine the effect of watershed curve number and the plotted results are shown in Figure 5. At larger watershed curve numbers (>80) the smaller storms exert more of an influence on annual runoff but not a significant one. At a curve number of 50 the relation of storm contribution to annual runoff is nearly linear with cumulative storm frequency.

The fraction of total runoff contributed by small storms depends on the SCS runoff curve number. For large curve numbers (~90) the fraction of total runoff up to the 2 year storm is 10% but for low curve numbers (~60) the fraction is only about 2%. In fact, for very low curve numbers (~40) the small storms contribute little or nothing to annual runoff.

It is clear that the mechanism that keeps the contributions somewhat linear is the balance of return period and rainfall amount. In other words, larger storms provide more rainfall per storm but only occur infrequently. Likewise, there are numerous small storms annually, but each only produces small amounts of runoff. In fact, many small storms produce no runoff.

Figure 5: Contributions to Annual Runoff (0-500 years)

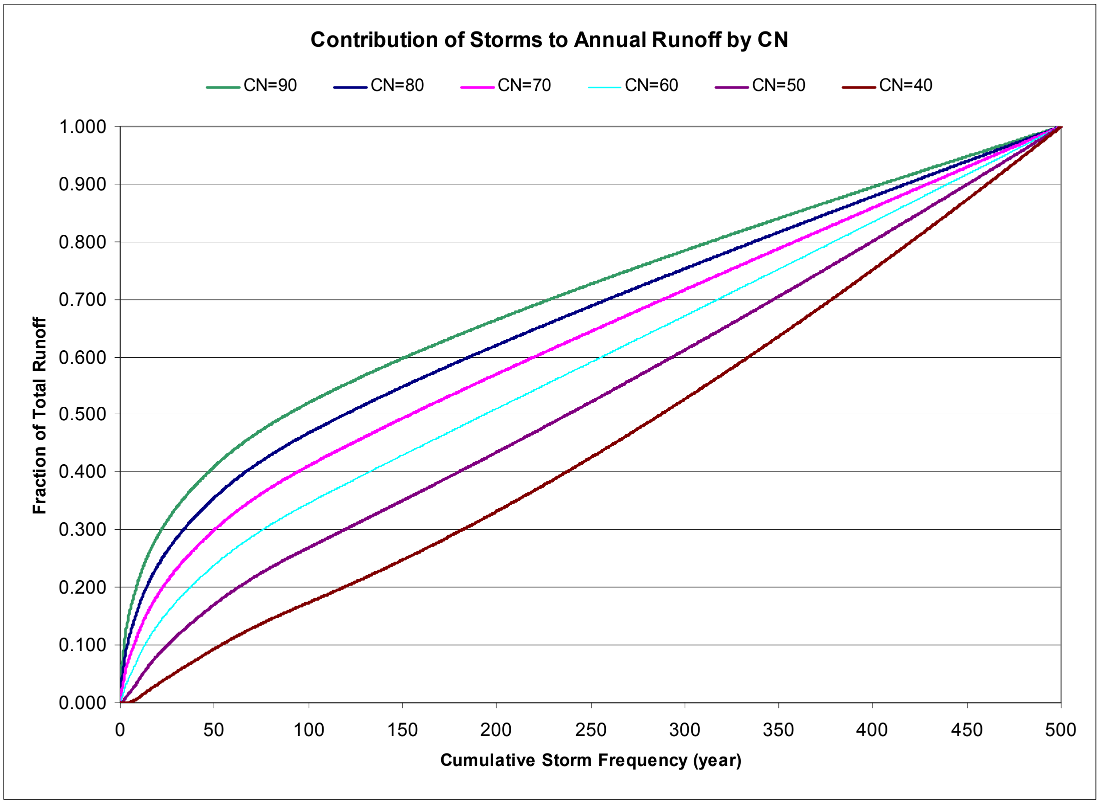
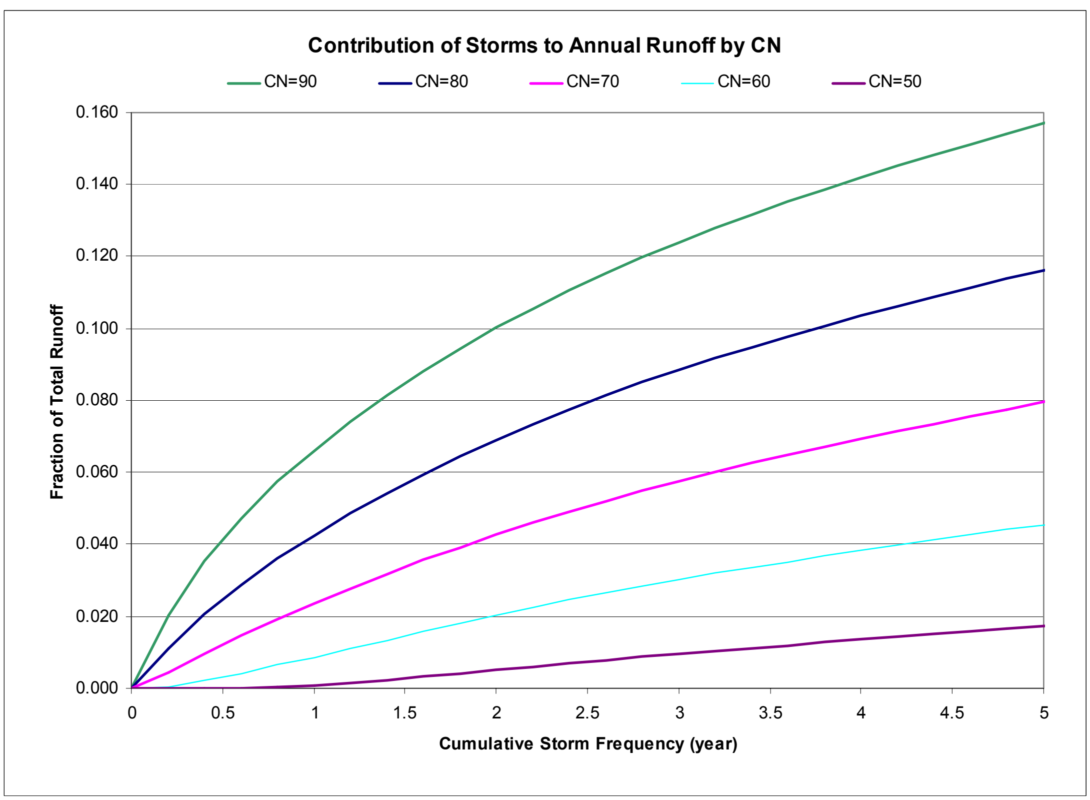


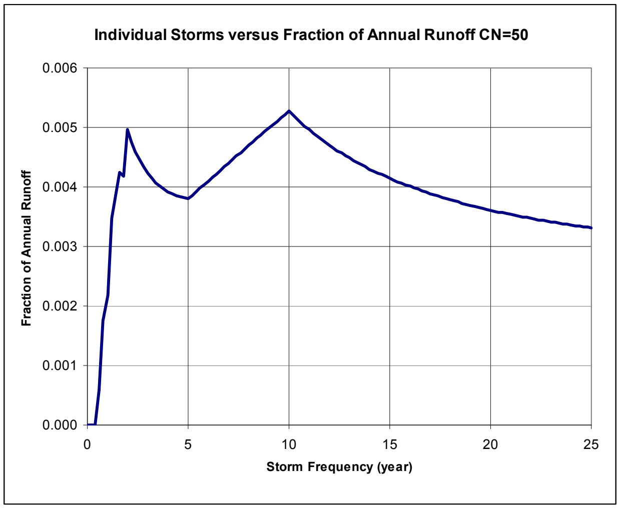
Figure 6: Contributions to Annual Runoff (0-5 years)

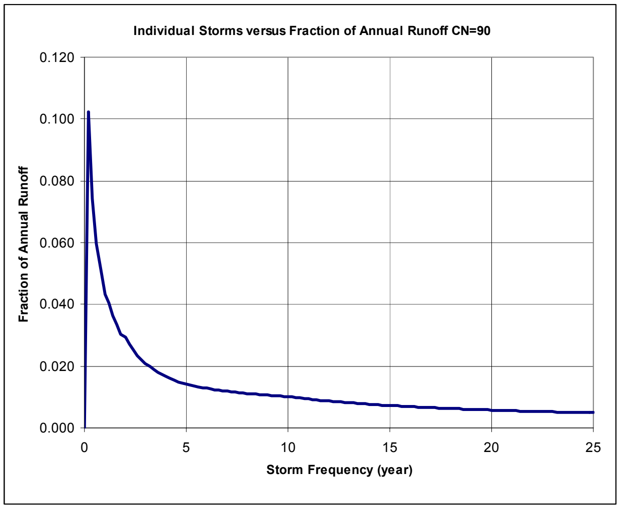


Further Interpretations and Uses of the Model

The model provides several other interesting conclusions about the annual runoff cycle and storm frequency. For a watershed with a curve number of 50 the plot in Figure 7 (left) shows that any storm from about the 2 year storm to the 25 year storm contribute runoff in nearly identical quantities of about 0.004 (0.4%) of the total annual runoff. This figure illustrates the aforementioned balance between individual storm frequency and annual runoff especially for a watershed with a low runoff curve number (CN).

Figure 7: Relationships of Annual Runoff to Individual Storm Frequency





For watersheds with a very high curve number (e.g. 90) the smaller individual storms provide a higher contribution to annual runoff than larger storms, as can be seen in Figure 7 right. For example, the 2 year storm provides about 3% of the annual runoff while the 10 year storm provides only about 0.01 (1%) of annual runoff and the 25 year storm about 0.5%. This example does, however, explain the general notion that for a high CN watershed, individual small storms contribute more to annual runoff than larger storms.

It must be made clear that the relationships shown in Figure 7 have little practical meaning as they portray individual storms as differentiated from a range of storm plotted as cumulative storm frequencies shown in earlier plots. The cumulative frequency plots are actually the numerical integration of the graphs in Figure 8 and represent the total contribution from storms up to and including the design year.

Annual Runoff Formula

Now that we have a working hydrologic model, additional information becomes available. For example, by plotting the ratio of runoff to rainfall on an annual basis, as compared to the watershed curve number, we can develop an empirical relationship, as follows:

$$R = 0.00009 * CN^2 + 0.0009 * CN - 0.0344$$

Where: R= the fraction of annual runoff to annual rainfall
CN = SCS runoff Curve Number
Range is CN>=10; CN<=100
Coefficient of Determination (closeness of fit) = 0.9998

This relationship should allow us to predict the annual amount of runoff from watersheds where we know the runoff curve number. Since the methods to develop this formula here were almost independent of any intrinsic climatic or regional conditions, the formula should be applicable to other regions. For a sensitivity analysis we modified the 100 year storm value by 20% and noted that the plot and formula varied insignificantly. This relative insensitivity to rainfall changes indicates the formula applies to a wide variety of rainfall intensities and thus, other locales by using other local storm frequencies.

Figure 8: Plot of Fraction of Annual Runoff / Annual Precipitation to Runoff Curve Number

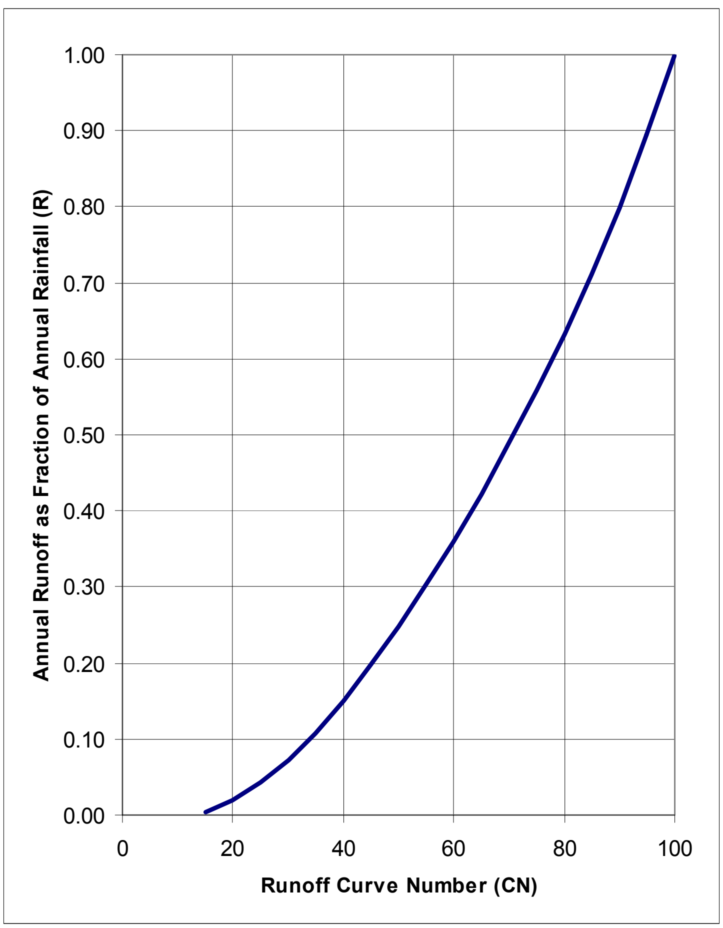


Table 7: Table of Values Plotted

CN	Annual Runoff	Fraction of Total Rainfall
10	0.0	0.00
15	0.2	0.00
20	0.9	0.02
25	1.9	0.04
30	3.2	0.07
35	4.8	0.11
40	6.7	0.15
45	8.7	0.20
50	11.0	0.25
55	13.5	0.30
60	15.9	0.36
65	18.7	0.42
70	21.6	0.49
75	24.7	0.56
80	28.0	0.63
85	31.5	0.71
90	35.4	0.80
95	39.6	0.89
100	44.3	1.00

Conclusion

The closeness of the points of calibration are compelling indicators that we have accurately represented the rainfall / runoff mechanism with this model.

Based on the results of this study, we can make the following general statements about annual rainfall and annual runoff:

1. The fraction of runoff that is contributed by small storms is highly dependent on the SCS runoff curve number of the watershed.

2. In watersheds with very low curve numbers (<43) the small storms of less than 2 year frequency contribute no runoff and thus, do not contribute to the annual runoff.

3. The amount of runoff provided by small storms up to the 2 year storm is a relatively small fraction of the annual runoff, generally around 5 per cent for a typical watershed, to 10% for watersheds with very high curve numbers.

4. In typical residential / wooded watersheds, rainfall greater than the 2 year storm contribute heavily, providing 95% of the annual runoff.

Generally, the capture of all runoff up to the 2 year storm by various stormwater devices would remove only a small fraction of the annual runoff implying that there would be little or no effect on natural systems.

Finally, as a direct offshoot of the model, we have found that the annual runoff may be represented by a formula that is dependent on the annual rainfall and the watershed runoff curve number.

In summary, we have created an impressive model that effectively simulates the response of annual runoff to annual rainfall.

References:

1) NRCS Publication TR-55, Urban Hydrology for Small Watersheds

2) Data Websites:

   a) www.noaa.gov

   b) www.weather.com

   c) http://www.ncdc.noaa.gov/oa/climate/research/cag3/nt.html

3) Westchester County Best Management Practice Manual for Stormwater Management, 1984

4) NYCDEP handout (storm frequencies versus rainfall for NYC watersheds) reputed to be interpreted from NWS map TP-40

5) Thaler, Jerome S., Weather History and Climate Guide to the Lower Hudson Valley (WHCGLHV)

6) National Weather Service map number TP-40

7) USGS, Lower Hudson Valley Water Report for 2003

8) National Oceanic and Atmospheric Service, Probable Maximum Precipitation (PMP) Hydrologic Meteorology Report No 51